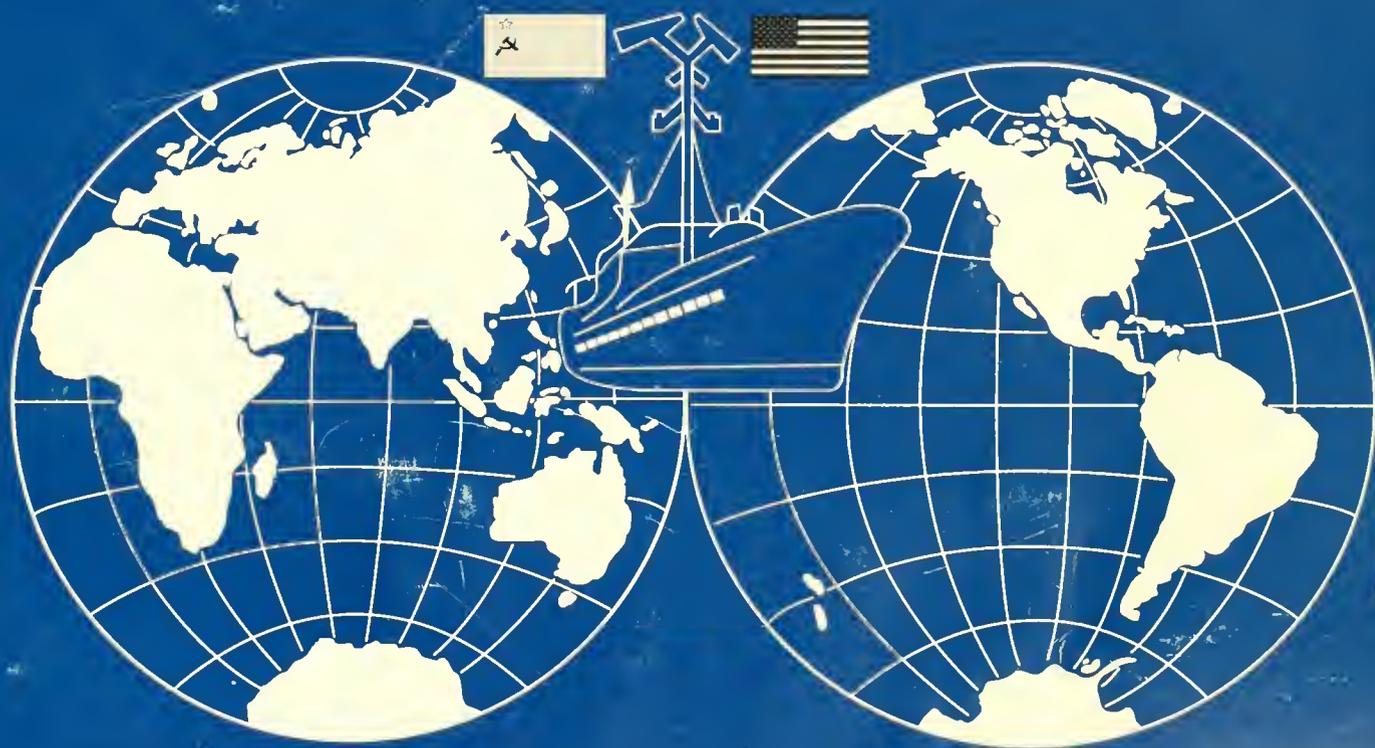
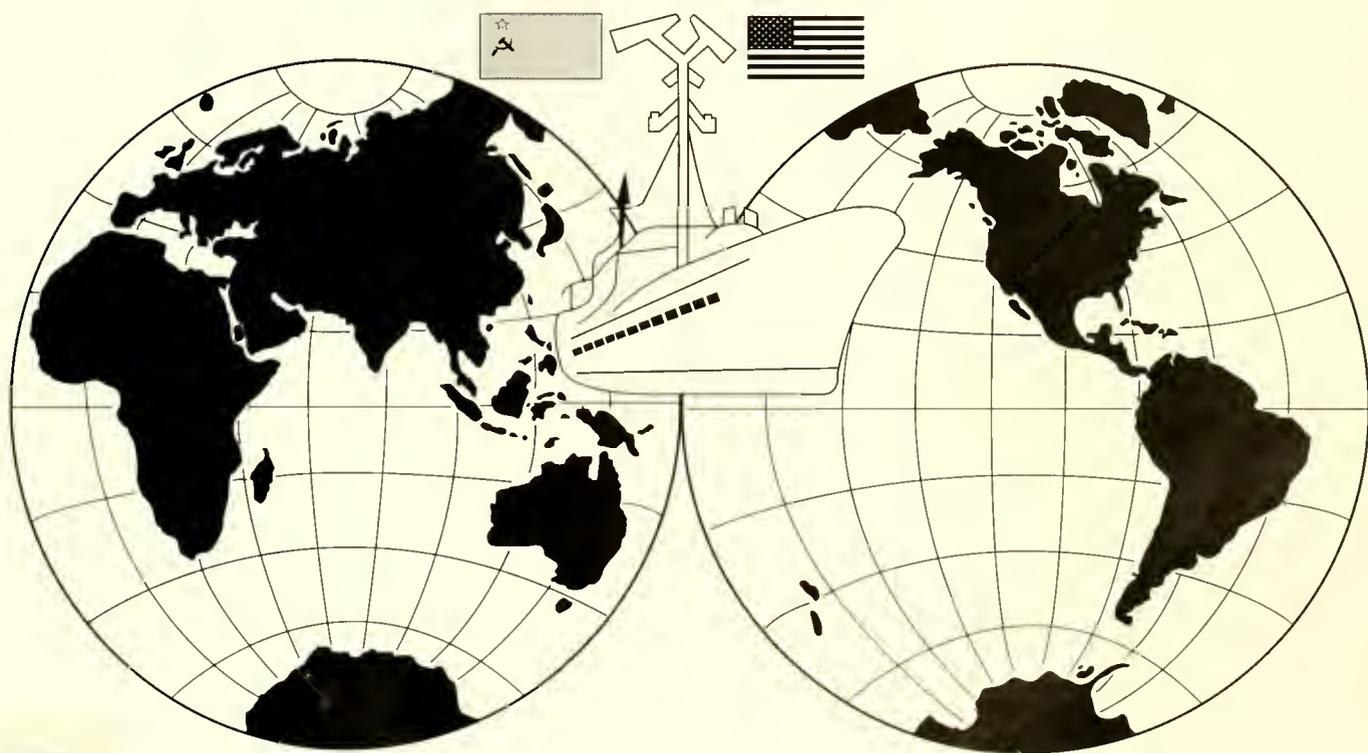


RESULTS OF THE THIRD JOINT US-USSR BERING & CHUKCHI SEAS EXPEDITION (BERPAC)



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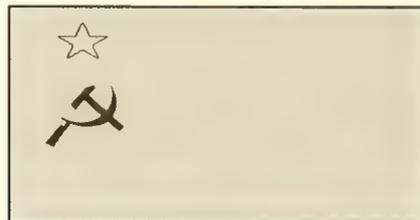
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**Results of the Third Joint
US-USSR Bering & Chukchi Seas
Expedition (BERPAC)**

Summer 1988



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Disclaimer:

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Foreword

In the last few years, an ever-growing anthropogenic impact on different natural ecosystems and the adverse effects resulting from this impact have led humanity to realize the real threat of potential global ecological disasters and to give a high priority to environmental protection.

Natural factors cause the bulk of nearly all man-made chemicals to eventually enter the World Ocean, which, owing to this, can be considered a tremendous reservoir/accumulator of contaminants. Elimination of these contaminants through natural processes of the ocean (i. e., self-purification) occurs through a complex system of physical, chemical, and biological processes taking place in the ocean. However, conditions favorable for the existence of certain hydrobionts that were established over whole geological epochs are being disturbed by these anthropogenic impacts. For these reasons, it is obvious that while studying ocean pollution and its ecological consequences, it becomes necessary to have complex physical, chemical, and biological investigations, which calls for principally new, interdisciplinary approaches to the solution of this problem.

The protection of the marine environment against the undesirable influence of anthropogenic factors are global problems common to all mankind. They can, and must, be solved by joint efforts of scientists from different countries. For this reason, and taking into consideration that the Bering and Chukchi Seas wash the US and USSR coasts (countries equally interested in the further fate of these unique regions of the World Ocean), it was considered appropriate that the efforts and knowledge of scientists of both countries be joined to study the state of the ecosystems of these seas.

It is important to note that 1992 is the 20th anniversary of the US–USSR Agreement on “Cooperation in the Field of the Protection of the Environment” and the 15th anniversary of the beginning of joint US–USSR research within the framework of the special subproject “The Bering Sea.” In 1977, 1984, and 1988, US–USSR integrated ecological expeditions aimed at investigations of Bering Sea ecosystems were carried out within the framework of the above agreement. These expeditions enabled scientists of both countries to add to the volume of knowledge of this poorly understood body of water. The following are the major research thrusts: a more detailed study of the oceanographic regime; accumulation of data on the spatial (horizontal and vertical) variability of nutrient concentrations; the study of the dynamics of arrival and elimination of the most important pollutants; acquisition of data on the structural and functional characteristics of planktonic and benthic communities; a more detailed study of the microbiological regime; and determination of the role of microorganisms in the biogeochemical cycles of elements in the destruction of organic pollutants.

Long-term integrated investigations in the Bering Sea began on the first US–USSR expedition on board the R/V *Volna* in 1977. The scientific results of the expedition were presented in joint monographs published in the US (US Fish and Wildlife Service, 1982) and USSR (Izrael & Tsyban, 1983). These investigations were further developed during the expedition carried out by Soviet scientists in 1981 on board the R/V *Akademik Shirshov*. New scientific data were obtained on the characteristics of the state of the Bering Sea ecosystem, the composition and physiological activity of bacterial populations, quantitative and qualitative composition of microzooplankton, and, investigated for the first time, the biogeochemical cycle of polyaromatic hydrocarbons (using the benzo(a)pyrene as the model compound). Scientific results of the expedition were published in the monograph *Comprehensive Analysis of the Bering Sea Ecosystem* (Izrael & Tsyban, 1987).

The Second Joint US–USSR Bering Sea Expedition was carried out on board the R/V *Akademik Korolev* in 1984. During this expedition, a broad spectrum of questions were studied; they are considered in joint monographs published in the US (Roscigno, 1990) and the USSR (Izrael & Tsyban, 1990).

The Third Joint US–USSR Bering & Chukchi Seas Expedition also took place on board the R/V *Akademik Korolev* in the summer of 1988. During the expedition, the Bering Sea (already investigated in 1981 and 1984), the Gulf of Anadyr, the Chirikov basin, and the southern Chukchi Sea were investigated (see Protocol of the Third Joint US–USSR Bering & Chukchi Seas Expedition . . .). In the course of the third expedition, comprehensive studies of the state of Bering Sea ecosystems were continued and investigations in the Chukchi Sea were initiated. The present monograph contains scientific results obtained during the expedition and results which were obtained through *in situ* laboratory experiments on samples collected during this expedition.

The scope of problems elucidated in the monograph is wide: it includes the study of oceanographic aspects, hydrochemical conditions, variability of the spatial structure of planktonic biocenoses, microbial oxidation of organic pollutants, effect of toxic substances on the state of planktonic communities in conditions near to *in situ*, assessment of the elements of the ecosystem biotic balance, determination of the ratio between the processes of new formation and destruction of organic matter in the Bering Sea ecosystem, and determination of the elements of the biogeochemical cycles of organic pollutants in the Bering and Chukchi Seas.

The investigations made it possible to conclude that, at present, the ecosystems of the Bering and Chukchi Seas are in a relatively favorable state. However, to maintain this state under conditions of ever-growing anthropogenic impacts from

both countries, a careful scientific approach is necessary to prevent exploitation of the natural resources of this unique area of the World Ocean. Scientific information obtained in the course of these joint ecological expeditions contributes to the development of such an approach.

In conclusion, it should be noted that fundamental studies of northern polar marine ecosystems now have become even more important considering the newly emerging problems of global climate change. Ecological consequences of the predicted

climate change on marine ecosystems may first manifest themselves in arctic areas of the ocean and affect fundamental natural phenomena, such as biogeochemical carbon cycling, sea level rise, production/destruction processes of organic matter, and others. Thus, these joint investigations of the role of arctic ecosystems in global climate formation processes, which were started by Soviet and American scientists, need continued extension and development.

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Protocol of the Third Joint US–USSR Bering & Chukchi Seas Expedition on the R/V *Akademik Korolev*

In accordance with the memorandum of the 11th meeting of the US–USSR Joint Committee on the Environment Protection (Moscow, USSR, February 1988), the recommendation of the “Soviet–American Conference on the Ecology of the Bering Sea” (Batumi, USSR, March 1988), and the plan of the joint bilateral activity of 02.07–2101 “Comprehensive Analysis of Marine Ecosystems and Ecological Problems of the World Ocean”, the Third Joint US–USSR Bering & Chukchi Seas Expedition was held on 26 July–2 September 1988 on board the Soviet research vessel *Akademik Korolev*. The delegation was headed by Prof. Alla V. Tsyban and Mr. Harold J. O’Connor (Project Leaders 02.07-2101).

The Soviet delegates were represented by participants in the cruise from the USSR State Committee for Hydrometeorology and Control of Natural Environment; the Academy of Sciences from the USSR; and the Academies of Sciences from Ukraine, Belyorussia, and Estonia. A list of participants is given as Appendix A.

The American delegates were represented by participants from the US Department of the Interior, Fish and Wildlife Service; University of Texas; Texas A&M University; University of Alaska; University of New England (Maine); University of Washington; University of South Carolina; Skidaway Institute of Oceanography; and Lamont-Doherty Geological Observatory. A list of participants is given as Appendix A.

The principal objective of the Third Joint US–USSR Expedition was to characterize the contemporary condition of the fundamental oceanographic, hydrochemical (including pollution levels), and the hydrobiological parameters of marine ecosystems and to assess their assimilative capacity for marine pollution. This research was undertaken both on the polygons of long term investigations and in new areas of the Bering Sea (Gulf of Anadyr, Chirikov basin, and the Bering Strait) and the southern portion of the Chukchi Sea.

The main scientific tasks were

1. Biological, chemical, and physical fundamental data were collected to provide a comprehensive ecological and oceanographic profile of the Bering and Chukchi Seas.
2. Studies of the physiological and ecological characteristics of plankton organisms were conducted.
3. The ecological health of the Bering Sea was assessed.

In accordance with protocols of the Joint American–Soviet meeting (Batumi, Mar. 1988), the research vessel *Akademik Korolev*, with the Soviet participants on board, arrived in Dutch Harbor, USA, on 24 July 1988. During a three-day port of call, the American specialists and their scientific equipment were taken on board. The Third US–USSR Expedition started on 27 July with the transit to the East Polygon.

Complex ecological investigations in the Bering and Chukchi Seas were accomplished in four stages. In the first stage, work was started in the East Polygon (Stations 1–6) and was completed in the Gulf of Anadyr (Stations 6–43). The next stage studied the areas of the southern Chukchi Sea (Stations 6–43) and included a transect of the Bering Strait. After a port of call to Nome, Alaska (USA, 17–18 August), investigations were continued in the Chirikov basin from the Bering Strait to St. Lawrence Island. The final stage of the expedition consisted of six stations (109–113) including the South Polygon. Complex ecological studies (see Frontispiece) were conducted in 113 stations of the transects and of three polygons (East, North, and South). A map and station locations are found in the Frontispiece. The joint work and debarkation was completed on 2 September 1988 in Dutch Harbor. The entire duration of the Third US–USSR Expedition to the Bering and Chukchi Seas was 42 days.

In accordance with specialties of the expedition’s participants, working groups were organized (Appendix A). At these meetings, work schedules, joint studies, and model experiments were planned. During the expedition, several meetings of the Scientific Council Board were held.

Examined were:

1. ecological problems of monitoring studies of highly productive regions of the World Ocean;
2. the contemporary state of the knowledge of the Bering and Chukchi Seas’ ecosystem; and
3. preliminary scientific results of the Third US–USSR Bering & Chukchi Seas Expedition.

In the course of the meeting, scientific reports to the American and Soviet specialists were presented.

During the Third Joint US–USSR Bering & Chukchi Seas Expedition, the following preliminary results were obtained: the research was undertaken in five different ecosystems in the Bering and Chukchi Seas. Two ecosystems were situated in the East and South Polygons and they have the characteristics of deep-water ecosystems. Three ecosystems were in shallow-water areas of the Bering Sea (Gulf of Anadyr, Bering Strait, Chirikov basin) and the Chukchi Sea (southern portion) and were typical shelf ecosystems.

The structure of the water mass on the East Polygon consisted of the shelf’s boundary and was influenced greatly by the Bering Current flowing along the continental shelf-slope. Analysis of the distribution of temperature revealed the existence of two water layers. The minimum temperature was found at the depth of 150–250 m (boundary of the shelf-water of the Bering Current), and the maximum temperature was found at the depth of 400–500 m (intermediate water of the Bering Sea). We must note that both the minimum (1.6°C) and the maximum (8.9°C) temperatures were approximately 0.3–0.5°C higher than the average long term data for the region.

The distribution of nutrients of the East Polygon was typical of such a shelf-slope region. In the surface layers the nutrients concentration was found to be low and their concentration increased slowly below 100 m.

The microbiological community was characterized by variability of water mass in the East Polygon. The development of the heterotrophic, saprophytic microflora proved to be lower in total numbers in the deepwater stations 1 and 3 at the depth of 500 m (the indicator forms were completely absent). There were upper and lower layers where the number of saprophytic bacteria varied from 0 cells/ml to 10^3 cells/ml.

Preliminary data indicated that microbial community structure on the East Polygon did not change in comparison with the 1984 results. The highest quantity and biomass of neuston organisms was found on the East Polygon (in comparison with the other investigated areas). The average biomass was found to be four times higher than those results reported in 1984.

Very interesting experiments were undertaken for the first time in the northern regions of the Bering (Gulf of Anadyr) and Chukchi Seas. The ecosystems of the northern areas of the sea are some of the most productive in the World Ocean. Results of primary production showed values more than $12 \text{ g C/m}^2 \text{ d}^{-1}$. High concentrations of nutrients in the water masses are responsible for the high primary production. Significantly, the water mass is enriched with nutrients transported from the Gulf of Anadyr through the Chirikov basin and the Bering Strait to the southern area of the Chukchi Sea. This constant flow fuels the increase of phytoplankton numbers and production occurs at the boundaries of these water masses.

During the expedition, three local areas that had high phytoplankton production were discovered along the axis of the current. At these areas, the increase in biogenic sedimentation was also observed with the particulate matter settling from the euphotic zone containing more than 1.5% biogenic carbon.

The lowest temperature (-1.6°C) was discovered in the Gulf of Anadyr. Such low temperatures have not been observed here during the last 20 years. In spite of the low temperatures, significant phytoplankton biomass was found in the Gulf of Anadyr. The highest values of chlorophyll *a* in the gulf reached 55 mg/m^3 . The only values that were higher were those found in the Chukchi Sea.

In the coastal area of the Gulf of Anadyr, a high quantity and biomass of microzooplankton and benthos were observed. Biomass of benthic organisms reached $1,000 \text{ g/m}^2$ in several investigated stations. The ecosystems in the Chirikov basin depend greatly on the Anadyr Current, which carries into the gulf different amounts of nutrients that are necessary for the growth of phytoplankton. In turn, large amounts of nutrients were carried from the Chirikov basin through the Bering Strait to the Chukchi Sea.

The southern area of the Chukchi Sea, being influenced by Bering Sea waters, was rich in nutrients and unstudied until this time. Also, new practical knowledge of oceanographic features such as mass circulation, temperature, salinity distribution, and the general structural and functional characteristics of the ecosystems was determined.

During the expedition, we noticed that the function of the ecosystems of the Chukchi Sea was determined by at least two currents. High-salinity, nutrient-enriched, water masses are transported from south to north. They are carried by a flow that exits from the Gulf of Anadyr, crosses the Chirikov basin, flows through the Bering Strait, and ends in the Chukchi Sea. There is one more current, formed from the cold and relatively high salinity coastal Siberian waters, that is also enriched with nutrients. This current flows from northwest to southeast. These two flows of nutrients, discovered in the Chukchi Sea, determine the high biological productivity of this ecosystem. The merging of these two currents formed a wide area in the southeastern part of the sea. This area is characterized by the following: 1. concentrations of chlorophyll *a* reaches 77 mg/m^3 (a phytoplankton bloom was noticed at Station 45); 2. the average number of neuston organisms was $4,000 \text{ specimens/m}^2$; 3. the number of infusoria of the Chukchi Sea was much larger than in the Bering Sea; 4. a maximum number of mesozooplankton was in the larvae of benthic organisms, which was dominated in the metazooplankton; and 5. high average biomass of benthic organisms—about 900 g/m^2 —was found, reaching $1,500 \text{ g/m}^2$ and even $2,000 \text{ g/m}^2$ at some individual stations.

New species, which were not known before in the Chukchi Sea (testaceous mollusks, some echinodermata, and others) were found during the expedition. Many birds and mammals were also observed.

From various investigations, the data indicate that the biological productivity is high in the Bering Sea and higher still in the Chukchi Sea. In spite of the fact that the investigated regions are far away from industrial areas, an array of anthropogenic organic contaminants (polychlorinated biphenyls (PCB's), hexachlorocyclohexane, chlordane, and DDT) were found in the surface waters of these seas. The average measured concentration of hexachlorocyclohexane in the surface waters of both seas was more than 10 times the values of other anthropogenic contaminants (2.5 ng/l isomer and 1.2 ng/l isomer). Such levels of toxicants in the Bering and Chukchi Seas are potentially hazardous for the vulnerable arctic ecosystems. Analysis of the atmospheric samples produced similar results: concentrations of benzene hexachloride averaged 0.25 ng/m^3 and that for the isomer, 0.12 ng/m^3 .

The process of the degradation of the PCB's by natural microbial populations of the Bering and Chukchi Seas was studied. The preliminary results indicated that during the exposure (21 days) at temperate $6\text{--}10^\circ\text{C}$, the microorganisms oxidized up to 18% dichlorobiphenyl, up to 6% trichlorobiphenyl, 1% tetrachlorobiphenyl, and $<1\%$ penta/*n*-hexachlorobiphenyl (as compared to total amounts of these compounds compared in industrial mixtures of PCB). It is important to note that the toxic compound 2, 3, 6, 2', 3', 6'-hexachlorobiphenyl was degraded by 50–70% by various bacterial populations for 21 days. Altogether these facts indicated that a considerable part of chlorinated hydrocarbons may be retained and may accumulate in this arctic environment. This causes serious concern as these pollutants have known negative effects on biological processes.

Experiments were conducted to study the photochemical decomposition of polyaromatic hydrocarbons (PAH's). For example, only a 3-hour exposure to sunlight of benzo(a)pyrene already showed a significant quantitative breakdown of this carcinogenic chemical.

From the results of these studies, and from previous estimates of the accumulation of these compounds in the marine ecosystem, one needs to determine in detail the intensity of microbial destruction of pollutants; establish a "critical" concentration of individual pollutants that affect the ecological system; and study factors that affect important processes of the ecosystem. For example, the new formation of organic pollutants from the metabolic activity of microorganisms should be examined.

During the period of the expedition, joint American-Soviet experiments were conducted. Preliminary results of these experiments allowed us to assess the range of "critical" concentrations of pollutants for microzooplankton in the Bering and Chukchi Seas. The range varied as follows:

Benzo(a)pyrene	0.1-1 µg/l
Copper	2-8 µg/l
PCB	10-40 µg/l
Cadmium	20-40 µg/l

It is important to note that the established critical concentrations were 1,000× higher than those found in natural seawater.

With the results of the joint, multidisciplinary experiments, we have demonstrated that separate combinations of low concentration of nitrogen and phosphorus, which were typical for natural for natural water masses, not only do not stimulate but inhibit the growth of plankton communities.

Most of the collected biological and chemical samples during the expedition need a prolonged series of studies in a laboratory with special equipment and instrumentation for final results to be obtained. However, even incomplete preliminary results obtained on board the ship, allowed us to assess the ecological structure and function in the Bering and Chukchi Seas as being intact, with both of these areas remaining as highly productive as any region in the World Ocean.

Altogether, the distribution of chlorinated hydrocarbons (PCB, biphenyls, HCH) observed in the surface waters of these seas were probably transported by global atmospheric processes.

At the end of the Joint Expedition on board the *Akademik Korolev*, there was an exchange of preliminary data. The future

exchange of the joint analysis of data between American and Soviet scientists will occur in a series of three exchanges: 1. 1 March 1988; 2. 1 June 1988; and 3. 1 October 1989.

The two sides had agreed that the obtained data and results of the analyses belong to both sides. Any publications based on these materials should indicate that the results were generated during the Third Joint US-USSR Bering & Chukchi Seas Expedition. Both sides considered it useful to prepare and publish the joint manuscript containing the final analysis of the American-Soviet research of the 1988 Expedition to the Bering and Chukchi Seas.

American and Soviet participants expressed their interest in further development of joint research and consider it worthwhile to carry out further joint expeditions aimed to the fundamental studies of the ecological situation and the oceanographic regimes of the Bering and Chukchi Seas. Separate proposals for future joint research should be considered by the appropriate institutions in the respective countries. With this aim, the participants of the Third Joint US-USSR Bering & Chukchi Seas Expedition recommended that planning begin for the Fourth US-USSR Expedition to the Bering & Chukchi Seas, and the central Pacific Ocean in 1990. It is recommended also by the American-Soviet participants that a joint five-year program of ecological and oceanographic investigations for the Bering and Chukchi Seas will be jointly developed and published during 1989.

Both sides note with satisfaction the friendly and constructive atmosphere of the expedition's work and the effectiveness of joint observations allowing for a variety of oceanographic and ecological studies.

The American delegation would like to express their sincerest thanks and gratitude to the Captain and crew of the *Akademik Korolev* for their hospitality and cooperativeness.

The American delegation thanks the Soviet delegation for providing an atmosphere of mutual respect, productive collaboration, and fruitful exchange of data. The associations established on this cruise will result in the exchange of data and information for many years to come.

The Soviet participants of the expedition express their sincere gratitude and thanks to the American specialists for the fruitful and productive cooperation during the joint investigations of the Bering and Chukchi Seas.

This protocol was written in English and Russian and was signed on board the research vessel *Akademik Korolev*, 2 September 1988. Both texts are equally authentic.

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(This text is a reproduction of the protocol written on board the R/V *Akademik Korolev* in 1988. The original was signed by both project leaders.)

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Without each participant of the expedition and each author of research results, there would be no need for a monograph. There are far too many to name here; however, their names are listed with each subchapter and in Appendix A in this volume. It is their interest and excitement for the research presented here, and their spirit of cooperation so necessary for an international project, that provide the essence of the scientific accomplishments.

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Harold J. O'Connor

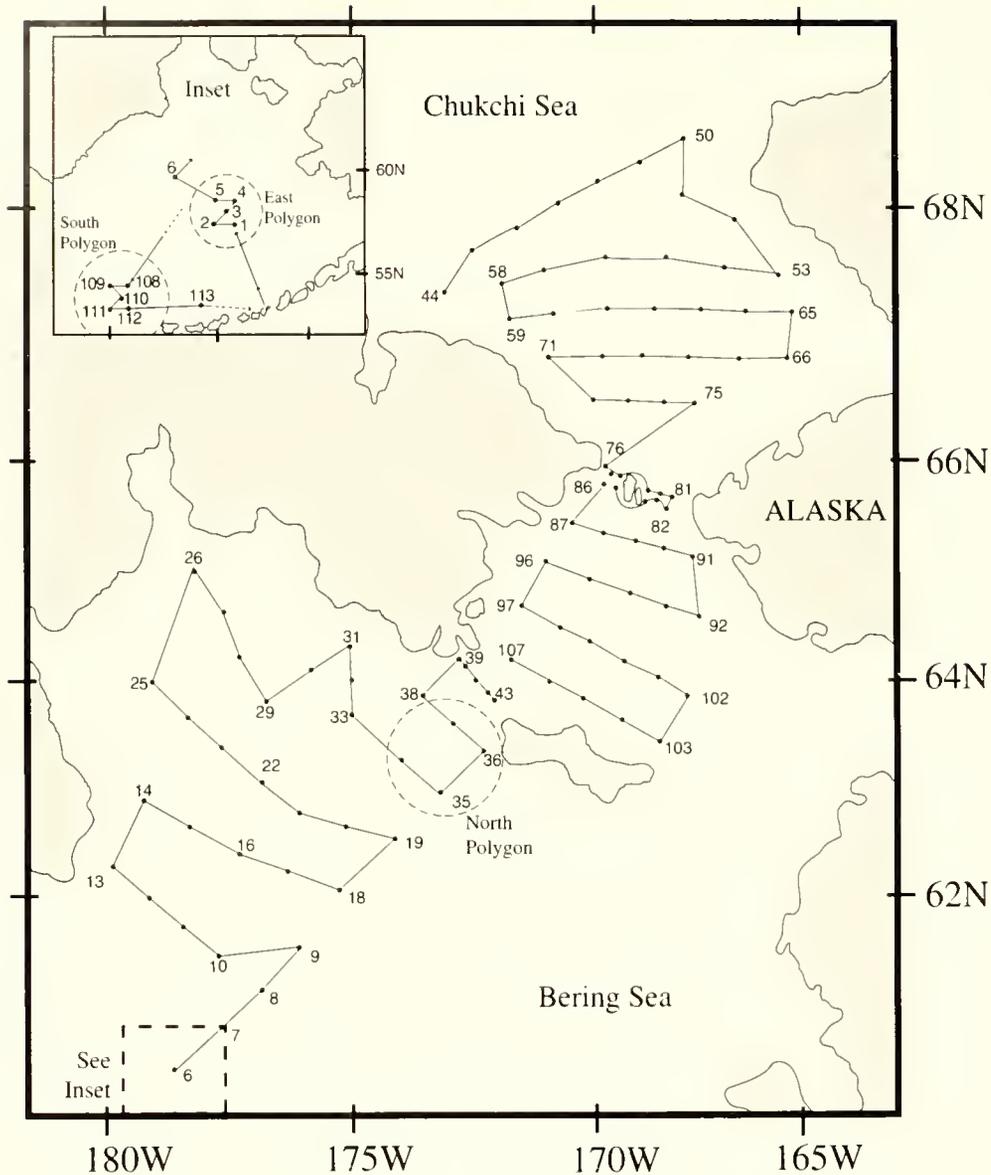
Alla V. Tsyban

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Frontispiece. Sampling stations of the Third Joint US-USSR Bering-Chukchi Seas Expedition, Summer 1988, aboard the research vessel *Akademic Korolev*.

Coordinates of the sampling stations on the Expedition.

Station	Latitude	Longitude	Station	Latitude	Longitude
1	57°53'67"N	174°49'85"W	10	61°25'00"N	177°76'00"W
2	57°49'97"N	175°51'83"W	11	61°58'33"N	178°65'00"W
3	57°94'50"N	175°07'50"W	12	61°88'17"N	179°42'00"W
4	58°50'83"N	174°50'33"W	13	62°18'33"N	179°85'00"E
5	58°50'00"N	175°50'00"W	14	62°83'68"N	179°51'08"W
6	59°50'00"N	179°50'00"W	15	62°55'00"N	178°50'00"W
7	60°47'43"N	177°87'03"W	16	62°34'17"N	177°33'17"W
8	60°93'53"N	176°94'62"W	17	62°16'67"N	176°33'33"W
9	61°33'52"N	176°10'27"W	18	62°00'42"N	175°00'00"W

Coordinates of the sampling stations on the expedition - *continued*

Station	Latitude	Longitude	Station	Latitude	Longitude
19	62°41'67"N	174°00'00"W	67	66°93'33"N	166°83'33"W
20	62°34'70"N	175°03'50"W	68	66°91'67"N	167°83'33"W
21	62°73'33"N	176°18'33"W	69	66°90'75"N	168°91'08"W
22	63°00'67"N	177°00'17"W	70	66°91'67"N	169°91'67"W
23	63°36'67"N	177°83'33"W	71	66°91'67"N	171°00'00"W
24	63°68'00"N	178°47'35"W	72	66°55'00"N	170°16'67"W
25	64°00'00"N	179°33'33"W	73	66°55'00"N	169°31'67"W
26	65°00'00"N	178°66'67"W	74	66°55'00"N	168°60'00"W
27	64°74'00"N	177°77'50"W	75	66°55'00"N	167°23'33"W
28	64°25'00"N	177°50'00"W	76	65°93'33"N	169°58'33"W
29	63°83'00"N	176°97'33"W	77	65°91'67"N	169°36'67"W
30	64°17'33"N	175°96'83"W	78	65°85'00"N	169°21'67"W
31	64°33'33"N	175°00'00"W	79	65°70'33"N	168°67'50"W
32	64°00'00"N	175°00'00"W	80	65°66'67"N	168°50'00"W
33	63°50'00"N	175°00'00"W	81	65°63'33"N	168°35'00"W
34	63°16'67"N	174°00'00"W	82	65°63'83"N	168°33'33"W
35	63°00'00"N	173°00'00"W	83	65°67'13"N	168°49'83"W
36	63°42'83"N	172°16'67"W	84	65°71'17"N	168°68'33"W
37	63°66'17"N	172°82'67"W	85	65°83'33"N	169°16'67"W
38	63°91'67"N	173°58'33"W	86	65°93'83"N	169°38'17"W
39	64°22'83"N	172°70'00"W	87	65°40'83"N	170°35'83"W
40	64°13'33"N	172°50'00"W	88	65°36'00"N	169°98'83"W
41	64°02'83"N	172°21'17"W	89	65°23'33"N	169°33'33"W
42	63°92'00"N	172°07'33"W	90	65°17'50"N	168°65'83"W
43	63°49'60"N	171°55'00"W	91	65°22'67"N	168°01'33"W
44	67°36'67"N	173°33'33"W	92	64°67'33"N	167°69'33"W
45	67°73'33"N	172°83'33"W	93	64°75'00"N	168°43'33"W
46	67°91'67"N	171°75'00"W	94	64°85'00"N	169°20'00"W
47	68°10'00"N	170°88'33"W	95	64°97'00"N	169°97'67"W
48	68°26'67"N	170°00'00"W	96	65°08'33"N	170°73'33"W
49	68°46'67"N	169°13'33"W	97	64°74'83"N	171°49'50"W
50	68°66'17"N	168°33'33"W	98	64°71'83"N	170°87'33"W
51	68°16'17"N	168°73'50"W	99	64°53'33"N	170°01'67"W
52	68°08'33"N	167°00'00"W	100	64°38'33"N	169°15'00"W
53	67°42'00"N	165°43'10"W	101	64°23'33"N	168°31'70"W
54	67°76'33"N	167°31'50"W	102	64°08'67"N	167°38'83"W
55	67°73'50"N	168°44'00"W	103	63°66'67"N	168°33'33"W
56	67°73'67"N	169°92'67"W	104	63°84'50"N	169°20'50"W
57	67°71'00"N	171°34'50"W	105	64°03'33"N	170°08'50"W
58	67°50'00"N	172°20'00"W	106	64°22'33"N	170°98'17"W
59	67°15'33"N	172°00'00"W	107	64°38'33"N	171°65'00"W
60	67°26'17"N	170°82'67"W	108	54°49'33"N	176°49'17"E
61	67°33'33"N	169°75'00"W	109	54°53'83"N	175°47'50"E
62	67°33'33"N	168°71'67"W	110	53°95'00"N	176°01'17"E
63	67°34'17"N	167°73'33"W	111	53°52'67"N	175°53'17"E
64	67°29'67"N	166°71'00"W	112	53°18'67"N	177°30'17"W
65	67°33'33"N	165°00'00"W	113	53°13'67"N	177°19'50"W
66	66°92'50"N	165°91'83"W			

Chapter 1:
GENERAL ECOLOGY

Editors:

**ALLA V. TSYBAN &
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1.1 Program on Long-term Ecological Investigations of the Bering Sea and Other Pacific Ocean Ecosystems (BERPAC Program)

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Introduction

Deterioration of ecosystems on a large scale threatens many functional equilibria in the biosphere. This problem is particularly urgent for the World Ocean, which is the sink for many different pollutants that can produce significant ecological impacts.

The ocean is able to assimilate a certain amount of anthropogenic compounds due to "self-purification" without visible deterioration of the ecosystem. However, continuous increase in the flux of pollutants to the ocean creates the need for study of the resistance of marine ecosystems to anthropogenic impacts. Investigations of ecological consequences and elucidation of causal relationships between the impact levels and adverse biological effects are only poorly understood for the marine environment. The study of these interactions and responses is interdisciplinary in character and covers different fields of biology, ecology, chemistry, and physics of the sea.

The dynamics of marine ecosystems, including biological and physical processes and biogeochemical cycles, are closely related to changes in the climate of the Earth. The predicted global warming may have a pronounced effect on certain vital processes in the World Ocean, especially the resistance of its ecosystems to anthropogenic contamination. This is because the living ocean determines, to a great degree, the normal functions of the Earth's climatic system.

Long-term observations of physical, geochemical and hydrobiological processes are necessary for the assessment of ecological consequences of contamination in the ocean environment and isolation of local anthropogenic effects compared to the effect of climatic variability.

The Bering Sea is located between the coasts of the Soviet Far East (USSR) and Alaska (USA) and, naturally, an interest in the study of its ecosystems has been shown by Soviet and American scientists (Izrael & Tsyban, 1983a, 1977, 1990; Roseigno, 1990).

In spite of comprehensive studies carried out in the Bering Sea in the last few years (Izrael *et al.*, 1988b; Izrael & Tsyban, 1989, 1990; Coachman, 1990; Roseigno, 1990), a number of the oceanographic, hydrochemical, and biological parameters determining its ecosystem functions are as yet poorly known, when compared with, for instance, the Baltic, Mediterranean, and Black Seas. For example, the joint bilateral program of Bering/Chukchi investigations have been carried out for more than 13 years with the production of three monographs of cruise results. However, the as yet inadequate data on the characteristics and processes occurring in the ecosystems of the Bering Sea and North Pacific waters have led to the organization and implementation of an international program: Long-term Ecological Research of the Marine Ecosystems in the Arctic and Pacific Oceans (BERPAC Program).

Goals, Objectives, and Scientific Basis of the BERPAC Program

Goals

The goal of the BERPAC Program is to examine the status of marine ecosystems of the Pacific Ocean, Bering Sea, and Chukchi Sea and to assess their role in determining global climate. BERPAC will study the dynamics of these ecosystems related to conditions of global climate change and anthropogenic contamination.

Objectives and Scientific Basis of the BERPAC Program

Objectives of the BERPAC Program consist of the study of the biogeochemical cycles of contaminants, related oceanographic processes, and food-web interactions in the North Pacific waters that flow through the Bering/Chukchi Seas, including study of the behavior of organic pollutants at the water/sediment interface since sediments are sources of the secondary pollution of ecosystems. Important topics of study are the control and the accumulation of pollutants in bottom

deposits and the study of their migration within the sediments and their exchange with overlying waters .

1. Assessment of Ecological Consequences of Contamination

Progressively severe changes in chemical contamination of the ocean biosphere are on the increase. Anthropogenic impacts influence not only the biotic component of the marine environment but different abiotic components as well. Such impacts lead to even more significant changes in the World Ocean and in the biosphere as a whole.

Specific features of the Bering Sea and other ecosystems with "background" levels of contamination are such that they are especially vulnerable because of the continual input of small doses of pollution. This leads to a gradual accumulation of pollutants and may ultimately cause the degradation of the ecosystems. Therefore, ecological investigations and monitoring of the background regions of the ocean, especially in such highly bioproduktive zones as the Bering Sea, are of great importance. In order to assess the ecological consequences of the pollution and isolate anthropogenic effects from the background of natural variability, it is necessary to make long-term observations of fundamental physical, chemical, and biological processes in selected areas of the above regions. These regions differ in their geographical location as well as in the subsystems of their ecosystems and are subjected to different anthropogenic impacts.

2. Study of the Processes Determining the Assimilative Capacity for Contaminants in Marine Ecosystems

In the marine environment various physical, chemical, and biological processes occur through which contaminants can be eliminated from the ecosystem without serious disturbances of the biogeochemical cycles of the elements or changes in the biota. Diverse oceanological investigations carried out in the last few years have shown that the biotic component is important in the fluxes of pollutants.

The ability of an ecosystem to protect itself against a foreign interference at the expense of many biological, physical, and chemical processes is its natural "immunity," and the measure of this immunity is its assimilative capacity.

According to the contemporary interpretation (Izrael & Tsyban, 1983b, 1989; Izrael *et al.*, 1988b,c), the assimilative capacity of a marine ecosystem is an integral function of its existing environmental status that reflects the ability of physical, chemical, and biological processes for elimination of pollutants and their impacts on the biota.

When using the concept of assimilative capacity in practice, it is necessary to bear in mind that a marine ecosystem occupies a finite volume that may be isolated on the basis of the spatial distribution of organisms of various trophic levels, groups of ecologically similar species, and production/destruction processes, as well as physical and chemical characteristics. Hence, the assimilative capacity of each specific ecosystem also has a value that objectively characterizes existing properties of the marine environment. This value could be determined in practice on the basis of integrated investigations and monitoring of the marine environment carried out in accordance with existing methodological recommendations (Izrael & Tsyban, 1983b, 1985, 1987, 1989; Izrael *et al.*, 1988b).

The use of this concept in the BERPAC studies will include investigations of the following basic problems: 1. quantitative assessment of the balance of chemical elements in the ecosystem and possible changes in residence times due to disturbances; 2. assessment of adverse biological effects at the level of population and communities; and 3. determination of the critical concentrations at which contaminants adversely impact the marine organisms and communities.

Thus, a conceptual model of the assimilative capacity, based on a better understanding of the laws of marine ecosystem functions, can serve as a theoretical basis for the development of forecasts of both the immediate and long-range consequences of anthropogenic and climatic impacts on the ocean ecosystems.

3. Study of the Elements of the Biogeochemical Carbon Cycle and its Role in Global Climatic Processes

Global warming predicted in connection with the developing greenhouse effect depends directly upon the biogeochemical cycle of carbon — the most important process forming the Earth's climate. The basic elements of this cycle are carbon dioxide and other "greenhouse gases" exchanged within the ocean-atmosphere system, the function of the carbonate system, and the turnover of organic forms of carbon in the ocean.

The most intensive uptake of atmospheric CO₂ occurs at high latitudes as a result of favorable thermal and hydrological conditions in the region (low sea surface temperature and permanent downwelling). These peculiarities explain the important role of the Bering Sea, a subarctic body of water having a large area, in the global cycle of carbon dioxide.

The relationship between the rates and directions of CO₂ flow within the ocean-atmosphere system directly affects the functioning of the carbonate system. So, in the conditions where global warming is induced by an increase in the concentration of atmospheric CO₂, a shift of the equilibrium between carbonate forms of carbon in seawater might occur, which will be accompanied by a decrease of pH and, consequently, elevation of the lysocline.

Investigations of these processes, directly affecting the sedimentation of organic carbon and the vital functions of marine organisms, are only possible with direct determination of all components of the carbonate system (i.e., HCO₃⁻, CO₃²⁻, H₂CO₃, and CO₂).

To fully understand all of the characteristics of the oceanic portion of the global carbon cycle, it is necessary to study the processes of the circulation of its organic forms in the composition of dissolved and particulate matter and in the cells of living organisms (Zaitsev, 1970, 1980, 1985).

The dynamic equilibrium of dissolved and particulate organic matter, living matter, and the content of organic carbon within water masses depends on the relations between production/destruction processes established in the ecosystem. In this connection, the predicted effects of global warming on the bioproduktivity of the Bering Sea ecosystem will influence the organic carbon cycle. In order to study possible changes, long-term observations of the concentrations of all organic forms of carbon are necessary.

Thus, to establish the carbon balance in the Bering Sea ecosystem, comprehensive long-term observations of all carbon

constituents in the aquatic interface and the study of quantitative and qualitative composition of both the carbonate system and organic forms of carbon are required.

4. Investigation of the Physical Mechanisms Related to Climate Variations

Existing global physical models of the ocean-atmosphere system do not make it possible to predict possible climate changes on a regional scale because of the extreme complexity of the modeled systems. Additional investigations of the physical development of regional models, in particular of a model for the Bering Sea, are an important need for long-term climate forecasting at the present time.

This problem could be solved on the basis of long-term oceanological observations, in different regions of the Bering Sea, which are aimed at the acquisition of systematic information on the vertical distribution of temperature, heat content of the active layer and its variability with time, the structure and variability of ocean circulation, heat transfer by the basic sea currents, and heat and moisture fluxes across the sea surface.

To develop the above models it is necessary to know the regularity of water mass formation in the deep basins of the Bering Sea. The following issues are not yet clear: North Pacific water must be involved in bottom water formation, but given the topographic isolation of Bowers and the central basins, how and where does this take place? Are sources the same for the different basins? What are the flushing rates (e.g., residence times)?

There are three hypothetical mechanisms by which bottom water might possibly be formed: 1. modification of surface (upper layer) water within the confines of the sea by cooling and brine enhancement through ice formation, creating water sufficiently dense to sink to the bottom; 2. subsurface mixings of North Pacific water with appropriate Bering Sea waters as it crosses the sills in the Aleutian-Komandorskiy island arc passages; and 3. direct advection of deep North Pacific water in through Kamchatka Strait and then sequentially through the gaps into the other basins.

The BERPAC Program will investigate the mechanism of deep water formation, renewal rates, and flushing of the basins.

Area of Investigations

While selecting the study areas and location of stations in the Bering Sea, the diversity and contrast of ecological conditions in different regions of the sea were taken into account.

In order to reflect a variety of ecological conditions in the Bering Sea more completely, it seems appropriate that integrated expeditions include work on polygons located in different areas of the sea (with the purpose of obtaining representative data on the structure and functions of the basic marine ecosystems) and work across transects (with the purpose of determining the space and time variations of the key ecological parameters).

Investigations within the framework of BERPAC will be conducted on four polygons where investigations were carried out in 1981 (during the integrated ecological expedition aboard the research vessel [R/V] *Akademik Shirshov*), and in 1984 and

1988 (during the second and third Soviet-American ecological expeditions aboard the R/V *Akademik Korolev*) (Izrael & Tsyban, 1987, 1990; Izrael *et al.*, 1988a; Roscigno, 1990).

Deep stations will be repeated at four centered polygons in the four deep basins. The center station of each polygon will also be a location for a mooring containing sediment traps and current meters, funding permitting. Four other mooring locations will cover the entrance from the North Pacific (in the deep channel northwest of Komandorskiy Island), the main gaps in the ridges north of Attu, and a location on the east side of the central basin under the Bering Slope current. The mooring locations are also deep oceanographic stations, and 11 additional stations will provide continuity among the deep waters.

In addition to polygons, observations are planned at stations along the transects located in areas that are not yet completely understood, such as the Gulf of Anadyr, the Chirikov basin, the Gulf of Alaska, the northern portion of the Pacific Ocean, and the deep-water central and southwestern areas of the sea. Larger scale studies in the Chukchi Sea and central Pacific ecosystems are also planned. The program for individual expeditions will be discussed specifically during joint symposia.

Proposed Observations

Complex observations during the ecological expeditions include meteorological (including aerological and geophysical studies), oceanographical, and ecological observations. Specifically, the following observations will be made:

A. Meteorological observations will include routine observations of meteorological parameters, such as studies of direct solar radiation intensity and ultraviolet irradiation, cloud and cloud type studies, and collection of samples of atmospheric precipitation for chemical analyses. Aerological and geophysical observations will include temperature and wind sounding with the aid of radiosondes. Air samples will be collected for determination of sulfates and nitrogen oxides. Visual observations of oil and oil product contamination on the sea surface will be recorded.

B. Oceanographic observations at designated sampling depths in the water column will include temperature, salinity, nutrients, oxygen content, water color and transparency, biogenic elements, alkalinity, and petroleum hydrocarbons. Tracers for water mass types will include stable isotope content of seawater (oxygen, deuterium, tritium, freons, silica, and carbon 14). In addition, current velocity and direction will be determined, and sediment trap collections will be made.

C. Ecological observations will include studies of the atmosphere, sea surface microlayer, water column, and bottom deposits in the environment.

1. Atmosphere

In rainfall, pH and the content of organic contaminants will be determined. In dust particles, the content of organic contaminants and metals will be determined. In the air at the sea surface, the content of "greenhouse" gases (CO₂, nitrogen oxides), oxygen, and chlorinated hydrocarbons will be determined.

2. Sea Surface Microlayer, Water Column, and Bottom Deposits

Water samples will be collected in the surface microlayer and at standard hydrological depths and at selected experimental depths (e.g., thermocline, pycnocline, phyto- and zooplankton maxima, and sediment–water interface) (Zaitsev, 1980).

a. In the surface microlayer, the following elements and parameters will be determined:

- organic carbon
- contaminants (toxic metals, and aliphatic aromatic and chlorinated hydrocarbons), the state of neustonic communities; determination of the structural characteristics of bacterioplankton; total numbers, biomass of microorganisms, most probable numbers (MPN) of indicator groups of bacteria (e.g., paraffin-oxidizers, PCB-transforming and neurotrophic saprophyte groups), and indices of phyto- and zooneuston (numbers, biomass, species, size composition, species mass, and indicator forms), mutation (teratogenesis) of zooneuston organisms.

b. In the water column, the following parameters will be determined:

- water optical indices
- contaminants (toxic metals, and aromatic, aliphatic, and chlorinated hydrocarbons)
- the total concentrations of organic carbon and its composition
- elements of the carbonate system (CO_3 , HCO_3 , CO_2)
- characteristics of bacterioplankton (total numbers, biomass, MPN, and distribution of indicator groups) and their biochemical and genetic capacities
- structural characteristics of phyto-, microzoo-, and mesozooplankton (numbers, biomass, size, and species composition, species mass, and indicator forms)
- functional characteristics of planktonic communities (heterotrophic CO_2 assimilation by bacteria, bacterial production, phytoplankton productivity)
- biosedimentation rate of particulate matter.

c. In the biota, the following parameters will be determined:

- contaminants (toxic metals, and aromatic, chlorinated, and aliphatic hydrocarbons)
- organic carbon content, stable carbon, and nitrogen isotope content.

d. In bottom sediments, the following elements will be determined:

- determinants (toxic metals, and aromatic, chlorinated, and aliphatic hydrocarbons)
- total organic carbon and nitrogen
- stable carbon and nitrogen isotopes
- structural characteristics of zoobenthos (numbers, biomass, species composition, and species mass)

3. Higher Trophic Levels

During the expedition, zoological observations will be carried out: numbers, distribution, and migratory patterns of fish, birds, and marine mammals.

4. Model Experiments

Model experiments will be performed under conditions similar to natural situations. During these experiments, the following parameters will be studied:

- photochemical oxidation of organic contaminants
- biodegradation potential of bacterioplankton with respect to organic contaminants (benzo(a)pyrene, PCB, etc.)
- combined influence of contaminants on biological “targets” and establishment of “critical” concentrations of the impact on plankton communities in the conditions of controlled ecosystems (Izrael, *et al.*, 1988a)
- sediment respiration and nutrient flux experiments.

Connection with other International Programs

The BERPAC Program has much in common with other international programs, but at the same time it has its own particular features mentioned earlier. Wide cooperation with other similar international projects is built within the framework of this program—in particular, in the preparation of joint marine expeditions. Wide data exchange is also planned.

Schedule of Activities and Applications of Results

Since 1977, successful joint investigations of Soviet and American scientists have been carried out in the Bering Sea within the framework of the specific theme of the bilateral cooperation “Bering Sea” (Project “Comprehensive Environmental Analysis”; Subproject “Comprehensive Analysis of Marine Ecosystem State and Ecological Problems of the World Ocean”). Important stages of this cooperation were three joint ecological Soviet–American expeditions in the Bering Sea on the R/V *Volna* (Summer, 1977) and R/V *Akademik Korolev* (Summer, 1984 and 1988), several symposia on the preparation of scientific programs, and analyses of the results of these expeditions, as well as three monographs describing the results of long-term Soviet–American investigations in the Bering Sea (Izrael & Tsyban, 1990; Roscigno, 1990). It is expected that these expeditions will be every four years and followed by international symposia and joint publications.

Monographs on the results of future expeditions will be published. It is expected that seminars and symposia within the framework of the BERPAC Program will be conducted. Also included in the plans are special intercalibrations, a wide exchange of specialists, and joint experimental work.

1.2 Polar Marine Ecosystems and Climate

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Introduction

The warming of the global climate predicted to have occurred by the middle of the next century will have a profound effect on the state of the World Ocean and, therefore, on the entire realm of relations between it and man. The magnitude and thrust of this effect may vary widely from one geographic zone to another. Possible physicochemical, ecological, or socioeconomic consequences will be determined by the specific character of marine ecosystems functioning, by regional factors, and by the roles played by particular regions in world and national economies.

According to present predictions, the regions that will be most significantly impacted by global warming are those in higher latitudes (Roots, 1989), where most marked changes in the functioning of marine ecosystems may occur. This fact makes it a matter of urgency that we generalize the findings of ongoing environmental observations with a view to diagnosing the possible effects of global warming as early as is feasible. The assessment of these effects on circumpolar and polar marine ecosystems calls for the mobilization of a broad assortment of scientific methods and approaches.

To this end, the present paper relies upon predictive assessments made available by global circulation models (GCM's) of the coupled ocean-atmosphere systems when applied to high-latitude regions; upon results obtained by modeling of the oceanic branch of carbon circulation in the marine environment; upon analyses of long-term environmental observations; and finally upon economic projections.

The concluding section of the paper draws on these methods for an analysis of possible changes in the physicochemical parameters of the Bering Sea ecosystem that are expected to ensue as a result of the presumed warming of the world's climate.

Effect on Physicochemical Processes

Effect of Global Warming on the Temperature Regime and Water Circulation in the High-latitude Ocean

Given all of its diverse ramifications, evaluation of the effect of global warming on the temperature regime and water circulation in the World Ocean is tantamount to the task of predicting possible changes in all fundamental natural processes as a result of new climatic conditions.

Since changes in the composition of the atmosphere and its circulation affect processes occurring in the ocean and vice versa, dealing with this problem requires consideration of the operation of the ocean-atmosphere system in conditions of a developing "greenhouse effect." In this connection, one of the most promising methods of investigating the sensitivity of the climatic system to the mix of gases constituting the atmosphere involves performing numerical experiments using models of global circulation in the unitary ocean-atmosphere system (Manabe & Stouffer, 1980; Schlesinger, 1986). Results obtained from such calculations make it possible to predict changes in temperature over the entire air column and in the surface layer of the ocean as a function of a given atmospheric composition and more especially as a function of CO₂ levels in the atmosphere.

Of the numerous GCM's presently available for describing the behavior of the ocean-atmosphere system, we would suggest that the models that are most carefully developed and take into account the maximum number of factors affecting circulation processes are those developed by Oregon State University (Ghan, 1982; Schlesinger & Mitchell, 1987); Goddard Institute for Space Studies (Hansen *et al.*, 1983, 1988); and by the NOAA Fluid Dynamics Geophysical Laboratory at Princeton (Manabe & Wetherald, 1980, 1987).

Considerable quantitative differences notwithstanding, results obtained from numerical experiments run on the basis of the above models have shown close qualitative agreement of predicted trends in the behavior of the ocean-atmosphere thermal balance in high-latitude regions in the event of a doubling of the CO₂ content of the atmosphere. A constant problem with such models is the extremely widespread ice cover and the very weak thermohaline circulation in the northern part of the North Atlantic and Arctic Oceans (Bryan *et al.*, 1988). According to calculations, the temperature of the lower layers of the atmosphere may be expected to rise by from 1.3° to 4.2°C, with greater warming occurring over land than over water; the surface waters of the ocean would become 0.2° to 2.5°C warmer. Analysis of the seasonal dynamics of the temperature field with all three models indicate that maximum warming would occur in the Arctic and Antarctic regions during the winter period.

The particular importance of the latter factor for the system of water circulation in the World Ocean should be noted. Thus, significant warming in the polar latitudes would

be associated with a decrease in the temperature gradient between the equator and the poles and, as a consequence, with a decrease in the intensity of winds and oceanic currents (Mitchell, 1988). This in turn could lead to a shrinkage of oceanic upwelling areas and weakened upwelling.

In addition to its effect on the circulation of World Ocean waters, warming in the Arctic and Antarctic region would have a marked impact on the state of the Earth's cryosphere (glaciers, shelf and marine ice). Such changes would in turn affect the functioning of the climatic system.

First, the ice that covers 11% of the World Ocean's surface area to a large extent determines heat transfer between ocean water masses and the energy balance at the ocean-atmosphere interface. These factors influence the intensity of oceanic convection, which in turn establishes the time scale of processes that extend to great depths (e.g., CO₂ circulation). In addition, exposed ocean waters absorb considerably more solar radiation than do ice-covered waters (Walsh, 1983). Hence, changes in the extent of ocean ice cover would inevitably affect atmospheric circulation and temperature.

Second, even minor changes in the Earth's cryosphere would lead to a significant change in global sea level as compared with current values.

The rise in air temperature expected to occur in the Arctic would have considerable consequences for the extent of marine ice cover. Thus, summers could bring about the complete melting of the ice cover around Svalbard, along the north coast of Siberia, and along the Arctic coast of Canada. Nevertheless, in our view the global warming predicted by the middle of the 21st century will not lead to a major diminution of the ice mass of the Antarctic and Greenland ice shields. Indeed, recent studies in the Northern Hemisphere have shown that the extent of ice cover over the past decade has increased despite a small rise in mean annual temperature (Bryan *et al.*, 1988). On the other hand, the warming by 4° to 5°C that is expected (Mitchell, 1988) may lead to an acceleration of the flow of continental ice sliding into the ocean and, therefore, to some decrease in ice-cover thickness in the western Antarctic (Bud'ko & Izrael, 1987).

It may be noted in summary that global warming would very likely entail displacement of surface isotherms toward the poles, changes in the functioning of upwelling areas, and some shrinkage of ice cover in the Arctic. Melting of sea ice in the Arctic may produce a freshening of waters in the northern Atlantic with consequential changes in the formation of ocean-bottom waters. This process may affect heat flow in a northerly direction, which might ultimately result in a shift in global oceanic circulation (Bryan *et al.*, 1988).

Changes in the Carbon Cycle

The doubling of the carbon dioxide content of the atmosphere predicted for the year 2050 may well disrupt the global carbon cycle and therefore involve severe consequences for the formation of the Earth's climate. Assessment of these consequences requires profound insight into the cause-and-effect relationships that constrained the natural variability of CO₂ content in past geologic ages.

It should be noted that the elevated solubility of carbonates occasioned by the increased salinity of seawater resulting from

increased CO₂ levels produces increased alkalinity and therefore augments the ocean's CO₂-holding capacity (Boyle, 1988). Furthermore, CO₂ absorption in upwelling areas occurs largely through the photosynthetic activity of phytoplankton, whereas in the higher latitudes considerable amounts of atmospheric CO₂ are extracted by oceanic masses in the process of deep-water formation, particularly in places where the deep waters in question rise to the surface (Roots, 1989). In addition, increased carbonate solubility (as a consequence of the acidulation of the surface layer by increased amounts of dissolved CO₂) can raise the alkalinity of seawater and hence enhance the ocean's ability to absorb CO₂ (Boyle, 1988). Possible increases in the amount of organic matter deposited in bottom sediments due to augmented entry into the marine environment of biogenic elements due to sea level rise can also be regarded as a probable mechanism of removal of human-generated CO₂ from the atmosphere (Siegenthaler, 1989).

It is therefore evident that rises in the carbon dioxide content of the atmosphere may result in a disruption of the global carbon cycle. The scale and thrust of possible changes would be determined largely by the particularities of upwelling ecosystem functioning under global warming conditions.

Changes in Biogenic Elements

Increased releases into the atmosphere of gases and aerosols containing nitrogen, phosphorus, and sulfur compounds as a result of human activities in highly industrialized countries such as those of the North Atlantic seaboard are increasing the amount of these substances entering the ocean (Oppenheimer, 1989). This process is particularly significant in the case of nitrogen and sulfur, whose entry into the photic zone of the ocean through the atmosphere may be compared with its delivery by diffusion convection (Duce, 1986). Rises of nitrogen and sulfur levels of regional scale, especially in impacted ocean areas, may be accompanied by rises in the bioproductivity of the affected ecosystems. Such phenomena have already been reported for the coastal marine areas of the North Sea (Lancelot *et al.*, 1987).

Sea level rises accompanied by flooding and soil erosion would result in considerably augmented influx of N, P, and S into coastal areas, which might well produce intensified eutrophication processes in the ecosystems thus impacted. One consequence of this may be an acceleration of the biogeochemical cycles of all biogenic elements (Oppenheimer, 1989). This would depend on regional circumstances, however. In the Beaufort Sea, for example, the erosion-susceptible peat might become an important source of organic carbon for the food chain in adjacent coastal waters. On the other hand, most continental high-latitude regions can expect increased precipitation, which would tend to increase biogenic-element input into the nearby ocean.

Changes in Pollutant Cycles

Being associated with the intensification of microbial degradation processes, the rise in marine surface-water temperature currently predicted for the higher latitudes could result in the accelerated biodegradation of globally occurring pollutants (chlorinated and petrolic hydrocarbons, phenols, etc.), which would, in turn, promote the decomposition of such

compounds down to their low-molecular-weight components and their flushing from the photic layer of the ocean (Tanabe, 1985; Izrael *et al.*, 1990). On the other hand, higher temperatures imply reduced absorption of organic pollutants on suspended matter (Pierce *et al.*, 1974), which would have the effect of diminishing the amounts of pollutants deposited in sea-bottom sediments.

The increased fluxes of UV-B radiation being predicted in connection with the depletion of stratospheric ozone layer would intensify photochemical processes, especially at that ocean-atmosphere interface (Zika, 1989). This would enhance the photodegradation of both chlorinated and petrolic hydrocarbons, possibly reducing this type of pollution of marine environments (Doskey & Andren, 1987). It should be noted, however, that apart from this positive effect of promoting the removal of organic pollutants from seawater, prolonged UV-B irradiation may also prove very detrimental to any number of marine organisms inhabiting the surface layer of the ocean (US EPA, 1987).

It may be expected that rises in the concentration of atmospheric CO₂ would produce a certain acidulation of surface waters (Wilson & Mitchell, 1987). Even though this would not affect the behavior of hydrophobic organic pollutants, the consequences might prove very tangible from the standpoint of ionogenic compounds. Thus, lower pH values would tend to increase the permeability of cell membranes with respect to such compounds, and hence to the accumulation of the latter in marine organisms (Landner, 1989). In addition, higher acidity may reduce the stability of heavy metals bound by compounds of humic origin (Mantoura & Riley, 1975; Paxeus, 1985). This process could in turn exacerbate the toxic effects of heavy metals on marine biota (Sunda & Lewis, 1978; Sedlacek *et al.*, 1983).

Effects on Environmental Processes

The predicted changes in the physicochemical parameters of the marine environment as a result of global warming would no doubt have considerable impact on the intensity and balance of the fundamental environmental processes occurring in marine ecosystems, as well as on the condition of biological resources both in coastal waters and in open sea and open ocean areas.

Changes in the Conditions of Habitation of Marine Organisms

As a rule, marine organisms possess considerable environmental (genetic, behavioral, etc.) flexibility, which enables them to adapt to continuously varying environmental conditions. This adaptability of marine organisms accounts for the relative stability of zoogeographic zonation with respect to climatic fluctuations (Odum, 1986). It is to be expected that global warming would be accompanied by directed ecological succession that would enable communities to adapt to a warmer climate; some high-latitude communities may acquire the characteristics of boreal communities, while temperate zone communities might become more like their subtropical counterparts.

The processes described above could have serious consequences for the formation and distribution of all marine

biological communities, including those of commercially important fish species. The effect of warming would be especially pronounced in subpolar-front regions (Roots, 1989), where increases of even a few tenths of a degree in deep water temperature can lead to a noticeable redistribution of both pelagic and benthic communities. On the other hand, comparable temperature rises in the tropical latitudes would have no significant effect on the functioning of marine organisms.

It should be noted that temperature is not the only parameter that would be decisive for the state of marine life communities in the higher latitudes under global warming conditions. Another set of factors of considerable importance would be associated with possible changes in oceanic and atmospheric circulation (Bakun, 1990), which is an important influence on the distribution and density of marine populations.

Changes occurring in the open ocean and in coastal areas might be associated with changes in species diversity. This effect would probably be less in evidence in the open ocean than in estuaries and tidal zones. Polar marine ecosystems in open areas would move more readily into new geographic zones, while coastal ecosystems would be more rigidly restricted by the physical characteristics of the relevant shoreline.

This leads to the general conclusion that what one may expect in conditions of global warming that can entail considerable changes in the living condition of marine biota is a redistribution of marine life communities with the inevitable consequences for the fishing industry worldwide.

Changes in Production-Degradation Processes and Biogenic Sedimentation

In contrast to tropical and temperate regions where productivity is determined largely by biogenic-element levels alone, the chief limiting factors in circumpolar and polar areas are light and temperature. In this connection, the predicted warming of surface waters would lengthen the phytoplankton vegetation season, and therefore increase the productivity of such areas.

On the other hand, temperature rises would be accompanied by accelerated microbial decomposition of organic matter. The most pronounced intensification of decomposition processes (by a factor from 1.1 to 1.3) might be expected to occur in the higher latitudes and more particularly in the shelf waters and surficial water masses of the boreal zone (Odum, 1986; Izrael & Tsyban, 1989).

The rates of degradation processes in surface waters in the lower latitudes is determined by the influx of organic matter from the Arctic and Antarctic as intermediate and deep waters arrive by meridional transfer. This is why the effect of temperature on the rates of degradation processes in the equatorial and tropical regions is negligible. The changes in production-degradation parameters would have a considerable effect on the course of biosedimentation processes.

According to one model (Suess, 1980), the magnitude and velocity of the biosedimentary flux is increasing in direct proportion to rising productivity. Given this circumstance, climate warming could increase biosedimentary fluxes in coastal upwelling areas where a significant rise in productivity is expected to occur (Bakun, 1990). The same could happen in

coastal land areas that would be flooded as result of sea level rise. On the other hand, the acceleration of biodegradation processes in the higher latitudes would preclude any marked increases in biosedimentary fluxes.

In addition to rising temperature, another factor that would affect the formation of new organic matter in the ocean would be the further intensification of ocean pollution due to human activities. According to present estimates, pollutant levels in the euphotic layer of the ocean by the middle of the next century can be expected to rise from 25% to 30% above current values (Izrael & Tsyban, 1989). Moreover, warming of water masses coupled with the acceleration of chemical reaction could increase the toxicity of pollutants for marine biota. This would necessarily have an adverse effect on the productivity of polar oceanic ecosystems (Patin, 1979; Tsyban *et al.*, 1985).

It should be noted in conclusion that primary production values for a region do not constitute an adequate yardstick for assessing commercial fish resources. What is more important, as far as the fishing industry is concerned, would be the shifting of the most productive zones of the World Ocean, and especially of upwelling areas, as this would be fraught with serious repercussions in terms of the distribution of commercial fish stocks and fish resources replenishment.

The Role of Ice in Sustaining Marine Polar Ecosystems

Ice plays an important role in the development and sustenance of marine polar ecosystems for the following reasons: 1. it is extremely important to the growth of the marine algae that are the primary food source in marine ecosystems; 2. it creates conditions conducive to primary-production synthesis at the ice-water interface, allowing plants to bloom, thus maintaining the abundance and species diversity of biological communities; 3. it is extremely important to the vital activity of the organisms that ensure energy transfer from the primary-production level (algae and phytoplankton) up to higher trophic levels (fishes, marine birds and mammals); and 4. the latter factor in turn operates to maintain existent numbers of marine communities.

One of the possible consequences of global warming might be the shrinkage and diminished stability of marine ice, which would directly affect the productivity of polarecosystems. For example, the absence of ice over the continental shelf of the Arctic Ocean would produce a sharp rise in the productivity of this region, provided sufficient biogenic elements are available.

Polar mammals need ice to obtain their food and to reproduce. For example, the extent of the polar bear's habitat is determined by the maximum seasonal surface area of marine ice in a given year. This means that the disappearance of ice would threaten the very survival of the polar bear and of certain marine seals. Similarly, a reduction of ice cover would reduce food supplies for penguins and walrus and increase their vulnerability to natural predators and human hunters and poachers. Should the ice cover shrink, animals such as the sea otter would have to migrate to new territories. Furthermore, it remains unclear how the contraction of ice cover would affect the migration routes of animal (such as whales) that follow the ice front.

Changes in water temperature and wind patterns as a result of global warming would almost certainly affect the distribution and size of the polynyas (unfrozen patches of water surrounded by ice), which are so vital to the maintenance of polarecosystems. In addition, changes in the extent and persistence of marine ice, combined with changes in the characteristics of currents such as the circumpolar current in the southern latitudes, could influence the distribution, biomass, and volume of available krill. Krill is an important link in the food chain of Antarctic Ocean fauna and is also of great importance for commercial fisheries. A proper understanding of the way in which the productivity of the Antarctic Ocean would change under new climatic conditions is essential in assessing the consequences of global warming for the World Ocean environment.

Effects on Fish Stocks

Climate change is one of the paramount factors that determine the fish reserves of the World Ocean, even though the sensitivity to this factor of particular stocks varies considerably from population to population and from region to region.

Each population of a given species community is fitted to a particular hydrodynamic structure with definite temporal and spatial characteristics. Given this fact, changes in ocean circulation could lead to the disappearance of certain populations or to the appearance of new ones. Most seriously affected would be the populations localized in habitat boundary waters (Troadek, 1989).

One of the promising avenues for predicting the possible consequences of climate warming on the status of fish fauna is the method of historical analogies. This method involves isolating salient features in the distribution and biomass of fish stocks over a number of past intervals such that each interval is associated with specific climatic, and therefore environmental, characteristics, the purpose being to draw further analogies. The application of this method for describing the state of fish resources over the present century has made it possible to discern certain essential features. The warming that occurred in the first half of the 20th century was accompanied by the penetration of northern fish species into subarctic and arctic seas, something that was observed both in the North Pacific and the North Atlantic. Thus, a favorable change in environmental conditions as a result of warming can generate new commercial fish stocks. Moreover, the warming of the 1940's and 1950's showed that warming of the marine environment can have quite different consequences even for a single fish species, depending on specific features of habitat. For example, this period saw the most sizeable generations of Atlantic-Scandinavian herring, while the number of North Sea herring plummeted.

Recent studies in the North Atlantic have brought to light a direct link between climatic variation on the one hand and the distribution and replenishment of fish resources on the other. Particularly noteworthy in this connection is the so-called "1970's anomaly" (Jenkins & Ephraums, 1990), remarkable for the concurrent effects it involved for several commercial stocks. Originating off the coast of eastern Greenland in the

late 1960's, it went on to skirt Greenland and Labrador in the direction of the North Atlantic current, reaching the Barents Sea in 1979–80 (Dickson *et al.*, 1984). In the late 1980's, this anomaly led to extremely low prevailing temperatures in the waters off northern Iceland, which was probably the cause for the drop in numbers of Atlantic–Scandinavian herring.

The above changes in fish resources were brought about by relatively short-term fluctuations in the temperature of the environment. Proceeding on the assumption that global warming would entail a long-term upward creep of temperatures, this factor may be expected to have even more profound effects on the fish resources of the ocean. A rise in the mean temperature of polar and subpolar waters of the World Ocean of just 1°C could have a substantial influence on the distribution, growth, and replenishment of fish populations. Commercially valuable fish stocks may acquire new spawning grounds, which would entail considerable changes in their distribution patterns.

The strong homing instincts of salmonids in the Northern Hemisphere would probably render changes in the geographic distribution of these species to be fairly difficult. On the other hand, salmonid populations may suffer considerable attrition should geographic shifts of habitat become an absolute necessity for them.

A more complete assessment of the effects of global warming on the state of fish resources in the high latitudes of the World Ocean requires allowance not only for temperature rises, but also for increased hard ultraviolet radiation fluxes. The latter factor would impact first and foremost upon those fishes whose early developmental stages live either in neuston communities or in coastal ecosystems. It must be borne in mind that notwithstanding the relative opaqueness of seawater to ultraviolet radiation, the roe and fry floating and swimming near the surface, together with the accompanying phyto- and zooplankton, corals, and algae of tidal zones, would be subjected to prolonged and intense irradiation, which may well increase the mortality of young fish and adversely affect the gene pool of the marine organisms in question.

Regional Aspects of the Problem (Using the Bering Sea as an Example)

Taking into account all of the foregoing, we would draw particular attention to the extensive body of information concerning the functioning of the Bering Sea ecosystem built up in the course of long-term joint US–USSR studies (the project entitled Comprehensive Analysis of the Bering Sea Ecosystem, under the “Bering Sea” Program).

According to predictions based on the use of GCM's, the effect of global warming on the Bering Sea region could take the form of a displacement of surface water isotherms toward the North Pole (warming by 0.5°C over a single decade would be accompanied by a shift in isotherms of over 50 km [Hansen *et al.*, 1988]). Temperature rises could lead to earlier vernal

blooming of phytoplankton and to a lengthening of the entire blooming season.

By present estimates, primary production in the Bering Sea averages 0.65 g C/m²/day, attaining 7 g C/m²/day in some places (McRoy & Goering, 1976; Izrael *et al.*, 1986; Whittedge *et al.*, 1988). The predicted advent of conditions more conducive to phytoplankton vegetation suggests increases of primary production up to 0.75–0.90 g C/m²/day.

Starting from a current rate of degradation of organic matter in the Bering Sea that averages 0.3 g C/m³/year (Izrael *et al.*, 1986; Whittedge *et al.*, 1988), global warming might bring this value up to 0.35–0.50 g C/m³/year.

The expected acceleration of microbiological and photochemical processes would be accompanied by more rapid decomposition of organic pollutants and, as a consequence, by a reduction of levels of pollution of the given ecosystems by human activities (Izrael *et al.*, 1990).

An intensification of production–degradation processes could also result in the acceleration of biosedimentation processes, especially in coastal areas. According to the latest experimental assessments based on determinations of organic-matter biosedimentation rates (Izrael *et al.*, 1986), 1.6 × 10⁸ tons of C settle to the bottom of the Bering Sea annually. On condition that the balanced character of the biogeochemical carbon cycle is maintained, this value can be taken as the lower limit for the influx of atmospheric carbon into the waters of the Bering. It is relevant in the connection to mention that the total contribution of carbon to the World Ocean is 53 × 10⁸ tons/year (Odum, 1986). These figures confirm the significance of subarctic ecosystems in the overall context of the global carbon cycle and point up their major role in shaping the Earth's climate.

One of the most significant consequences of global warming may be the displacement of the subarctic front, which would entail radical changes in the environment of pelagic and benthic communities, including many valuable fish species. Since the Bering Sea is a fishing area of enormous importance to a number of countries that together catch 3 × 10⁶ tons of fish annually (Wilimovsky, 1974), it is imperative to foresee possible detrimental consequences of global warming in this region as they impact upon the distribution and replenishment of many valuable species of fish, birds, and mammals. Elaboration of prognoses of the state of living resources in the Bering Sea area in conditions of global warming would greatly facilitate the development of an effective system of adaptive responses for this region.

The long-term studies in the Bering and Chukchi Sea conducted over the past decade will continue and will in future encompass the issues discussed in the present paper within the context of BERPAC¹.

¹Efforts under BERPAC are part of the USSR's MONOK program: The Integrated Ecological Ocean.

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Chapter 2:
OCEANOGRAPHY

Editors:

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2.1 Northern Bering–Chukchi Sea Ecosystem: The Physical Basis

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Introduction

The northern Bering and Chukchi Seas, encompassing the Bering Strait (Fig. 1), together constitute the most enormous shelf sea of the World Ocean—that is, over 1,000 km in north–south extent with depths less than 100 m. The longer-term (>1 month) average flow is northward of Bering Sea water across the whole area into the Arctic Ocean, providing the Northern Hemisphere oceanic link between Pacific and Atlantic Ocean systems. It has been known that North America and Asia are separated by the Bering Strait since Simeon Dezhnev transited the strait inadvertently (blown by a storm) in 1648; and that the general flow of the water through the strait is northward since the voyages of Bering and Cook in the 18th century.

integrated nature of the whole system: that the waters and its transported properties were intimately connected across the entire shelf sea from the Bering Sea basin to the Arctic Ocean and that the dominant property distribution mechanism is everywhere is advection (with the generally northward flow).

Investigations of various biochemical properties within the region, from which the production of organic matter and its subsequent fate can be determined and explained, began much later than the physical studies. These were also much more piecemeal and limited in scope until the advent of the Inner Shelf Transfer and Recycling Program (ISHTAR) in 1985 (Walsh *et al.*, 1990), which undertook an integrated physical/chemical/biological study (i.e., measurements of all fundamentals of the basic ecosystem) of those portions of the region to which they had access, *viz.* the Chirikov basin and eastern part of the Chukchi Sea. The results from ISHTAR, after four years of intensive sampling and analysis, clearly demonstrate that the whole region, integrated into one regime by the north advection, is also integrated as an enormous ecosystem containing some of the highest primary production values ever measured in the World Ocean. The ecosystem is sketched schematically in Fig. 2. The generally northward water flow is composed mostly of water from the northern Bering Sea basin, which enters the region in the

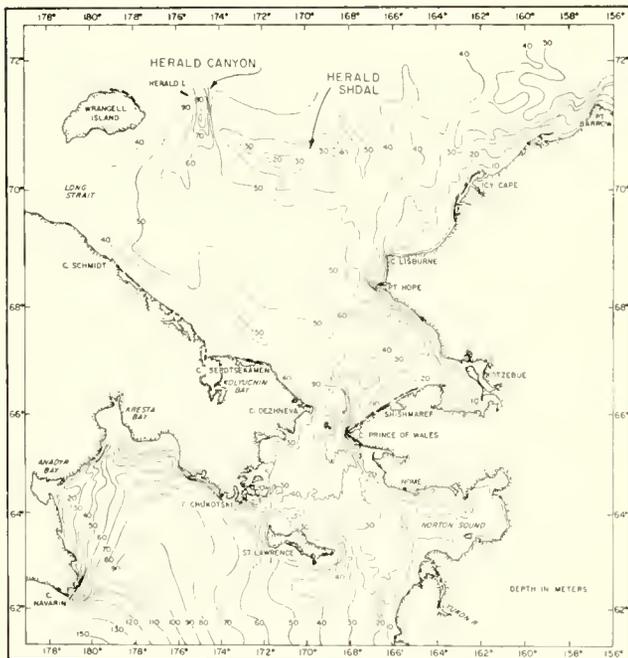


Fig. 1. Bathymetry of the northern Bering and Chukchi Seas.

Modern studies of the physical oceanography of various parts of this large regime, begun in the 1930's by G. E. Ratmanov (1937a,b) and C. A. Barnes (Barnes & Thompson, 1938), were synthesized in *Bering Strait: The Regional Physical Oceanography* (Coachman *et al.*, 1975). This study summarized the water masses, their distributions, something of the temporal and spatial variations in properties and causes thereof, and quantified the northward flow and its variations. It showed the

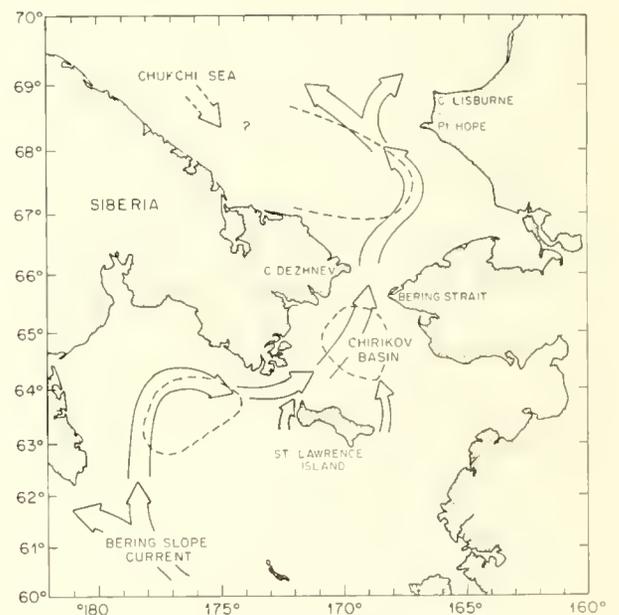


Fig. 2. Schematic of the northern Bering Sea ecosystem. Open arrows indicate advection along which ecosystem activity is aligned; dashed lines encompass the three production/deposition centers.

Gulf of Anadyr. The continuity of this flow, entirely through the system into the Arctic Ocean, provides integration between three serially-aligned production/deposition/regeneration centers: the output of the upstream Gulf of Anadyr center materially effects the biochemical activity of the Chirikov basin center, which in turn feeds the center in the Chukchi Sea.

Confirmation of the integrated nature of the ecosystem is provided by measurements made during the first synoptic survey of the whole region from the Gulf of Anadyr through the southern Chukchi. The opportunity arose from amalgamation of ISHTAR into the Third Joint US-USSR Bering & Chukchi Seas Expedition, 25 July–2 September 1988, on board the research vessel (R/V) *Akademik Korolev* (*Korolev*). The areal distribution of integrated chlorophyll (Fig. 3) clearly shows in essence the ecosystem arrangement sketched in Fig. 2—three high-production centers arranged sequentially along the pathway of flow of Bering Sea water from the northern Bering through the Gulf of Anadyr, then the Chirikov basin and Bering Strait, and on through the southern Chukchi. Thus, we are dealing with a single ecosystem. It is the purpose of this paper to describe, to the extent of current knowledge, the physical basis of this ecosystem: the water masses and their characteristics, the flow field, and the variabilities of the physical features. The paper concludes with a discussion of the downstream end of the system in the Chukchi Sea, about which very little is as yet known.

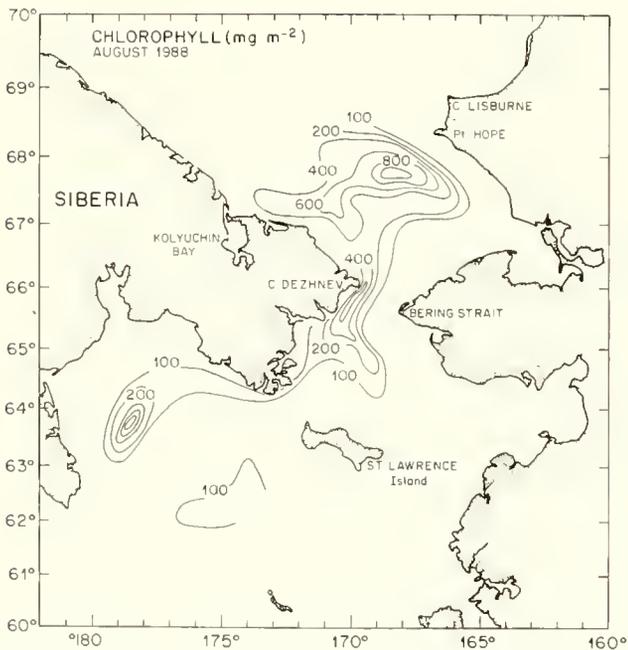


Fig. 3. Integrated chlorophyll from the cruise of the *Akademik Korolev*, August 1988. Notice the three major production centers, and the edge of a fourth area of high chlorophyll biomass off Kolyuchin Bay in the Chukchi Sea (after Springer, McRoy & Whitledge, in press).

Water Masses

Salinity is the variable delimiting the water masses because in the colder high-latitude waters, it, rather than temperature, has the primary influence on water density. Based on sources

and modifications, there are three water masses fundamental to the system (Coachman *et al.*, 1975), and it is convenient to define two others, more local products of modifications.

The three basic water masses, Alaskan Coastal, Bering Shelf, and Anadyr Current, are arranged side-by-side in the east–west direction. Identification of the water masses obtained at any particular time are done from T/S diagrams of stations from sections crossing Anadyr and Shpanberg Straits; these capture the characteristics of the three basic water masses at the same time. Figure 4 shows an example. Typically, in the T/S plane, values beneath the surface layer fall naturally into three groups: a group with intermediate values of *S* but very cold; and somewhat warmer groups to each side, both less and more saline. Spatial continuity shows the least saline group (Alaskan Coastal) to occupy the eastern part of Shpanberg Strait, the most saline group (Anadyr Current) are always stationed in the western part of Anadyr Strait, while Bering Shelf water of intermediate salinities can usually be found near both ends of St. Lawrence Island. Thus, from Fig. 4, the ranges of salinity for the three water masses were Anadyr Current—33.0 to 32.75; Bering Shelf—32.75 to 31.9; Alaskan Coastal—<31.9.

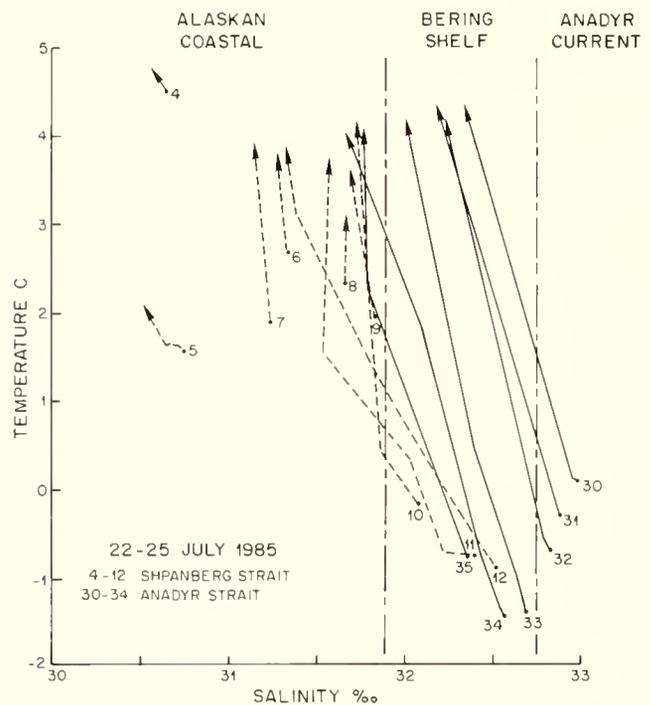


Fig. 4. T/S diagram of stations crossing Anadyr and Shpanberg Straits, illustrating the definition of the basic water masses. Station numbers are at the bottom of each water mass curve. Notice the natural separation into three salinity groups.

But salinity values of the water masses are not constant. There is a seasonal cycle because runoff at these high latitudes is markedly seasonal. Yukon River discharge peaks in June, when the flow grows in about one month's time to two orders of magnitude greater than in winter. The regional north flow is insufficient to flush all of this freshwater from the system immediately, so part of the freshwater accumulates over the summer and is only completely flushed by late fall (Coachman *et al.*, 1975). This effects primarily salinities of Alaskan

Coastal water and to a lesser extent Bering Shelf water; both these water masses show a decrease in S over the summer, which can amount to as much as one-half part per thousand.

There are also interannual variations in the water mass salinities that are the same magnitude as those of the seasonal cycle (about 0.5). Figure 5 shows the ranges of S values for the water masses for all the years when sections in June or early July encompassing Anadyr and Shpanberg Straits have been taken; similar times of year must be compared to avoid the seasonal variations. We see that, interannually, the salinities are not constant. Small year-to-year differences are probably not significant because definition of water mass boundary values can sometimes be somewhat fuzzy, but the long-term variation with either a 10 or 20-year period is definitely real. Anadyr Current water in the 1960's frequently had S values >33.0 , but during the 1970's and beginning of the 1980's, values this high were never observed; only in 1988 have salinities >33 reappeared.

Similar sized interannual variations in S have also been observed in the central shelf water of the southeast Bering Sea Shelf; ranges of S observed there (Coachman, 1986) are also plotted in Fig. 5. Clearly we are seeing the effects of large-scale climatic fluctuation causing similar property variations over the entire Bering Sea Shelf. This variation effects also the bottom water temperatures of central shelf waters, and the T and S are correlated—warmer with more saline and colder with fresher. The few measurements available of bottom water temperatures in the central Gulf of Anadyr, where the coldest water of the whole Bering Sea Shelf is always found (the so-called "cold center" of the Bering Sea; Barnes & Thompson, 1938), suggest an interannual variation in coldest T of at least 2°C may obtain, not unlike that of T on the southeast shelf (Fig. 5). The interannual climate variation is also manifested in interannual variability of ice cover of the Bering Shelf, which is primarily responsible for establishing the T and S conditions of bottom waters for the following year: minimum ice/warmer bottom temperatures/more saline, and vice versa.

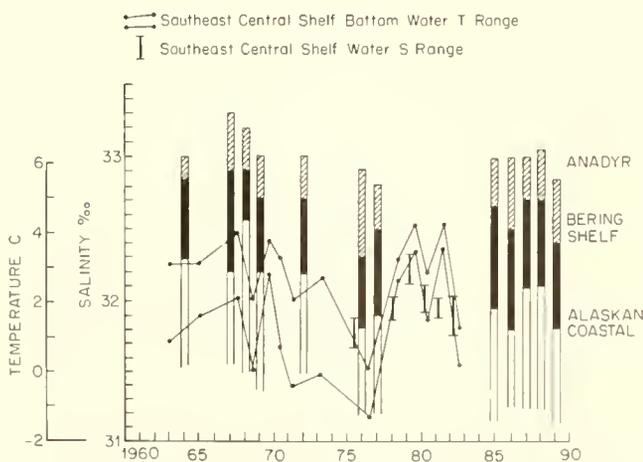


Fig. 5. Interannual variation of salinity ranges of the three basic water masses. Over the 25 years of observations, water masses were most saline in the late 1960's, and least saline in the mid-1970's. Temperatures and salinities of southeastern Bering Shelf water suggest similar variations, showing the changes to be part of a large-scale climatic variation.

The water mass sources are all to the south of the northern shelf area, and the advection carries them northward. As Alaskan Coastal, Bering Shelf, and Anadyr Current water masses are arranged sequentially east to west and there is very little lateral mixing or diffusion in the system, these waters maintain their east to west relationship as they are advected north. Figure 6 shows their distribution during August 1988, based on the *Korolev* data. The water masses were distinguished primarily by salinity of the deeper water, but temperature and water column structure (depth and degree of layering) were also considered. Anadyr Current water mass (Fig. 6, I) originates from water of the Bering Slope Current (Kinder *et al.*, 1975), a branch of which enters the Gulf of Anadyr in the west near Cape Navarin. This water hugs the western Siberian shore and remains identifiable as a distinct entity to Bering Strait. North of this strait, the water merges with and becomes indistinguishable from Bering Shelf water.

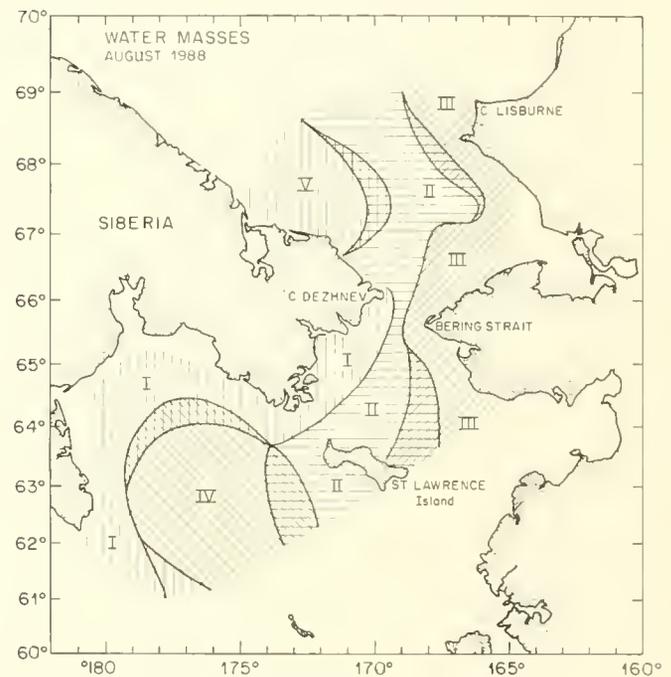


Fig. 6. Spatial distribution of water masses in August 1988 (*Korolev* data). I: Anadyr Current. II: Bering Shelf. III: Alaskan Coastal. IV: Gulf of Anadyr. V: Siberian Coastal.

On the east side of the system, Alaskan Coastal water (Fig. 6, III) originates well to the south of the region. It has the lowest salinities because it is the recipient of runoff from all along the coast, from the rivers of Bristol Bay and the Kuskokwim River. As Alaskan Coastal water enters the region, additions of Yukon River water near the east side of Shpanberg Strait "reinforce" the low salinities, which happens again when the water passes through Kotzebue Sound north of Bering Strait. Thus some parts of this water mass can become quite fresh in late summer ($S < 30$), and its area expands westward, but by the following winter the freshwater has flushed from the system and Alaskan Coastal water salinities are again >32 .

Bering Shelf water (Fig. 6, II) is the resident water mass of the whole central shelf region south of St. Lawrence Island. The waters filling the central shelf are basically mixtures of the two extremes: least saline coastal water and the most saline

water from the Bering Sea basin Shelf edge. Advection is small over the whole central shelf with water depths between 50 and 100 m (Coachman, 1986), so this water mass, intermediate in salinity and with long residence times, is most strongly conditioned by climatic factors such as brine rejection due to freezing and degree days of frost (see discussion in Coachman, 1986). Furthermore, Bering Shelf water in the area immediately south of St. Lawrence Island is directly influenced by special freezing conditions associated with the large polynya always found on its south side (Schumacher *et al.*, 1983). In the area of this polynya, the freezing over-winter of the equivalent of 8 to 10 m of ice causes a substantial increase in salinities of the shallow water columns. Thus increased in density, some of this water moves away to the southwest (in the direction of deepening) into the central Gulf of Anadyr, where it can be distinguished as a separate water mass we call Gulf of Anadyr water (Fig. 6, IV); this is in fact the "cold center" water of Barnes and Thompson because its temperatures over the summer normally remain close to freezing ($< -1.5^{\circ}\text{C}$) and are the coldest observed anywhere on the whole Bering Sea Shelf.

Most of the year, Bering Shelf water (Fig. 6, II) moves north around both ends of St. Lawrence Island and then occupies the middle area between Alaskan Coastal and Anadyr Current waters. In late summer, however, some years Alaskan Coastal water expands to nearly fill Shpanberg Strait, as in late August 1988, and northward transport of Bering Shelf at these times is predominately through Anadyr Strait (Fig. 6). North of Bering Strait, Anadyr Current water becomes so blended with the shelf water it loses identity. Across the Chukchi Sea we continue to identify this water mixture as Bering Shelf water, because salinities are little altered by the admixture of Anadyr water, and the name connotes its basic origin.

In the Chukchi Sea occurs another water mass, Siberian Coastal water (Fig. 6, V), identified by values of salinity greater than any entering the sea through Bering Strait contemporaneously. For example, in August 1988, the maximum observed S in Anadyr Current water was < 33.0 , while salinities of Siberian Coastal water were up to 33.6 . This water mass is associated with the Siberian Coastal Current.

Though lateral mixing is in general quite small in this regime of strong advection, and relatively discrete boundaries obtain between the water masses (transitions between two water masses are typically complete in < 10 km), there is some lateral interaction. This almost always takes the form of layering, the slightly heavier water mass on one side encroaches under the neighboring water, which forms a lighter surface water layer; or, frequently, the lighter water mass is driven by wind over the heavier.

Layering varies seasonally. In winter and spring there is practically none; all the shallow water columns are well mixed. Normally only in deeper areas like the central Gulf of Anadyr does a layered structure survive the winter cooling and freezing. Layered water columns appear with the advent of freshwater accumulation and some seasonal warming, usually late June and July, and is most widespread at the end of summer before

fall cooling begins. The extent and degree of layering observed in August 1988 (Fig. 7) is typical for late season. We make the following points and interpretations:

1. Strong layering is typical of the boundary between Alaskan Coastal and Bering Shelf water, particularly in the Chirikov basin (cf. Fig. 6).

2. Layering is minimal in very shallow near-shore waters, (e.g., in eastern Kotzebue Sound).

3. Both the Gulf of Anadyr and Siberian Coastal are basically layered water masses. In the Gulf of Anadyr depths in the central part deepen to 100 m (Fig. 1). Here the very cold water of the "cold center," with slightly enhanced salinities, resides beneath Bering Shelf water; water columns are sufficiently deep that the layering survives rigorous winter cooling and freezing. During the summer along the Siberian coast in the Chukchi Sea, runoff and ice melt create a very light, low salinity surface layer over the high salinity water at bottom; both layers are part of the Siberian Coastal Current.

4. Minimum stratification, even in late summer, is always observed directly downstream from Anadyr and Bering Straits, a consequence of turbulent energy generated in these constrictions.

We can now positively show that all waters of the ecosystem derive from a single source, the water of the Bering Slope Current of the northern Bering Sea. During the Third Joint US-USSR Bering & Chukchi Seas Expedition, samples from all the water masses were analyzed for ^{18}O heavy oxygen isotope. Two factors make these measurements diagnostic for water mass analysis:

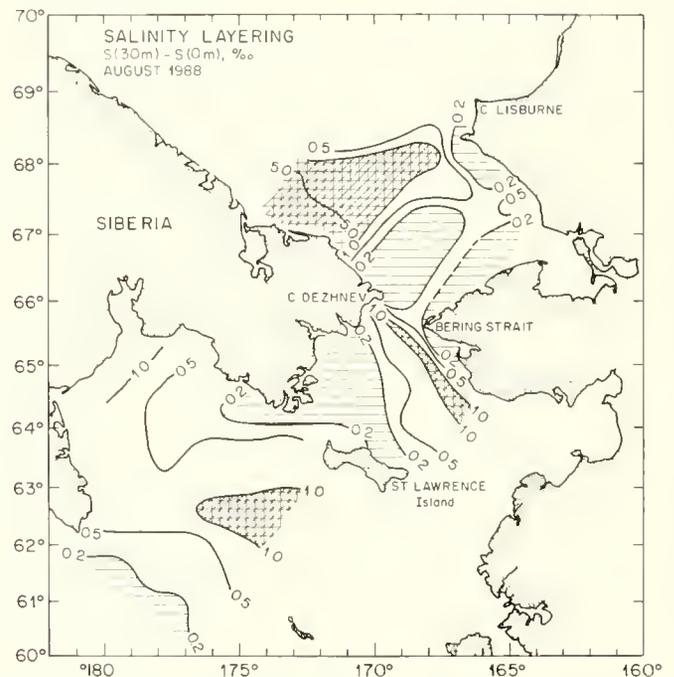


Fig. 7. Salinity layering (S at 30 m minus S near-surface) in August 1988. The distribution is typical: strong layering in the central Gulf of Anadyr (deeper water), along the boundary between Bering Shelf and Alaskan Coastal in the Chirikov basin, and in the Siberian Coastal Current. Very little layering in shallow water near Alaska, and in two plumes extending downstream from Anadyr and Bering Straits.

1. This stable isotope is most abundant in ocean water and least abundant in fresh precipitation and runoff, and so mixtures show intermediate values in proportion, just like salinity; and 2. the freezing process, which is important in increasing salinity of the northern shelf waters, does not alter the isotope abundance.

The correlations between salinity and oxygen isotope for the water masses are plotted in Fig. 8 (oxygen isotope data from Grebmeier *et al.*, 1990). Isotope values are plotted as deviations from standard mean ocean water ($^{18}\text{O}_{\text{SMOW}}$), so that most ocean waters have values close to 0 and freshwater is <-20 ppt. In Fig. 8, samples are plotted in two ways: as individual point correlations for samples from the Bering Slope Current (triangles), Alaskan Coastal (open circles) and Siberian Coastal (solid circles) water masses, and as envelopes encompassing many values for the other three.

All samples lie on or very close to a line from $S = 35$, $^{18}\text{O} = 0$ (ocean water) and $S = 0$, $^{18}\text{O} = -24.6$ (freshwater), from which we can conclude that all water masses are essentially simple dilutions of the most saline Bering Slope Current water by freshwater. The progression along the line is orderly. The

mass show much greater and more variable dilutions because of proximity to the high runoff along the eastern side of the system. They also do not follow the dilution curve as closely because selected areas are subject to strong local freezing and brine rejection, for example within Norton Sound (see Muench *et al.*, 1981). The value at $-3.3/31.5$ is a good case in point.

The two secondary water masses of the system, Gulf of Anadyr and Siberian Coastal, are both created from Bering Shelf water through salinity enhancement by freezing. The polynya south of St. Lawrence Island, as discussed, is the focal point for the salinity enhancement which turns Bering Shelf water into Gulf of Anadyr water: the overwinter freezing increases salinities by about 0.5 but without changing ^{18}O .

The Siberian Coastal water mass is apparently created in the same way. Bering Shelf water travels throughout the system, well north into the Chukchi Sea, without appreciable change in S . The whole system evidences very little lateral diffusion and exchange between water masses, and the Bering Shelf water, sandwiched in the middle, is effectively isolated from runoff and hence dilution from both Alaska and Siberia. In the Chukchi, vigorous freezing in certain areas in winter causes substantial increases in S values without modifying ^{18}O , and this water is recirculated the following year as part of the Siberian Coastal Current (see discussion below).

Flow Field

The Anadyr Current, the branch of the Bering Slope Current that enters the Gulf of Anadyr near Cape Navarin and continuously supplies the nutrients to fuel the ecosystem, is a topographic boundary current of the eastern Bering Sea Shelf; it is also, coincidentally, located along the western boundary of the shelf. This was convincingly demonstrated by Kinder *et al.* (1986) who employed both laboratory models and numerical simulations, achieving results in very close agreement with what we know of the Anadyr Current.

The basic driving force is the sink for Bering Sea water imposed by the northward flow through Bering Strait—that is, the pressure head created by a ~ 0.5 m height difference between the Bering Sea and the Arctic Ocean (Stigebrandt, 1984). Thus, Bering Sea water must move northward across a shoaling topography. In this situation, the topographic gradient, $f/h \sim 5 \times 10^{-12} \text{ cm}^{-1} \text{ s}^{-1}$, is more than an order greater than the variation of Coriolis parameter, $\beta \sim 1 \times 10^{-13} \text{ cm}^{-1} \text{ s}^{-1}$. The across-shelf flow is concentrated as a current along the lefthand boundary facing upslope (Fig. 9). Notice in the simulations that regardless of whether or not flow conditions are imposed along the Bering Sea slope, the cross-shelf flow still forms the same western boundary current on the shelf. The numerical simulations indicated a current width of 50 km and speeds of $10\text{--}20 \text{ cm s}^{-1}$, both in excellent agreement with available data on the real current. Of course, within the Gulf of Anadyr, the flow, being strongly steered along isobaths, actually circulates clockwise around the gulf (cf. Fig. 1).

Variability in flow of the Anadyr current is unknown. It seems probable, however, that it is a much steadier flow than those through Anadyr and Bering Straits. The large variability in the latter flows, predominantly at periods of a day to a week,

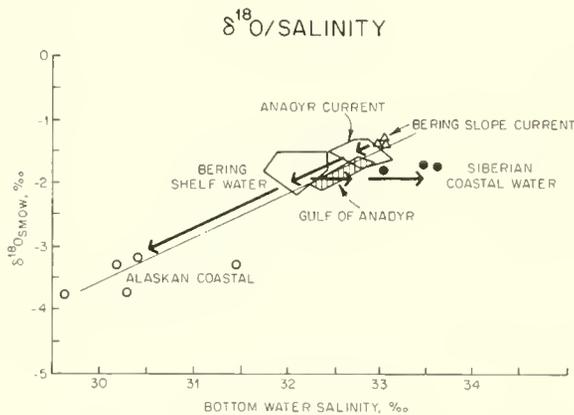


Fig. 8. Correlation of ^{18}O with salinity, *Korolev* cruise, August 1988. All water masses of the Northern Bering Sea Ecosystem are dilutions to varying degrees of Bering Slope Current water by freshwater. Gulf of Anadyr and Siberian Coastal waters are modifications of Bering Shelf water through salinity enhancement due to freezing. Arrows indicate direction of water mass modification. Data from Grebmeier, Cooper & DeNiro, 1990.

precursor water to the whole system from the Bering Slope Current has both the highest salinities and abundances of ^{18}O : $S \sim 33$ to 33.2 , $^{18}\text{O} \sim -1.5$. These values are, of course, already slightly diluted from SMOW. In the ecosystem, the first step in dilution is observed in the Anadyr Current, because the current mixes to some extent with runoff (particularly the Anadyr River) in its transit around the Gulf of Anadyr. [In Fig. 8, the pathways of water mass modification are indicated by arrows.] Further dilution of Anadyr Current water produces the Bering Shelf water mass, ubiquitous to the whole northern shelf. Not all Anadyr Current water transits Anadyr Strait, but some is deflected to the south of St. Lawrence Island, where it meets and mixes with fresher waters from the Alaskan side of the system, forming this water mass with slightly reduced salinities and ^{18}O . Samples from the Alaskan Coastal water

NUMERICAL SIMULATIONS OF BERING SHELF CIRCULATION

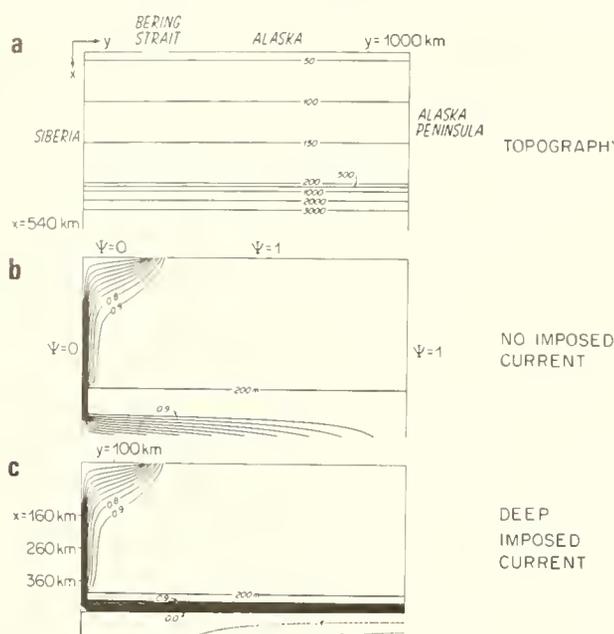


Fig. 9. Numerical simulations of a rectangular Bering Sea Shelf, showing the Anadyr Current to be a boundary current of concentrated flow resulting from northward flow across the shoaling shelf; the current is concentrated on the left looking up-slope. From Kinder, Chapman & Whitehead, 1986.

is produced by wind effects driving water against the shoreline boundaries adjacent to the straits and thereby altering the pressure head through them (Aagaard *et al.*, 1985; Coachman & Aagaard, 1988). The Anadyr Current is much less constrained by boundaries (also true of the downstream Chukchi Sea portion of the ecosystem). It also seems unlikely that the large-scale driving force due to the difference in sea levels changes sufficiently in magnitude or rapidly enough to cause variations like those observed in the Chirikov basin; in particular, it is unlikely the Anadyr Current ever ceases or reverses. This is of crucial importance to the ecosystem—it guarantees a relatively steady, continuous, and large supply of nutrients. Furthermore, the residence times of water parcels within the gulf, which is the site of the first production center (cf. Fig. 3), are likely to be much less variable than they are in the Chirikov basin; at 15 to 20 cm s^{-1} , water parcels will transit the gulf in about 1 month.

In contrast with the Gulf of Anadyr and Chukchi Sea, the middle active production center of the ecosystem—the Chirikov basin—has restrictive physical boundary conditions on its flow field. Two straits restrict inflow of water from the south, Shpanberg to the east of St. Lawrence and Anadyr to the west, and there is only one outlet, Bering Strait. From the Gulf of Anadyr, most of the Anadyr Current most of the time flows northward through Anadyr Strait into the Chirikov basin. It is joined by a transport of the less saline Bering Shelf water from south of St. Lawrence Island. Bering Shelf water enters the basin also around the eastern end of St. Lawrence through Shpanberg Strait, while the eastern part of this strait usually

carries Alaskan Coastal water from the south; the latter water mass forms a buoyancy boundary current along the entire Alaskan coast. All these waters pass northward out of the Chirikov basin through Bering Strait. Crossing Chirikov basin, the three water masses tend to remain discretely side-by-side; there is little lateral mixing between them (Coachman *et al.*, 1975). The production center is in the center and western part of the basin, associated with Anadyr and Bering Shelf water masses, not Alaskan Coastal.

The northward flow is constricted passing through the straits, which has important physical consequences for ecosystem production. In transiting the straits, the currents increase speed and greater amounts of bottom-friction-generated turbulent energy becomes available for mixing the water columns. Any stratification that has developed upstream from the straits is largely broken down, and materials (in particular nutrients) that have collected in the lower layer are redistributed into the upper layer.

A south-to-north section through Anadyr Strait from a 3-dimensional nonlinear dynamical model (Deleersnijder & Nihoul, 1988) shows these effects graphically (Fig. 10). Immediately north of Anadyr Strait, there are high amounts of turbulent kinetic energy in the upper 20 m (Fig. 10C) and upwelling velocities as great as $5 \times 10^{-3} \text{ cm s}^{-1}$ (Fig. 10A); these together have nearly broken down strong thermal stratification existing south of the strait (Fig. 10B). The result is a large plume of colder, nutrient-rich water spreading from Anadyr Strait northward along the Siberian shore and eastward across the Chirikov basin, frequently visible in satellite imagery (Nihoul *et al.*, 1990). The effect is registered in hydrographic data as much reduced vertical stratification; compare the plume of small lower–upper layer salinity differences in Fig. 7. Notice also a similar plume extending northward from Bering Strait.

The ecological importance of the enhanced vertical mixing in Anadyr Strait and, subsequently, in Bering Strait is enormous; it effectively “resets” the system downstream from areas of large production so that another production cycle can occur. Production takes place in the waters transiting the Gulf of Anadyr and some stratification develops from Anadyr runoff. Nutrients become depleted in the upper layer. The “resetting” feature mixes nutrients back into the upper layer where they can fuel another round of high production. The Chirikov basin production, and layering in its northern part due to Alaskan Coastal water in the funneling flow field (cf. Fig. 7), create a similar situation just south of Bering Strait. These conditions are “reset” by the Bering Strait flow leading to large production in the southeastern Chukchi (Fig. 3).

In the tightly bounded Chirikov basin another aspect of the flow field is important. The in- and outflows through the bounding straits are not one hundred percent correlated; there are periods ranging from days to weeks when the in-flow via Anadyr and Shpanberg Straits does not equal the outflow through Bering Strait. During these times water volume in the basin is not conserved, which is compensated by either a rise or fall in sea level (cf. Aagaard *et al.*, 1985); changes in sea level at Nome as great as 1 m in a couple of days have been observed.

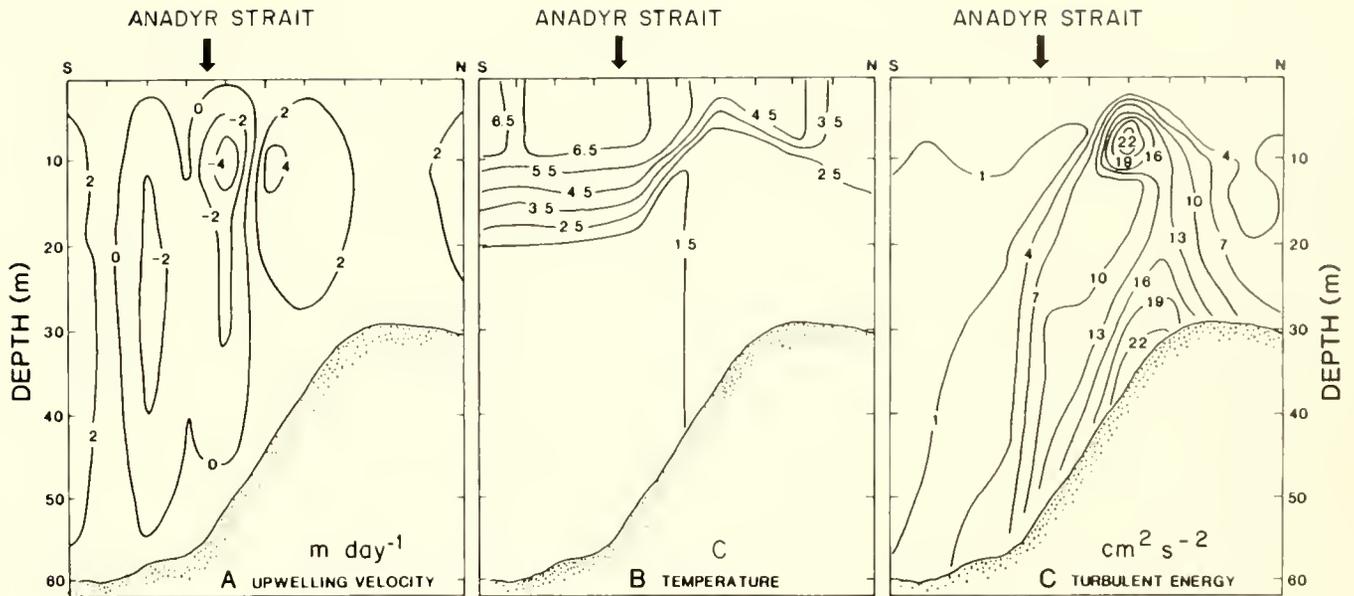


Fig. 10. North-south section through Anadyr Strait from a 3-d numerical model (Deleersnijder & Nihoul, 1988) showing (A) vertical velocities upward just north of the strait; (B) breakdown of stratification just north of the strait; and (C) high concentrations of turbulent kinetic energy just north of the strait. These result from physical constriction of the flow by the topography, and mix the water columns vertically, "resetting" the ecosystem.

The import to the ecosystem of nonconservative transport through Chirikov basin is a large variation in residence times of water parcels in the basin. This variability affects not so much the production but the proportion of production exported versus the proportion sequestered in the basin as sediments.

During the ISHTAR field programs, between six and ten moorings with current meters were deployed each year in the Chirikov basin. From these records, residence times of water parcels entering the basin through Anadyr and Shpanberg Straits were estimated. The data from each meter were considered to be representative of water in an area surrounding the mooring location extending halfway to adjacent meters. Mean daily excursions of water parcels were calculated and plotted sequentially, using the current data from the closest meter. The residence time is the number of days elapsing between the entrance of a water parcel through Anadyr Strait until its exit through Bering Strait.

Reconstructed water parcel trajectories representative of various length residence times are shown in Fig. 11. The most typical residence times in summer are about two weeks, when the flow is steadily northward with little variation. Under these flow conditions, water parcels take a relatively direct route from Anadyr into the center of the basin, then veer left and move directly to Bering Strait. The trajectories of minimum residence times are much the same—nearly a direct path between Anadyr and Bering Straits—and occur when the current speeds in both straits are exceptionally strong. Medium duration residences of three to four weeks occur when currents in the straits are still generally northward, but much slower, particularly in Bering Strait. During these times, the water entering through Anadyr floods eastward across the basin. The longest residence times are when flow actually reverses in the system; water parcels spend time describing gyres in the basin interior.

The residence times of water parcels in summer has been quite different over the four years of intensive study. The times for water entering through Anadyr Strait, beginning in early July each year 1985–1988, estimated for alternate days, are graphed in Fig. 12. The times are plotted according to the day the water entered the basin. The measured residence times vary by more than a factor of 5, from a very rapid transit of 9 days (mean speed ~ 34 cm/s) to more than 50 days. The variability

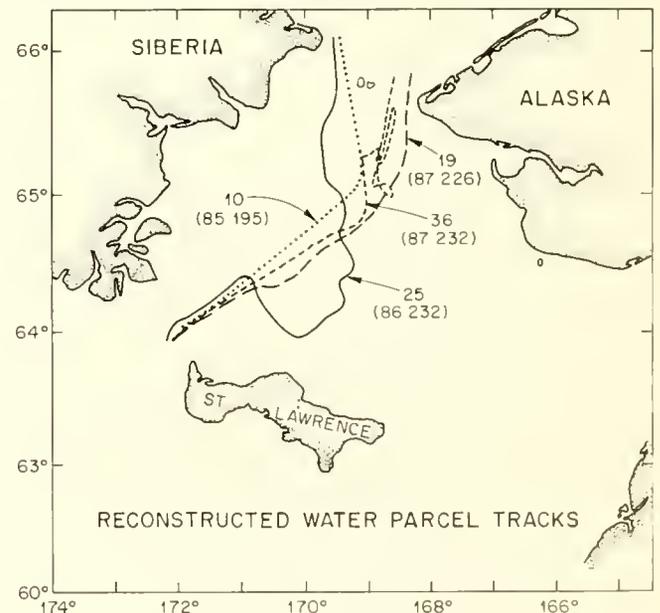


Fig. 11. Reconstructed trajectories of Anadyr Current water parcels, illustrating different residence times. Coding: above is residence time in days; below is (year: Julian day of ingress through Anadyr Strait). Note that with longer residence times water parcel excursions extend farther east; very long residence times involve gyre trajectories associated with flow reversals in the system.

is both seasonal and interannual. Early in the summer each year water transits the basin most rapidly, typical residence times being about two weeks. In 1985, this condition maintained until almost the end of August, in 1987 until the middle of August, and in 1988 the beginning of the month. Nineteen eighty-six was different; beginning the second week in July, residence times increased to about one month and remained so over the summer.

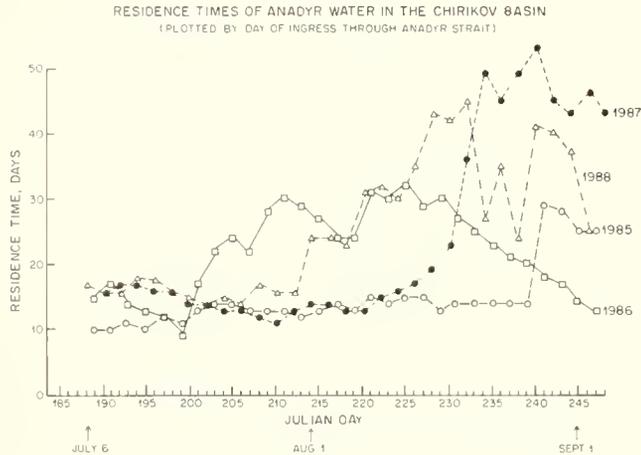


Fig. 12. Residence times of Anadyr Current water in the Chirikov basin for the four years of ISHTAR study. Times are plotted by day of ingress through Anadyr Strait. Notice typical residence times in summer are about 2-weeks through July, then a switch to much longer times sometime during August. Nineteen eighty-six was different, with residence times of 3 to 4 weeks over the summer.

The residence times are closely related to the wind regime and its variations. Over most of the year, the strength of north flow through the system, and variations in this flow (e.g., from north to south), are well correlated with the local winds; for example, Bering Strait north transport and the north-south wind component correlation is $r > 0.7$. In early summer each year, though, the correlation breaks down. Regional winds become light, without strong variations, the flow becomes decoupled from the wind, and the currents are stronger and directed more steadily to the north (Coachman & Aagaard, 1988). These are the conditions for short residence times, and were observed to obtain at the beginning of July each year.

Over the remainder of the year, winds are both stronger and more variable, and the flow is driven into variations that are reasonably correlated with those of the wind. Thus the periods of slow and reversed (southward) flow become more frequent, and residence times become markedly longer. This changeover from "summer" to normal wind regime occurred at different times between the beginning and end of August in 1985, 1987, and 1988. Nineteen eighty-six, however, was anomalous; the typical "summer" flow condition, decoupled from the wind, never really developed. The resulting longer residence times over the production season were undoubtedly responsible for the greater accumulation of biomass in the Chirikov than in the southeastern Chukchi basin in 1986, as opposed to more "normal" years when more accumulates in the Chukchi (Walsh *et al.*, 1989).

To provide more insight as to specific wind conditions causing longer residence times, Fig. 13 was prepared. First, the north-south component of wind at Bering Strait was examined by itself, but no relationship with residence times was apparent. The forces driving the flow field variations are obviously more complex than just the local wind in Bering Strait. So the wind at Anadyr Strait was added, and a qualitative picture emerges. A primary condition for long residence times seems to be a sustained trend of change in the winds to northerlies (i.e., directed to the south) combined with a sustained, strong divergence of the wind field over the Chirikov basin. The divergence is where the winds at Anadyr are either less strong to the north, or stronger to the south, than those at Bering Strait. Under these conditions, the normal sea surface slope down to the north is negated and readily reversed. Without a "push" from the south, water parcels can hang around in the Chirikov basin for very long times (as long as two months).

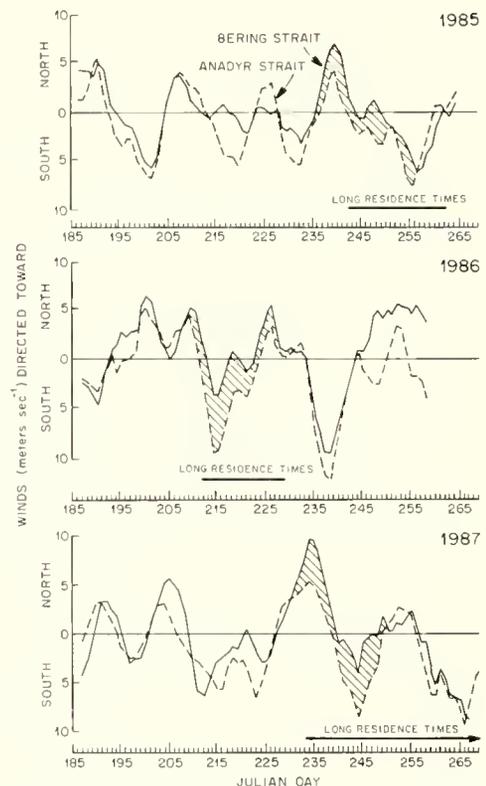


Fig. 13. North-south component of winds at Bering Strait and Anadyr Strait over the summers of 1985-87 (data smoothed with 5-point running means). Long residence times seem to be associated with changes toward strong south-directed winds and a sustained, strong divergence of the wind field over the Chirikov basin (hachured).

Chukchi Sea

The third, downstream production center of the northern Bering Sea ecosystem is in the Chukchi Sea. ISHTAR has studied the southeast corner of the region. Southwest from Pt. Hope lies a production center where huge chlorophyll biomass has been measured (cf. Fig. 3) and also some of the

highest values of primary productivity ever measured in the World Ocean. Fuel for this production center is provided by Bering Shelf water. The water mass transits Bering Strait (where it becomes combined with the Anadyr Current water mass; see Coachman *et al.*, 1975) and circulates counterclockwise around Kotzebue Sound following the bathymetry (cf. Fig. 1). It still contains, in spite of high utilization upstream, considerable nutrients (e.g., $\sim 10 \mu\text{g-at NO}_3/\text{l}$).

The cruise of the *Akademik Korolev* expanded the studies to the west as far as Kolyuchin Bay. The most important finding was another center of production in addition to that southwest of Pt. Hope (Fig. 14), which was associated with an entirely different water mass. The maximum observed salinity of Bering Shelf/Anadyr Current water in 1988 was <33 , while the salinities of the water of the center off Kolyuchin were up to 33.6 (Fig. 14, lower). At this time the Siberian Coastal Current did not extend all the way to Bering Strait, as demonstrated in the salinity distribution (Fig. 14, lower). The values >32.9 stopped about 100 km short of the strait; apparently the current turns east and northeast, closing a gyre with the Bering Shelf water flow to the northwest, southwest of Pt. Hope (cf. Fig. 2). There are times, however, when the Siberian Coastal Current does reach to Bering Strait; Ratmanov (1937b) documented penetration of Siberian Coastal water into the strait in 1933.

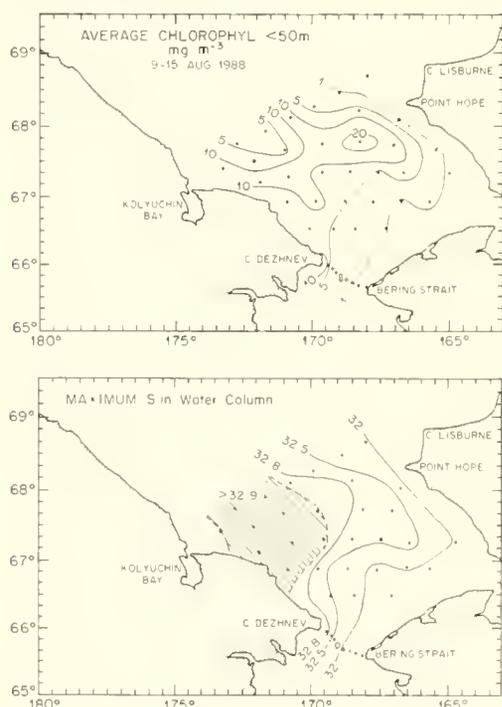


Fig. 14. Average chlorophyll biomass (upper) and maximum S in the water column (lower) in the southeastern Chukchi Sea, *Korolev* data, August 1988. Note high chlorophyll off Kolyuchin Bay in addition to the center southwest of Pt. Hope, associated with water with higher salinity than any entering through Bering Strait.

Thus, the full extent of the production area of the northern Bering Sea ecosystem in the Chukchi Sea is unknown. It is clearly much larger than previously envisioned. It is fueled by two different water masses—the Bering Shelf water from the south entering directly through Bering Strait, and a Siberian

Coastal water associated with the Siberian Coastal Current. Prime questions are the source and extent of the latter. Few data are available to help search for the source; the best are from the cruise of the USCGC *Northwind* in 1963 (US Coast Guard Oceanographic Unit, 1965). Figure 15 plots the salinities (upper) and nitrates (lower), averaged for the water columns >20 m, from these data for the Chukchi Sea and Long Strait. The distributions in August 1963 appear to be the same as in 1988. A water mass with salinities greater than any coming into the system from the south follow the Siberian coast. There is a focal point for this water near Wrangel Island; T/S analysis (Fig. 16) shows the water mass is not extant in the East-Siberian Sea to the west, but in fact shows the highest salinities at the stations in Long Strait, close to Wrangel Island. High nutrient concentrations are associated with this water; it is obviously this water that is responsible for the second region of production in the Chukchi Sea part of the ecosystem. The apparent source of this water in the vicinity of Wrangel Island is confirmed by sketchy data from three other cruises (Fig. 17): the *Maud* in 1922 (Sverdrup, 1929), *Northwind* in 1962 (US Coast Guard Oceanographic Unit, 1964), and *Oshoru Maru* in 1972 (Faculty of Fisheries, 1974). It appears that the whole area east of Wrangel Island shows evidence of this high salinity water mass.

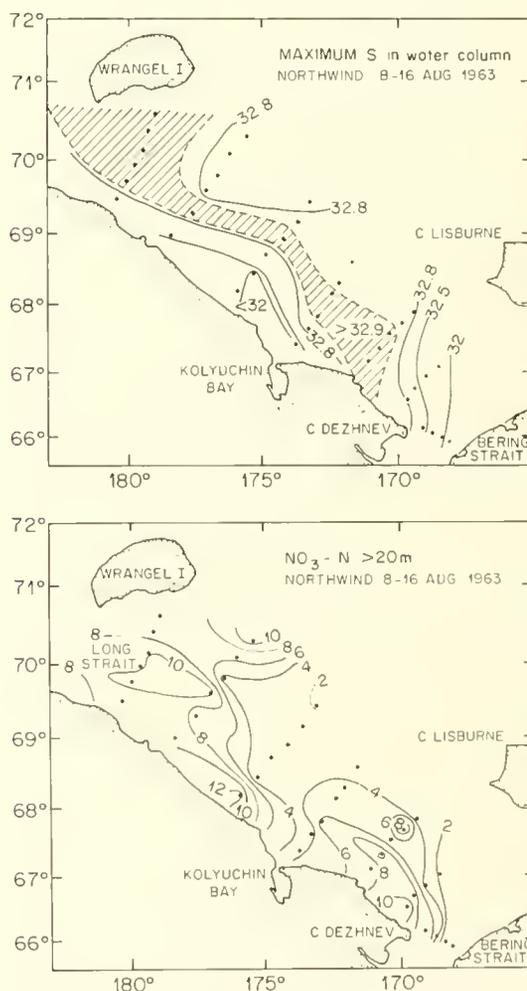


Fig. 15. Maximum S (upper) and nitrate concentration (lower) from the *Northwind*, August 1963. The high S water has high nitrates, and seems to be coming from the vicinity of Wrangel Island.

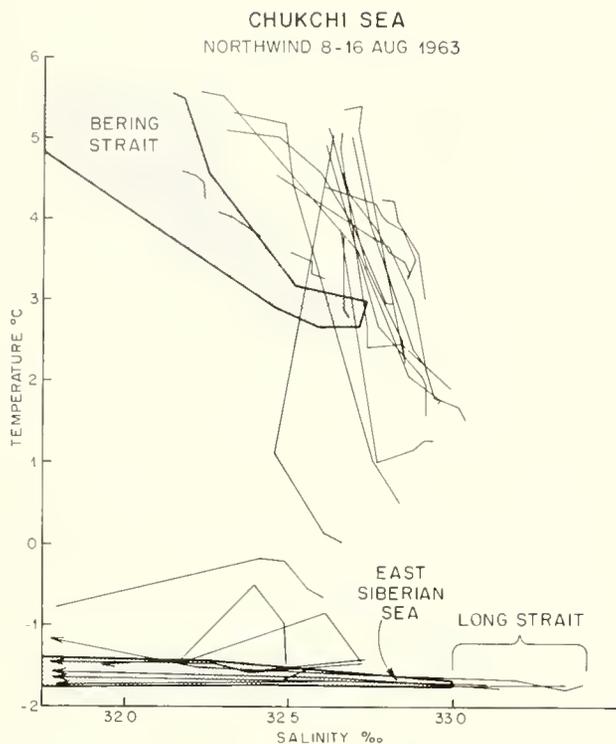


Fig. 16. T/S correlations for the Northwind data. Individual lines are all stations in the Chukchi Sea; stations from Bering Strait and the East-Siberian Sea are enclosed in envelopes. Stations from Long Strait (marked, see Fig. 15) have the highest S values of all.

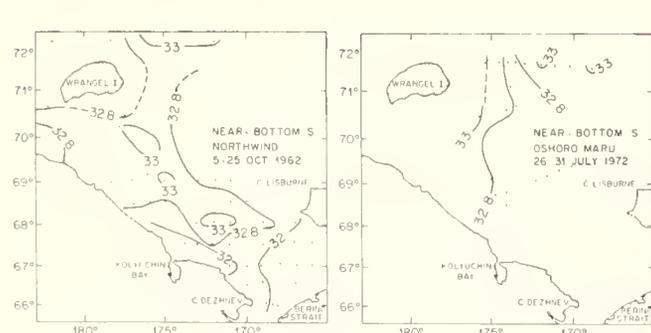


Fig. 17. Confirmation that the source of high salinity (and high nutrient) water is near Wrangel Island and Herald Shoal to its east side. Data from three cruises: (upper) *Maud*, 1922; (lower left) *Northwind*, 1962; (lower right) *Oshoro Maru*, 1972.

Where does this water come from? One possibility hypothesized initially was that the source of the water mass may be the pycnocline layer of the Arctic Ocean. The focal area east of Wrangel Island is the head of the Herald Submarine Canyon, which indents the Chukchi Shelf near Herald Island (see Fig. 1). The concept was that Arctic Ocean water might flow in-canyon along the bottom onto the shelf, as it does in Barrow Canyon on the eastern side of the Chukchi (Mountain *et al.*, 1976). This hypothesis can be ruled out because the phosphate content of the Siberian Coastal water mass is much too low to be Arctic Ocean water.

The most likely hypothesis is that the water mass is of Bering Sea origin. It is Bering Shelf water that enters the Chukchi Sea during fall and winter, where its salinities are enhanced through ice formation. Then the following summer the water is recirculated throughout the southern Chukchi Sea via the Siberian Coastal Current. Two observations in support of this hypothesis are: 1. the ^{18}O values of the water are precisely those of Bering Shelf water (Fig. 8); and 2. the focal point of highest salinities east of Wrangel Island is an area where the least amount of ice formation in winter is required to enhance salinities to the requisite ~ 33.5 (Fig. 18).

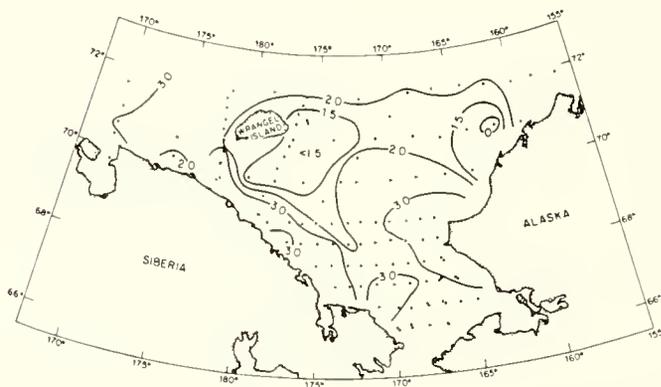


Fig. 18. The amount of ice growth required to raise the salinity of water columns to 33.5‰ . Notice the area of minimum necessary ice growth coincides with the area of highest salinities near Wrangel Island and Herald Shoal (from Aagaard, Coachman & Carmack, 1981).

With this hypothesis, the relatively high nutrient concentrations are supplied by the rich Bering Shelf water in winter that are not utilized or affected by freezing, so are available to fuel the Chukchi Sea end of the ecosystem the next summer. The circulation, insofar as it is known (Fig. 19), fits in with this hypothesis, though there must be more southerly components of flow in the western Chukchi, southwest of Herald Shoal, than indicated in the schematic depiction. The presence of the highest salinities near Herald Shoal, and particularly to its west and southwest, is not coincidence; the shoal water is undoubtedly important in providing the most effective environment for salinity enhancement by freezing.

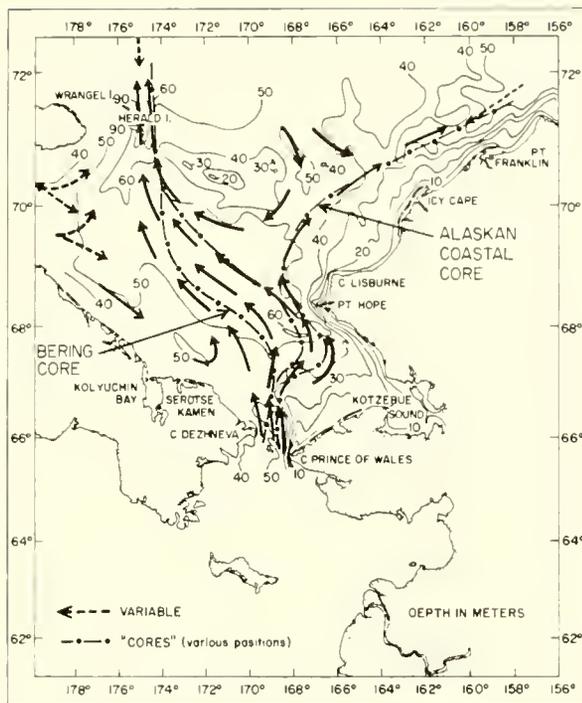


Fig. 19. A best guess of the circulation in the Chukchi Sea (from Coachman, Aagaard & Tripp, 1975). Notice that Herald Island and Shoal are in the main pathway of Bering Shelf water. However, there actually must be more movement of water toward the Siberian Coast near Wrangel Island than suggested in this schematic.

L'envoi

We have summarized the important physical oceanographic factors of the northern Bering Sea ecosystem. A unique set of features combine to make it one of the World Ocean's largest and most productive ecosystems. The key feature is advection of water from a rich pool of nutrients (the Bering Sea Continental Shelf edge), across an enormous distance in shallow water. The nutrient supply continuously injected by the current is sufficient that they never become depleted and limiting, even

with high production. There are two constrictions in the advective stream, dividing the system into three basins and three production centers. These are spaced such that the transit time of water across each basin, two to four weeks, is the same as a complete biological production–utilization–regeneration cycle. Turbulent energy injected into the water columns at the constrictions stirs them, "resetting" the system for the next round of production.

The advection is driven northward from the Bering Sea into the Arctic Ocean by a sea surface slope (the Arctic Ocean stands lower than the Bering). But there are important variations in the transport related to the local winds, which drive water against the land boundaries modifying the surface slope. Primary variations are over a few days (storm time scale), and as these are greatest and most frequent in winter, there is a seasonal cycle of lower net north transport in winter and greater in summer. Interannual variations are also significant. They affect mostly the geographically constricted Chirikov basin; here water parcel transit (residence) times can differ by a factor of five. The variability seems to have only a small influence on the actual amount of primary production in the ecosystem; rather, its importance lies in varying the amount of production that becomes deposited in the centers versus the amount that is transported through into the Arctic Ocean.

The downstream (Chukchi Sea) end of the ecosystem is virtually unknown. Nutrients supporting very large production are supplied to this center by Bering Shelf water entering directly via Bering Strait and from a second source presumed to be Bering Shelf water enhanced in salt content through freezing during the previous winter and recirculated via the Siberian Coastal Current. But this is hypothesis; the circulation of the Chukchi is not known, nor the amount and extent of production, nor the amount of carbon that is exported to the Arctic Ocean. Considering the possible significant role of Chukchi Sea carbon export in global carbon budgets and climate warming (Walsh *et al.*, 1989), further study of the Chukchi Sea end of the northern Bering Sea ecosystem has a very high priority.

2.2 Water Mass Modification from the Bering into the Chukchi Sea

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Introduction

The only Northern Hemisphere connection between the Pacific and Atlantic Oceans is across the shallow waters of the northern Bering and Chukchi Seas connected by the Bering

Strait. The seminal work on the oceanography of the northern Bering Sea (Barnes & Thompson, 1938) led to further investigations on this important region that continue to this day. Coachman *et al.* (1975) reviewed the regional physical oceanography in the most comprehensive work on the Bering

Strait region to date. Studies since then, notably the Inner shelf Transfer and Recycling (ISHTAR) program have expanded our understanding of the regional oceanography yet further (Coachman, 1986; Walsh *et al.*, 1989).

Complete, integrated studies of the region have been restricted by its strategic significance, national boundaries, and Exclusive Economic Zones. The Third Joint US–USSR Bering & Chukchi Seas Expedition on the Soviet research vessel *Akademik Korolev* (*Korolev*) in the summer of 1988 (AK-47) afforded an opportunity for US and Soviet scientists to study the oceanography of the northern Bering/Chukchi Seas without limitations imposed by territorial boundaries. The cruise took place from 26 July to 2 September 1988 and occupied 102 CTD stations in the Gulf of Anadyr, Chirikov basin, and southern Chukchi Sea (see Frontispiece). (An additional 11 stations were occupied near the Aleutian Islands and in deep parts of the Bering Sea, but are not discussed here.)

There are three primary water masses in the northern Bering Sea, and the basis for their identification is salinity (Coachman *et al.*, 1975). The most saline is water from the continental slope of the eastern Bering Sea Shelf edge, which enters the region via the Gulf of Anadyr and Anadyr Strait to the west of St. Lawrence Island. This is the most important water source to the extremely productive northern Bering/Chukchi Sea ecosystem because of its high nutrient loading. The least saline water lies in the east, the Alaskan Coastal water, which flows parallel to the Alaskan coast northward through Shpanberg Strait to the east of St. Lawrence Island. The water mass of intermediate salinity, which is also the coldest, is Bering Shelf water in residence over the extensive shelf area south of St. Lawrence Island. It is advected northward around both ends of St. Lawrence, through both Anadyr and Shpanberg Straits, and northward between the other two; part of the water mass modification occurring in the system is commingling of these three water masses as they are advected northward.

Salinity values of the water masses are not only space, but time-variable, as much as 0.5 ppt seasonally and interannually. Thus, in the absence of quasi-synoptic data from the whole system, the precise changes of water mass properties as they transit the various basins and straits have never been observed. As the *Korolev* data provide the first-ever quasi-synoptic picture of the regional water masses, this paper describes their modification as they are advected north from the shelf break of the Bering Sea through the Gulf of Anadyr, Chirikov basin, and the southern Chukchi Sea.

Methods

Conductivity–temperature–depth (CTD) casts were made surface-to-bottom using a Sea-Bird Electronics model SBE-9 system with a General Oceanics RMS 12 rosette water sampler. The rosette held 12, 2.5-liter “GO-FLO” water sampling bottles. These provided water samples for many other projects as well as samples for salinity analysis to compare with the CTD values. The salinity measurements were made using a Beckman RS7-C laboratory salinometer.

The Sea-Bird was delivered new, just two weeks before AK-47 began. It has a rated accuracy of $0.004^{\circ}\text{C}/\text{year}$ over the range -5 to $+35^{\circ}\text{C}$, 0.0003 S/m/month over the range 0 to 7 S/m, and 0.02% of full scale over the depth range 0–3,500 m. The instrument was calibrated by the US Northwest Calibration Center in Seattle before and immediately following the *Korolev* cruise, with nearly no changes in output. Later, the same CTD was used in the Antarctic, where salinities from some 1,000 points were compared with samples run on AGE and Guildline salinometers — differences were less than 0.01 ppt. Subsequent calibrations have shown this instrument to be very stable and its accuracy is well within the tolerances acceptable for modern physical oceanographic research.

Methods of CTD deployment and data reduction are pertinent to data quality, so they are outlined briefly. The CTD operator prepared the rosette and set up the computer about 15 min before each station. On station, the instrument was lowered to the sea surface (or up to 5 m below surface, depending on sea state) and held while the program to record data was started. It was then lowered at a rate between 15 and 30 m/min until it was about 5 m above the sea floor. When the instrument’s attitude in the water column was seen to be stable, it was then lowered another 2 or 3 m. The computer was then reset for the uptrace, and the rosette bottles were tripped at predetermined depths on the upcast.

Data is acquired by the Sea-Bird at a rate of 24 scans of pressure, temperature, and conductivity per second. For AK-47, scans were averaged in groups of six, giving four data groups per second to be recorded. At a drop rate of 30 m/min, CTD values were thus acquired approximately every 0.125 m. The data are averaged internally, digitized, and transmitted to the ship via the center conductor in the sea cable through winch slip rings into the deck laboratory. The deck unit (Sea-Bird model 11) converts the data to computer-compatible signals, which are fed into a Packard-Bell AT-type computer via an IEEE 488 (GPIB) bus.

Using Sea-Bird supplied software, the CTD data were displayed on the CRT monitor in real time as X-Y plots as the instrument was being lowered. As the rosette bottles were tripped on the upcast, the usual problems in calibrating the CTD conductivity sensor were encountered. Because of water disturbance on the upcast by the rosette and CTD housings, salinity readings by the CTD are suspect. Thus, comparison of salinity samples with the CTD output does not necessarily give valid *in situ* calibration data. Also, comparison with downcast values in shallow, highly variable shelf waters is likewise suspect. Nevertheless, at least two samples from each station were collected for checking the CTD calibration. An ancient Beckman salinometer was used to run these salinities, which presented problems with drift. In spite of all the difficulties, the results show 1. consistency in Sea-Bird CTD output station-to-station; 2. close agreement with SEACAT data when the two instruments were run together; and 3. close agreement between CTD values and laboratory determinations, providing confidence in the accuracy of the data from AK-47.

Raw CTD data were recorded on the computer's hard disk drive and archived on Omega Bernoulli 20-Megabyte removable disk cartridges. One-meter average values for each station were created using Sea-Bird supplied software. A data report gives standard-level listings for all CTD data from the cruise (Amos, 1990).

Results

water depths in the Gulf of Anadyr are less than 150 m, and mostly less than 100 m. In the Chirikov basin and southern Chukchi Sea, water depths are even less—almost everywhere 50 m or less. The north-south size of this shallow shelf sea is enormous, subtending about 1,200 km from the shelfbreak in the northern Bering Sea to the shelfbreak in the Arctic Ocean. In this shelf sea, diverse water properties are encountered. Based on AK-47 data, in summer temperatures range from nearly 12°C at the surface near the Alaskan coast in the Chirikov basin, to -1.6°C at the bottom in the central Anadyr Gulf, southwest of St. Lawrence. Salinities range from 24 ppt at the surface near the Chukchi coast off Kolyuchin Bay to 33.6 ppt at the bottom in the same location (Station 45).

A T/S diagram of all stations from AK-47 is shown in Fig. 1. Surface values of each station are marked by "T" and bottom values by "B," and the dots are 1-m average values. This diagram includes not only the shelf stations but the 11 stations taken in the deep Bering Sea. These latter form a tight grouping: surface values are all >32 ppt up to about 33.4 ppt; there is a temperature minimum in the S band 33.2–33.4 (forming a marked "V" shape in the diagram); deeper, there is a temperature maximum of 3.6<T<4.0°C, and below this, the bottom values merge to a water type ~1.8°C, 34.6 ppt.

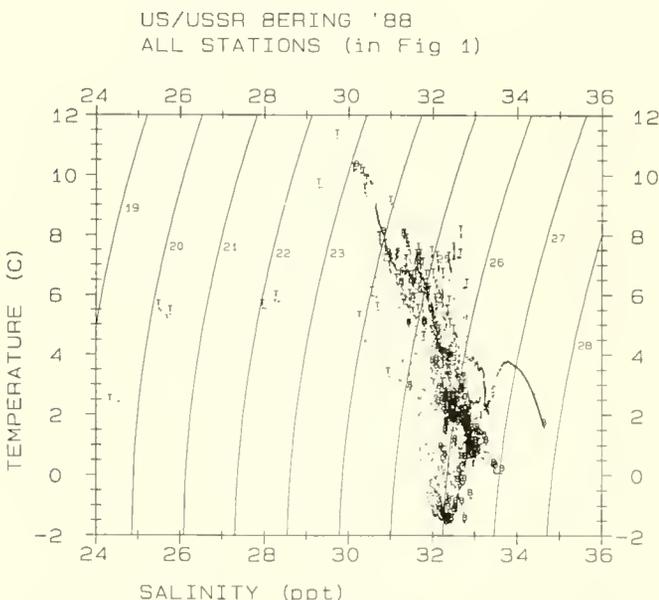


Fig. 1. Temperature-salinity diagram of all *Korolev* stations, from the shallow northern region (Frontispiece) and 11 stations from the deep Bering Sea basin. Bats are 1-m average values; for each station the surface value is marked by a "T" and deepest value by a "B".

The T/S values from shelf stations are massed, with few exceptions almost all associated with surface layer values, in the salinity range 31–33 ppt. There is one group with bottom water temperatures <0°C and another concentration of data points between -0.5 and 3°C. Surface T's are spread mostly between 3 and 10°C. There is a further scattering of surface values, with T's >4°C, toward low salinities. A few stations with bottom water temperatures ~0°C and S's >33 ppt deviate from the mass of points. It has long been known that the main flow in the northern Bering Sea is northward through Bering Strait into the Arctic Ocean. Coachman and Shigaev (Subchapter 2.1, this volume) trace a primary pathway of this flow. Water from the Bering Slope Current, which flows northwestward along the continental shelf edge of the eastern Bering Sea Shelf (Kinder *et al.*, 1975), crosses the continental shelf southwest of St. Lawrence Island in the Gulf of Anadyr. The flow maintains itself as a current (transport ~0.5 to 1 Sv) circumnavigating the gulf because its dynamics are analogous with those of a western boundary current (Kinder *et al.*, 1986). From the Strait of Anadyr, the flow follows the western side of Chirikov basin, transits Bering Strait, then curves northeastward into Kotzebue Sound before being steered by the topography to the north and west.

The second main regional flow is that of coastal water on the east, entering through Shpanberg Strait east of St. Lawrence and hugging the Alaskan coast northward through Bering Strait, around Kotzebue Sound, and then northwest passed Pt. Hope and Cape Lisburne. Between these flows is advected a third water mass of shelf water; because this water mass is made on the large Bering Sea Shelf south of St. Lawrence through mixing of dilute coastal water with the more saline Bering Sea continental slope water, it is identifiable as a separate water mass by its intermediate values of salinity; it is also the coldest of the water masses in summer south of Bering Strait (cf. Coachman *et al.*, 1975).

The *Korolev* data provide the first quasi-synoptic coverage of all these water masses within the region, thus allowing quantitative assessment of the changes in temperature and salinity as they are advected northward from the Bering Sea into the Chukchi Sea. We now examine the water mass modifications basin by basin.

Gulf of Anadyr

All CTD stations from the Gulf of Anadyr, together with Station 6 from the continental slope south of the gulf, are plotted in Fig. 2a. The latter is in the Bering Slope Current and thus shows the characteristics of this source water to the gulf. It has a water mass curve typical of the current; that is, a temperature minimum of ~2°C at S ~ 33.2 ppt, forming a "V" in T/S space, below which is a T maximum (T ~ 3.8°C at S ~ 33.7 ppt) followed by a T decrease and S increase to the deep basin bottom water type (T ~ 1.6°C; S ~ 34.7 ppt).

Surface temperatures in the gulf are typically 6 to 8°C at this time of year, with salinities spread over the range 31.5 to 33 ppt. The spread in values reflects the nonconservative nature of properties in the upper layer with exchange across the sea surface, true in particular for temperature.

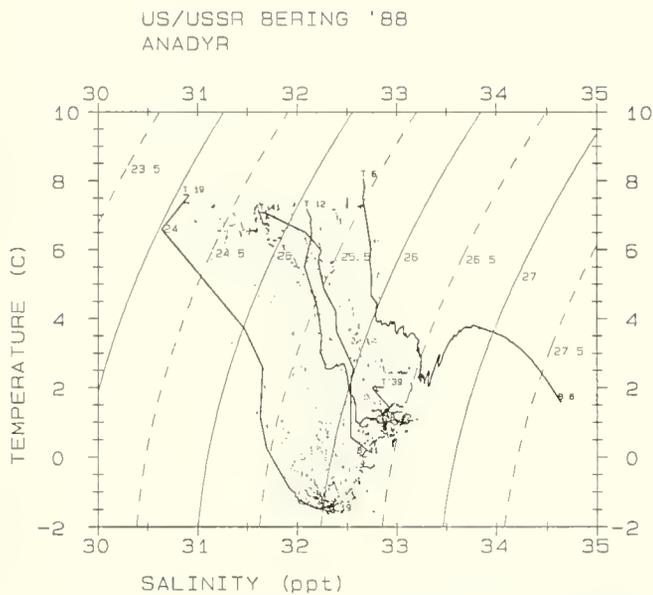


Fig. 2a. All CTD data (1-m average values) from the Gulf of Anadyr and Anadyr Strait stations, and Station 6 from the Bering Slope Current.

Localized sources of dilution, the main source of freshwater being the Anadyr River entering midway along its western boundary, contribute to the spread in salinity values. Horizontal mixing of waters of the surface layer is evidently small.

Bottom water values, on the other hand, are bunched much more tightly and cluster into two groups. One grouping is of cold water, $<0^{\circ}\text{C}$, in the salinity range ~ 32 to 32.7 ppt. The second group is warmer, ~ 0 to 2°C , and more saline, 32.7 to 33.3 ppt. When the spatial distribution of these stations is examined (cf. Frontispiece), we see that the stations of the cold, lower S group are all from the middle of the gulf, centered around Stations 18 and 19, while the stations with warmer and more saline deep water are from around its perimeter, including Stations 12, 13 through 25, 26, 29, 31, and 33 to 38.

Temperatures and salinities of the waters beneath the surface layer are conservative and are modified only through vertical and horizontal (lateral) mixing as the water masses transit the gulf. To expose the source water characteristics and their modifications within the gulf, Fig. 2b plots stations representative of each key water mass and location. The extreme of cold, lower salinity water is represented by Stations 18 and 19, from the central gulf. The temperatures are only about 0.1 to 0.2°C above freezing. This water is that of the "cold center" of the Bering Sea, identified already by Barnes and Thompson (1938). The water entering the gulf as the Anadyr Current is represented by Stations 12 and 13 close to Cape Navarin. This water is from the Bering Slope Current (Station 6), which is the source of highest salinity water to the gulf; the source level lies in the depth range ~ 50 – 200 m of the current. When the water mass enters the gulf off Cape Navarin, its characteristics are $T \sim 1$ to 2°C , $S \sim 32.5$ to 33 ppt. Thus, its properties have already been significantly modified in the 150 km transit across the shelf from the continental slope, not through surface exchange but through mixing with colder and less saline shelf water—the deep layers have been cooled ~ 1.5 to 2°C and freshened ~ 0.5 ppt.

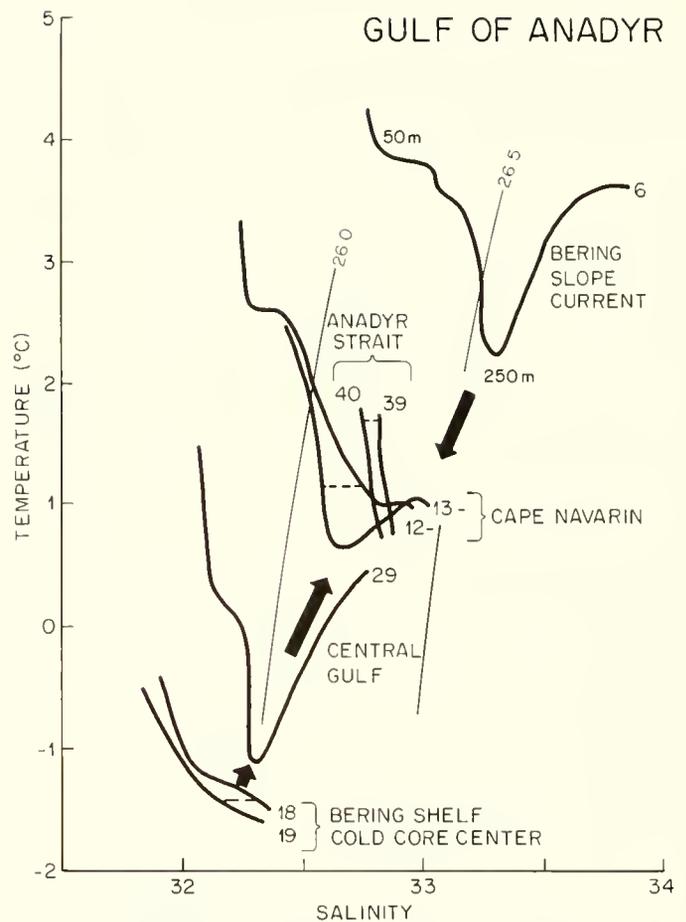


Fig. 2b. T/S diagram of key stations from the Gulf of Anadyr; solid arrows indicate directions of major modifications. Most surface layer values are not plotted. Water flowing north through Anadyr Strait is created from Bering Slope Current water by mixing with cold Bering Shelf water. The interaction is a two-stage process, first lateral layering (cf. Station 29) followed by vertical mixing.

This water mass then circumnavigates the perimeter of the Gulf of Anadyr following the bathymetric contours and interacting with water of the "cold center" enroute. The interaction is in two stages. First is a horizontal layering, or interleaving, of the less dense "cold center" water laterally above the denser water from the Bering Slope Current (now the Anadyr Current). Station 29, halfway around the gulf, clearly illustrates this stage of the interaction. Then vertical mixing becomes more effective, particularly as the water masses are required to shoal to 50 m as they enter Anadyr Strait, and the result is homogenization into narrow ranges of T and S. When the water exits the gulf through Anadyr Strait it has essentially median values of T and S (Stations 39, 40). The two-stage interaction, layering followed by effective vertical mixing, conforms precisely with the model of water mass modification in the gulf proposed by Coachman *et al.* (1975).

Chirikov basin

All CTD data from the Chirikov basin, including Stations 39–43 from Anadyr Strait and 76–86 from Bering Strait, are shown in Fig. 3a. There is a concentration of bottom water values with temperatures ~ 1 to 3°C in the S range 32.2 to 32.9 ppt. From these values, the remainder trend toward

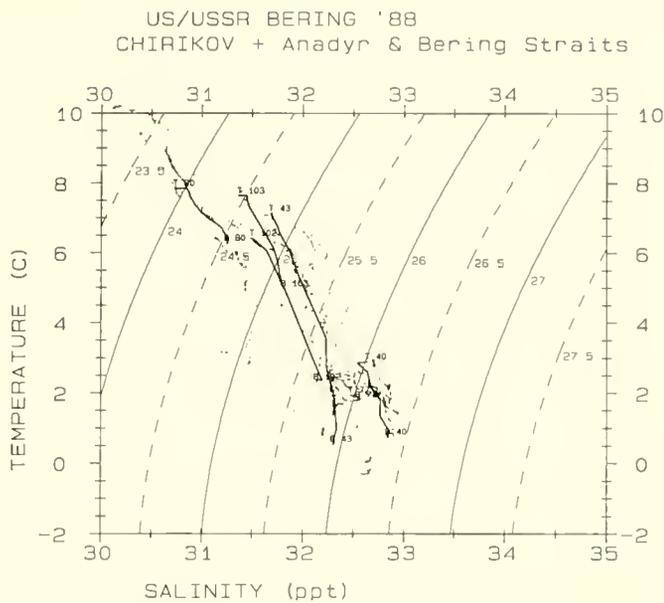


Fig. 3a. All CTD data (1-m average values) from the Chirikov basin, including Anadyr and Bering Straits.

warmer and less saline values (to the upper left in the T/S plane). Likewise, surface water values lie along the same general trend line. When the spatial distribution of stations is examined, we see that the colder, more saline water is associated with stations from the west side of the basin, while the warmer, least saline water is all on the eastern side.

The Chirikov basin is a little shoaler on the east side, 30 m grading downward to nearly 50 m off Siberia. The freshwater sources to the water masses in the basin are essentially confined to the eastern side — the Yukon River and other runoff from the Alaskan coast. The freshwater generates layering in the water masses of the eastern portion of the basin, and together with the shorter water columns, seasonal insolation is very effective in warming, producing temperatures up to 12°C in the upper layer (in contrast with maxima of ~8°C in the Gulf of Anadyr).

The coldest, most saline water is water of the Anadyr Current entering through the Strait of Anadyr (see above), and also shelf water from south of St. Lawrence Island (cold, relatively saline shelf water is probably also entering the basin around the eastern end of St. Lawrence, through the west side of Shpanberg Strait, but the *Korolev* data do not cover Shpanberg Strait).

To illustrate quantitatively the modifications occurring in the basin, Fig. 3b plots key stations. There is a salinity gradient of more than one-half ppt across Anadyr Strait. The most saline water is from the Anadyr Current (Station 39, cf. Fig. 2b). On the east side (Stations 42, 43), though, the waters are both less saline and colder—this is shelf water from south of St. Lawrence Island, which is originally Bering Slope water that has been in residence on the huge shelf south of St. Lawrence where it has become diluted to a small degree by a freshwater admixture from the Alaskan Coastal water (see Coachman & Shigaev, Subchapter 2.1, this volume) and further modified in winter by products from freezing activity in the perennial polynya south of St. Lawrence (Schumacher *et al.*, 1983). This is the origin

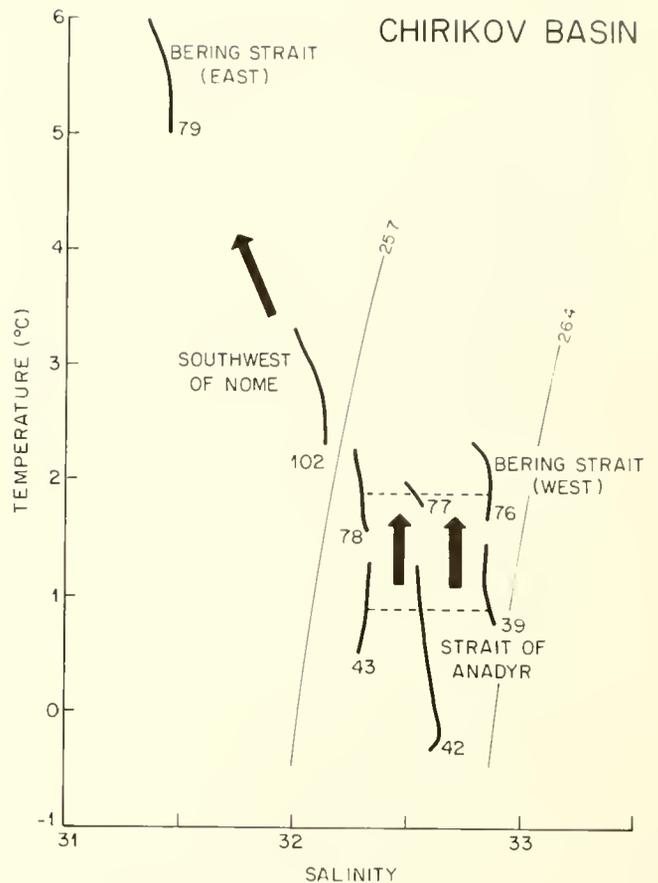


Fig. 3b. T/S diagram of key stations from the Chirikov basin, illustrating the major water mass modifications therein. No change in salinity of the water on the western side indicates no lateral mixing; only deeper temperatures are raised through vertical mixing. On the east, small lateral as well as vertical mixing makes Alaskan Coastal water less saline, warmer, and a little less dense.

also of the “cold center” water. The flow through the eastern part of Anadyr Strait is of this shelf water mass, not pure Anadyr water, giving rise to the cross-strait gradient in salinity.

The three stations across the western channel of Bering Strait, Stations 76 on the west to 78 near large Diomed Island, illustrate the characteristics of these water masses after transiting Chirikov basin. The cross-strait salinity gradient is precisely the same as in Anadyr Strait, only the waters have warmed—minimum temperatures are now about 1.5°C instead of <0°C. We can interpret that modification of the water masses flowing northward through the middle and western part of the basin includes no significant lateral mixing—there is no evidence of any interaction between adjacent water masses within the flow, nor any reduction in salinities by admixtures of Siberian Coastal runoff on the west or fresher Alaskan Coastal water on the east. The only significant mixing is vertically in the water columns, which by mixing down warmer surface water has raised bottom temperatures by ~1°C.

Alaskan Coastal water on the east side of the basin, not as well covered by *Korolev* data, is illustrated by Station 102 taken about halfway between Nome and St. Lawrence Island (see Fig. 1). This water is the warmest and least saline of the water masses, and the closer to the Alaskan coast, the warmer

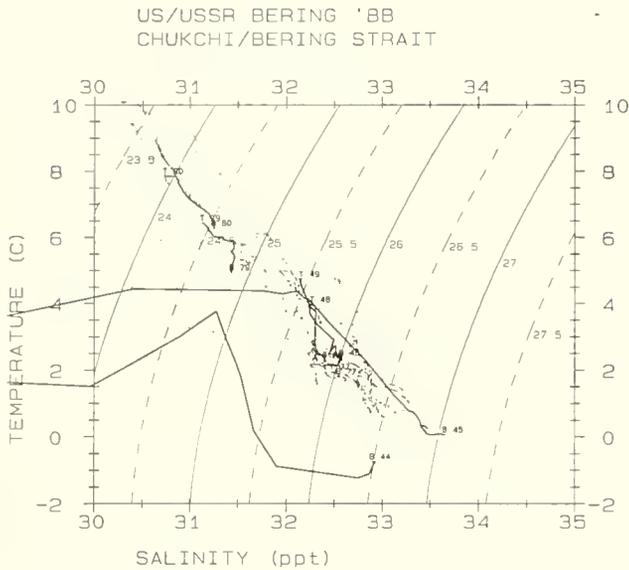


Fig. 4a. All CTD data (1-m average values) from Bering Strait and southern Chukchi Sea.

and fresher it becomes; this accounts for the trend of data points in Fig. 4a from about 3°C, 32 ppt, toward 12°C, 30 ppt. The flow is northward paralleling the coast, then through the eastern channel of Bering Strait, where its characteristics are illustrated by Station 79. Thus, the modification of the waters on the eastern side of the basin involves both lateral and vertical mixing. Salinities are reduced by about 1 ppt in transit through admixing with fresher waters closer to shore, ultimately of course due to substantial coastal runoff. As temperatures are in general higher in the shallower waters near shore, the lateral mixing also gives rise to some warming. Water temperatures are also increased through vertical mixing, as with the waters on the western side, and undoubtedly the warming is more effective in the shallower waters of the eastern side. Between the two effects, T increases are of the order of 3°C. We note that the mixing processes on the eastern side are diapycnal, leading to decreases in water densities, which is not true of the modifications in the west. The reason for this is the difference in effects of salinity and temperature on density; salinity is much more important in "controlling" density in cold water (cf. slopes of isopycnals in Fig. 2b).

Chukchi Sea

All CTD data from the Chukchi Sea are plotted in Fig. 4a. Similarly to the Chirikov basin, there is a concentration of bottom values in the salinity range ~32.2 to 32.9 ppt, but the temperatures of this water are slightly warmer than to the south, ranging from ~1.5 to 4°C. From this concentration, data points extend in two directions. One trend is toward warmer and fresher, toward ~10°C and 30 ppt, much like the trend in the Chirikov basin data (cf. Fig. 3a). These data are from the water masses that have entered the Chukchi Sea from the south, through the Bering Strait; salinities have not been modified appreciably since transiting Bering Strait, but the small warming indicates that heat continues to be added to the bottom water through vertical mixing.

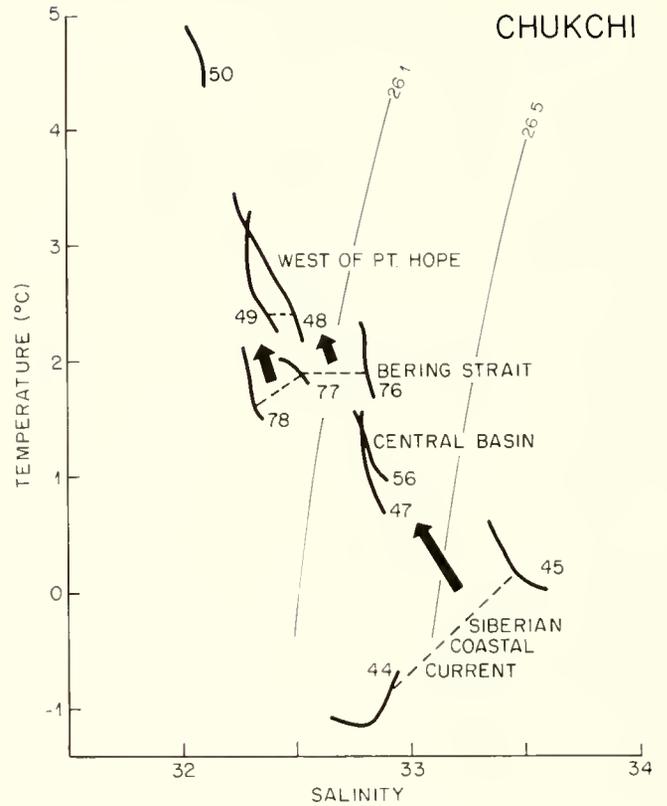


Fig. 4b. As with Figs. 2b, 3b, but illustrating the major water mass modifications occurring in the southern Chukchi Sea. The lateral and vertical mixing processes found in the eastern part of the Chirikov basin continue to modify the water masses flowing northward through Kotzebue Sound and passed Pt. Hope. A colder, more saline water mass indigenous to the Chukchi Sea is advected southeast by the Siberian Coastal Current, then circulates cyclonically and mixes with the water flowing north through Bering Strait.

The other trend is toward a colder and more saline water type, ~33.5 ppt and 0°C. This is water that appears nowhere south of the Bering Strait, so must be indigenous to the Chukchi Sea. The only water south of Bering Strait with $S > 33$ ppt is in the Gulf of Anadyr and was not observed north of Anadyr Strait, which positively rules out the northern Bering Sea as a possible source for this relatively cold, high salinity water.

Key stations illustrating the water masses in the southern Chukchi Sea are plotted in Fig. 4b. The current flowing northward through Bering Strait trends eastward into Kotzebue Sound, then turns north and west and flows passed Pt. Hope into the northern Chukchi Sea (cf. Coachman *et al.*, 1975, Chap. 4). The core of flow of this water, that with the highest salinities, is water transiting the western channel of Bering Strait (Stations 76–78; cf. Fig. 3b). This water is observed west of Pt. Hope at Stations 48 and 49. The water east of this core flow, between it and the Alaska coast (represented west of Pt. Hope by Station 50), is all less saline and warmer, and creates the data trend exposed in Fig. 4a. In traversing Kotzebue Sound (a distance of ~350 to 400 km) salinities of the core water have been reduced a little, about 0.2 to 0.3 ppt, and bottom temperatures have been increased a further 0.5°C. Thus, both vertical mixing and a small amount of lateral

mixing, as obtained throughout the eastern part of Chirikov basin, continues to modify these water masses from the south as they traverse the southern Chukchi Sea.

The relatively cold, saline water that is not coming from the south is found in the central and western parts of the southern Chukchi Sea; in the *Korolev* data the extreme values are from Stations 44 and 45, north of Kolyuchin Bay on the Siberian Coast (cf. Frontispiece). Current measurements (Coachman & Shigaev, Subchapter 2.1, this volume) indicated this water was flowing southeast, parallel with the Siberian coast, the so-called Siberian Coastal Current. This current is advecting the cold, high S water into the southern Chukchi Sea from somewhere in the northwest, perhaps near Long Strait (between Wrangel Island and the mainland). The flow did not, however, continue southeast as far as Bering Strait; no water with $S > 32.9$ ppt was observed there.

Thus, the Siberian Coastal Current separates from the coast before reaching Bering Strait, and curves eastward into the central part of the southern Chukchi Sea. Waters in the middle of the region, midway between Alaska and Siberia (Stations 47, 56), indicate considerable mixing has taken place between this cold, saline water, and the core water of the northward flow from Bering Strait that lies around the east and north sides of the central region. The interaction has reduced salinities of the Siberian Coastal water in the central region to ~ 33 ppt and warmed the mass by 1 to 2°C .

We note the situation in August 1988 is undoubtedly the normal summer flow pattern; however, under rare conditions it appears that the Siberian Coastal Current can penetrate farther southeast, as far as Bering Strait. Ratmanov (1937a) observed cold, saline water near Cape Dezhneva in summer 1933, but it was not moving southward through the strait. There is no evidence that this water ever penetrates into the Chirikov basin.

Summary of Modifications

The quantitative changes in temperature and salinity characteristics of the water masses as observed in August 1988 are summarized in Table 1. The changes are in characteristics of the water layers below the surface layer, which are conservative (i.e., T and S values are altered by the processes

of advection and diffusion only). The surface layer properties are affected also by surface exchange; in summer they are warmer and less saline than the deeper waters and much more variable.

Table 1 shows, in addition to the approximate T and S change, the estimated distance over which the change has taken place and the property value change per km. The latter statistic gives an idea of the effectiveness of the mixing in that part of the regime; comments list the major processes acting.

The greatest changes in water mass properties take place at the beginning, where the Bering Slope Current water crosses the outer shelf on its way into the Gulf of Anadyr. Layering of cold, less saline shelf water with warmer, more saline slope water, followed by vertical mixing, are effective in reducing S's and T's and, ultimately, creating the quite uniform Anadyr water mass, which is advected on northward through Bering Strait. The energy for the mixing is from shear in the Anadyr Current, generated both laterally as the current circumnavigates the gulf and vertically in the shoaling water columns.

Across the Chirikov basin the major mixing is vertical; this process is stronger on the east side in the shallower water. Lateral mixing is small; there is essentially none in the west, and it is small in the east, leading to small reductions in S of the coastal water. These same processes continue to modify Anadyr/Bering Shelf and Alaskan Coastal waters in the southern Chukchi Sea at about the same rate.

Siberian Coastal water, indigenous to the Chukchi Sea, enters the southern part of the sea from the northwest, and then apparently circulates in a cyclonic gyre, interacting with Anadyr water around its east and north sides. The interaction seems moderately active and analogous with that in the Gulf of Anadyr; first a layering and interleaving of the water masses (densities differ by ~ 0.5 st), followed by vertical mixing.

We acknowledge the help of Margaret Lavender both in the field and in data reduction. Captain O. A. Rostovstev and Chief Scientist, Professor A. V. Tsyban, deserve special thanks, as does all the crew of the *Korolev*. Viktor Shigaev was a great help in liaison and interpretation, and the skill of hydrographic specialists Sergei and Anatoly was much appreciated. The senior author is indebted to Dr. R. S. Jones for allowing his participation in the cruise and for use of the UTMSI equipment aboard the *Korolev*. This is Contribution No. 777 of the Marine Science Institute, University of Texas.

TABLE 1

Water Mass Property Modifications (Summer).

	km	Change per km ($\times 10^3$)				Comments
		ΔS (ppt)	ΔT (C)	T	S	
Gulf of Anadyr						
Bering Slope Cur. to C. Navarin	150	-0.4	-1.5	2.7	10.0	lateral & vertical mix. with shelf water
C. Navarin to mid-Gulf	250	-0.3	-.05	1.2	2.0	layering: small vertical mixing
mid-Gulf to Str. of Anadyr	250	-0.2	+0.5	0.8	2.0	vertical mixing (homo- genization)

"cold core" Water	500	+0.6	+2.0	1.2	4.0	layering, then vert. mix. in Anadyr curr.
Chirikov basin						
Anadyr to Bering Strait	280	0.0	+1.5	0.0	5.4	vertical mixing
Alaskan Coastal	180	-0.6	+2.5	3.3	14.0	strong vertical mix; lateral mix. with runoff
Chukchi Sea						
Anadyr/Bering Shelf to Pt. Hope	380	-0.2	+0.5	0.5	1.3	vertical mix.; small lateral mix. with runoff
Siberian Coastal to mid-basin	220	-0.2	+1.5	0.9	6.8	lateral mix. with Anadyr; vertical mixing

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Chapter 3:

HYDROCHEMISTRY

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3.1 Biogenic Nutrient Content

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Introduction

The early investigation of the biogenic nutrient content of Bering Sea waters have shown these elements that are necessary for phytoplankton growth to often be present in surface waters in quite high concentrations (Barnes & Thompson, 1938). More recently, the Processes and Resources of the Bering Sea Shelf (PROBES) program did an exhaustive study of the physical–biological ecosystem dynamics of the southeastern Bering Sea Shelf. Over a five-year period, the nutrient content across the shelf was observed to be related to three frontal systems that governed the nutrient dynamics in the open ocean, outer shelf, middle shelf, and inner shelf (Coachman, 1986; Whitledge *et al.*, 1986).

The later program of Inner Shelf Transfer and Recycling (ISHTAR) further investigated the transport of water and nutrients through the northern Bering Sea into the Chukchi Sea and studied the primary production/decomposition processes that occurred in the Alaskan Coastal water, Bering Shelf water and Anadyr water (Walsh *et al.*, 1990). The Third Joint US–USSR Bering & Chukchi Seas Expedition in 1988 was a tremendous enhancement to the ISHTAR sampling program, which had previously lacked a complete and quasi-synoptic sampling of all of the above water masses.

The biogenic nutrient content is indicative of the potential primary production that may occur in seawater and therefore is used to assess one of the major factors controlling primary food production in the marine environment. The concentration of nitrogen, in the form of nitrate and ammonium, is particularly useful because most oceanic environments contain small concentrations of nitrogen relative to phosphorus and silicon and is often thought to limit rates of primary production (Ryther & Dunstan, 1971). The uptake of biogenic nutrients along with carbon dioxide and light is important as fuel for primary production processes. The production of nutrients by regenerative processes must also be considered because the nutrients present in seawater are replenished on a continuous or periodic basis. These regeneration processes maintain the long-term primary production of an ecosystem especially on continental shelves where benthic regeneration also contributes nutrients to the euphotic zone. The biogenic nutrient content of water in the Bering and Chukchi Seas in general is high, reflecting its origin in the North Pacific Ocean. The deep Bering Sea, where few biological measurements have been taken, maintains high nutrient concentrations throughout the

year, and plant biomass represented by chlorophyll is small. The continental shelf, which comprises about 45% of the area of the Bering Sea, varies from high to low nutrient concentrations as the annual cycle of primary production occurs (Whitledge *et al.*, 1986).

The primary purpose of this paper is to describe the nutrient, oxygen, and pH variations of the south and east regions of the deep Bering Sea, the northern Bering Sea Shelf and the southern Chukchi Sea (Frontispiece). All of these areas were sampled on the Third Joint US–USSR Bering & Chukchi Seas Expedition in 1988 as a part of a program to investigate the ecology and health of the Bering and Chukchi Seas.

Methods

Water samples were collected on the upcast with a Sea-Bird CTD/rosette sampler. Water samples were immediately collected in polyethylene scintillation vials and were analyzed on a model 300 Alpkem segmented flow analyzer at 80 samples per hour. The analytical techniques were adapted to small volume glassware from previously described methods (Whitledge *et al.*, 1981). The basic analytical methods were described by Armstrong *et al.* (1967) for nitrate, phosphate, and silicate. Ammonium was measured by the phenohypochlorite method of Koroleff (1970) as adapted to a continuous analyzer by Slawyk and MacIsaac (1972) and modified by Patton and Crouch (1977). Standard Winkler titrations were used to determine the concentration of dissolved oxygen.

Results

Northern Shelf Regions

The physical transport of water from the North Pacific into the deep Bering Sea moves eastward and north in a counter-clockwise gyre until it nears the coastline of the Soviet Union where it bifurcates and a northern segment flows through the Gulf of Anadyr toward Bering Strait (Whitledge *et al.*, 1988). This long-term net movement of water carries a large quantity of biogenic nutrients from the deep Bering Sea onto the shallow northern shelf of the Bering and Chukchi Seas where primary production processes consume them. The northern flow of water varies from about 0.5 to 1.0 Sv and produces bathymetrically induced upwelling as a result of the 30–50 m water depths of the shelf.

The temperature and salinity distribution clearly define the general circulation patterns between the Gulf of Anadyr and the southern Chukchi Sea. The differential between surface and bottom water was as large as 8.5°C and 1.5 ‰ salinity in the Gulf of Anadyr (Fig. 1A,B) but decreased to less than 1°C and 0.5 ‰ in Chirikov basin after passing through Anadyr Strait. The low salinity (Fig. 1C,D) Alaskan Coastal waters and Bering Shelf waters maintain their eastern positions and reduced salinities throughout northward transport (Coachman & Shigaev, Subchapter 2.1, this volume). The relatively low temperature bottom water denoted by the -1.5°C isotherm delineates the cold high-salinity water formed during the previous winter months by production of ice. The presence of this cold water indicates the slow circulation velocities on the eastern Bering Sea Shelf. Accumulation of benthic regeneration products can occur in these waters.

The nitrate content of the surface water (Fig. 2A) displays a pattern of reduced concentrations where the waters are stratified in the Gulf of Anadyr and Chukchi Sea. The largest surface concentrations of nitrate occur in the Chirikov basin after upwelling and mixing in Anadyr Strait, especially on the west side along the Soviet coastline, and extend into the southern Chukchi Sea. These very large surface concentrations support the high primary production rates reported in the Bering Strait region (Sambrotto *et al.*, 1984). Near bottom nitrate concentrations (Fig. 2B) originating in the deep Bering Sea provide a substantial part of the nitrogen to feed primary production processes. The nitrate values larger than 30 $\mu\text{mole/l}$ are quite unusual for a shallow shelf region; even coastal upwelling regions seldom have greater than 15–20 $\mu\text{mole/l}$ inside the shelf break. Concentrations of near bottom nitrate above 30 $\mu\text{mole/l}$ disappear at Anadyr Strait

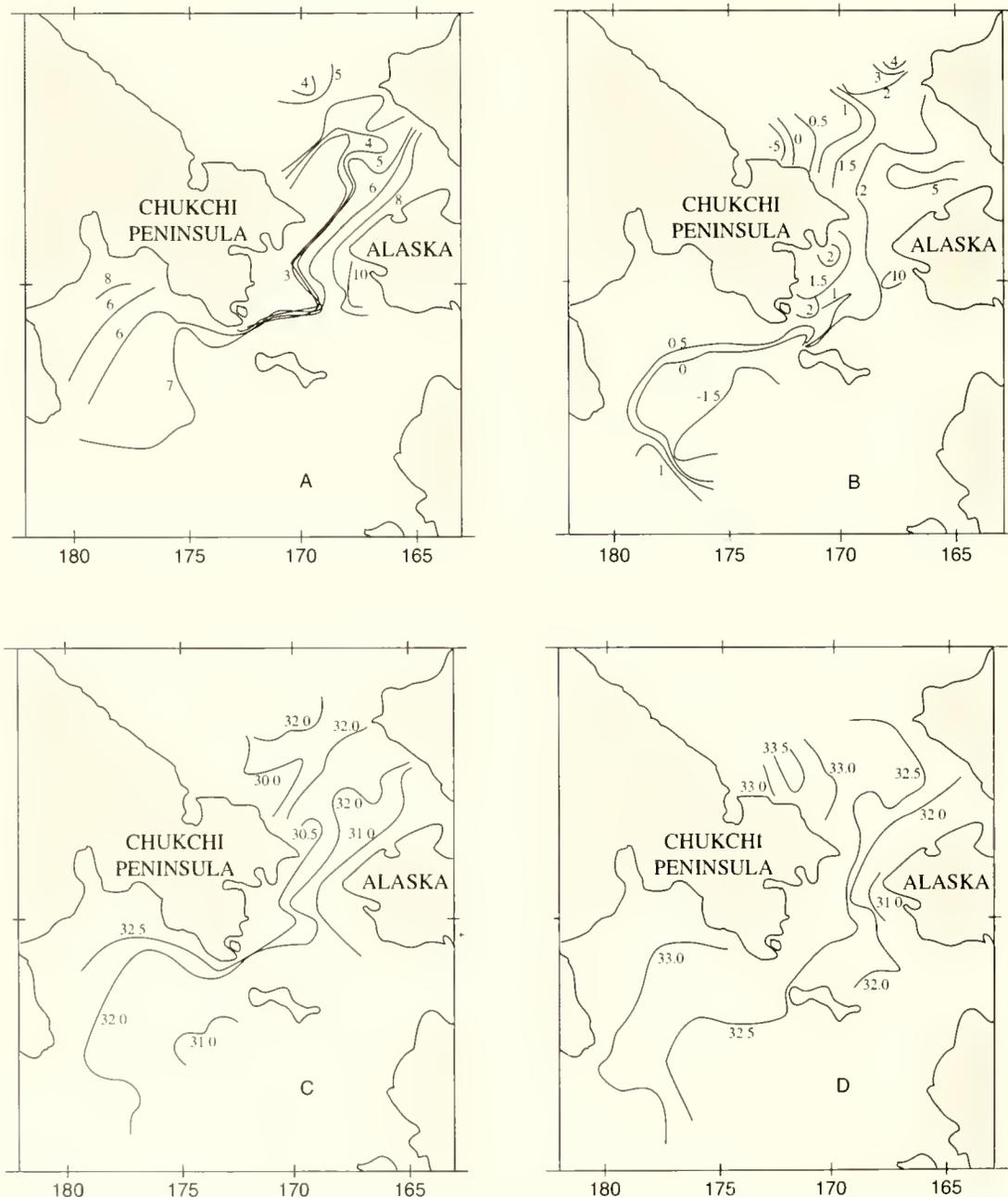


Fig. 1. The surface (A) and bottom (B) distribution of temperatures (°C), surface (C) and bottom (D) distribution of salinity (‰) measured in the northern Bering and Chukchi Seas.

probably as the result of strong vertical mixing; however, values larger than 20 $\mu\text{mole/l}$ were observed on the west side of all three regions (Gulf of Anadyr, Chirikov basin, Chukchi Sea). The presence of these large near-bottom nitrate concentrations are almost certainly due to some nitrification (ammonium conversion to nitrate by bacteria) occurring in the Chirikov basin and Chukchi Sea.

Ammonium, the regenerated form of nitrogen, was found to have very low concentrations (Fig. 2C) in surface waters. The very high affinity of phytoplankton to ammonium reduces concentrations to very low levels unless unusually large surface ammonium regeneration rates are occurring. The bottom ammonium concentrations (Fig. 2D) reflect the active nature of nutrient regeneration in the near bottom waters and sediments. Decomposition of organic matter releases large amounts of

ammonium especially where high primary production/deposition is occurring. This process is best shown in the central Chukchi Sea and to a smaller extent in the western Chirikov basin. Remember that the east side of the Bering and Chukchi Seas has very small organic production rates compared to the western portions. The highest near bottom ammonium concentrations were found in the low temperature "winter water" in the Gulf of Anadyr and along the Soviet coast in the Chukchi Sea. These large ammonium concentrations reflect the accumulation that occurred over the several months since the cold water was produced. In both cases more than 4 $\mu\text{mole/l}$ concentrations were observed in the two regions. The Gulf of Anadyr ammonium probably contributes to the surface increases of ammonium that are observed downstream after vertical mixing in Anadyr Strait.

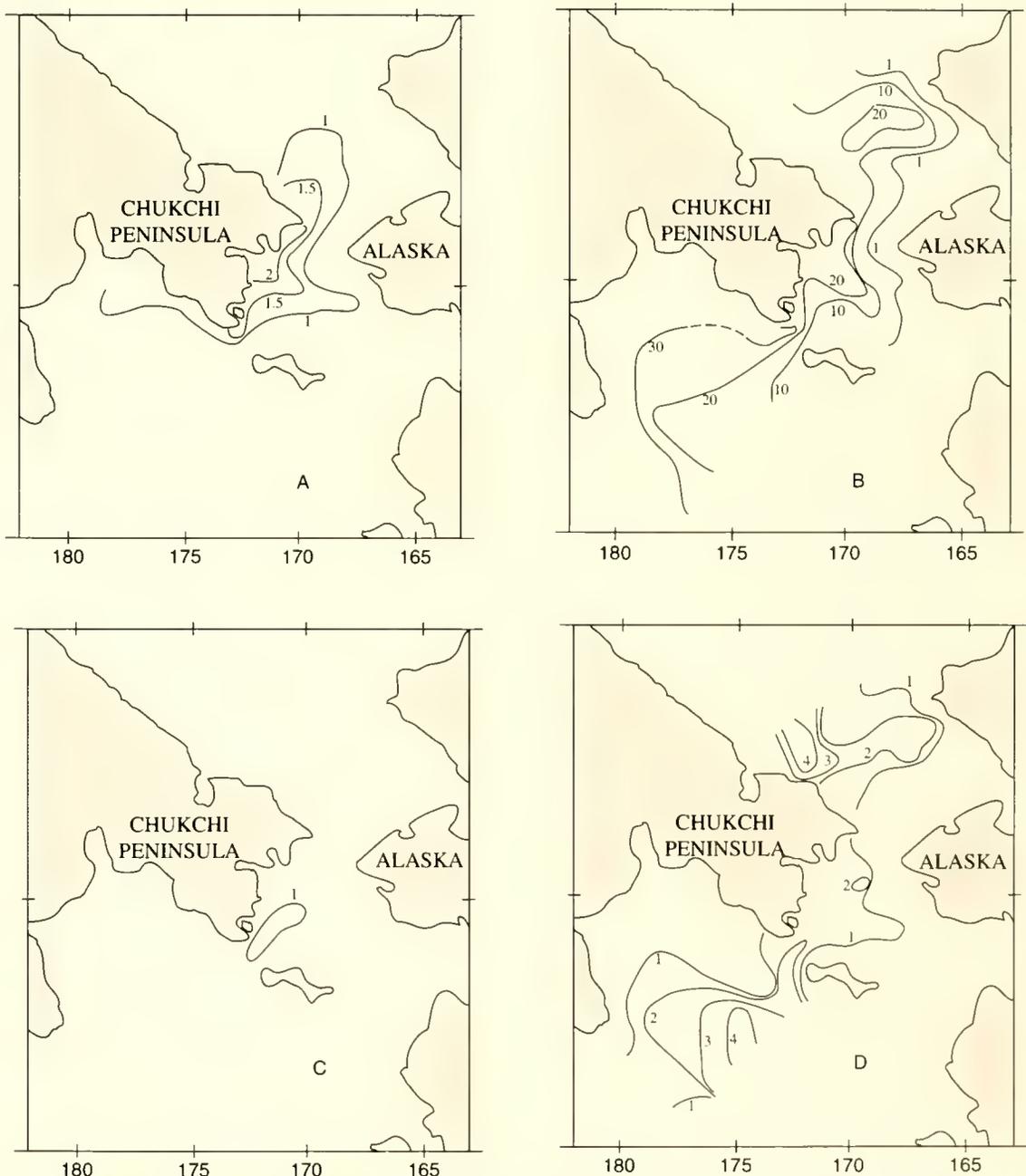


Fig. 2. The surface (A) and bottom (B) distribution of nitrate ($\mu\text{mole/l}$), the surface (C) and bottom (D) distribution of ammonium ($\mu\text{mole/l}$) measured in the northern Bering and Chukchi Seas.

The surface silicate concentrations (Fig. 3A) are similar to those of nitrate, especially the strong east–west gradient in the Chirikov basin. Silicate is mainly utilized by diatom populations but other phytoplankton may also have a silicate requirement. Even the areas where high silicate concentrations have been reported in river discharge contained less than 5 $\mu\text{mole/l}$. Near-bottom silicate concentrations (Fig. 3B) reflect the large concentrations present in deep Bering Sea water with values above 50 $\mu\text{mole/l}$. Vertical mixing in Anadyr Strait and subsequent uptake by phytoplankton reduce concentrations to the range of 10–30 $\mu\text{mole/l}$. The east side of the ecosystem all had values less than 10 $\mu\text{mole/l}$.

The surface phosphate concentrations (Fig. 3C) were adequate to support primary production processes throughout the area of investigation. Areas with phosphate concentrations

less than 0.5 $\mu\text{mole/l}$ also contained small amounts of nitrate and silicate; therefore, phosphate was always in plentiful supply compared to other nutrient forms. Near-bottom phosphate concentrations (Fig. 3D) reflect both the enrichment from the deep Bering Sea into the Gulf of Anadyr and the cumulative effects of phosphate regeneration in the Chirikov basin and Chukchi Sea.

The Gulf of Anadyr serves as the conduit for flow of water from the deep Bering Sea into the confined Chirikov basin. The center of the Gulf of Anadyr is stratified with the warmer surface waters depleted of nutrients (Fig. 4), but near the coast, all isopleths rise toward the surface, indicative of active coastal upwelling. Surface concentrations of all nutrients were low enough to reduce primary production. The highest chlorophyll measured in this region (24–28 $\mu\text{g/l}$) was on Station 26 at a

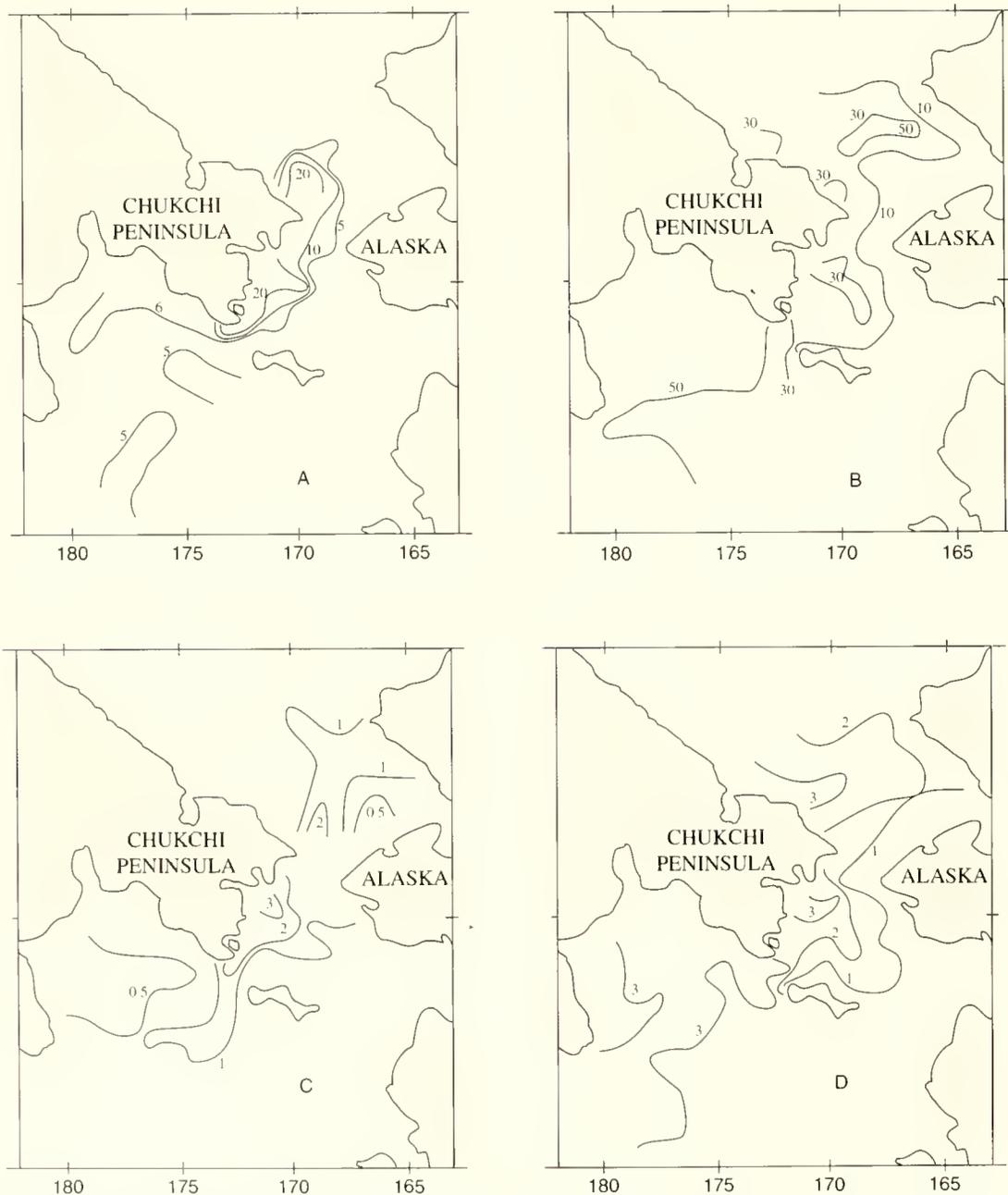


Fig. 3. The surface (A) and bottom (B) distribution of silicate ($\mu\text{mole/l}$), the surface (C) and bottom (D) distribution of phosphate ($\mu\text{mole/l}$) measured in the northern Bering and Chukchi Seas.

depth of 20–25 m, which coincides with the upwelling area, but the phytoplankton population was so great that nitrate, silicate, ammonium, and phosphate were reduced to 10.3, 1.2, 0.1, and 1.4 $\mu\text{mole/l}$ respectively. The outer end of this transect was located in the near-bottom winter shelf water as indicated by the ammonium signature (Fig. 4B).

The Chirikov basin receives water from the Gulf of Anadyr after nearly complete vertical mixing occurs throughout the water column in Anadyr Strait (Fig. 5). The very uniform vertical nutrient concentrations on the western end of the transect changes into a stratified system near the middle where Bering Shelf waters and Alaskan Coastal waters are encountered. The strong east–west gradients are the products of the lack of flow from the deep Bering Sea and the little vertical mixing in Shpanberg Strait on the east side of St. Lawrence Island.

The Chukchi Sea receives the waters that flow through Bering Strait after passing through Chirikov basin (Fig. 6). The nutrient content of this northward flowing water has been reduced somewhat in the Chirikov basin, but the major portion remains to support primary production in the Chukchi Sea. The strong east to west gradient of nutrients remains similar to the more southern areas. The Chukchi transect of stations shows the large near surface concentrations of nutrients which corresponds to observations of the largest chlorophyll concentrations. Nitrate, ammonium, and phosphate

concentrations show enhancement near the Soviet coast, which probably results from a southward flowing Siberian Coastal Current (Coachman & Shigaev, Subchapter 2.1, this volume). The Alaskan Coastal water displays a low nutrient content consistent with more southern transects except silicate, which is enriched by about 10 $\mu\text{mole/l}$. Even though past observations have shown all nitrogen in the Yukon River was removed quickly in the Chirikov basin, this nearshore increase in silicate may be related to the Yukon River. This would be consistent with the distribution of carbon isotope and C/N ratios as reported by Scalan *et al.* (Subchapter 8.5.1, this volume).

The temperature–salinity diagram for all samples collected on the 1988 joint cruise (Fig. 7A) shows the very cold water below 0°C that falls into the salinity range of 32–32.7‰. The low temperature water between 0 and 0.5°C has a salinity of 33–33.5‰, so this must represent water that was formed during ice production, which increases the salinity.

The nitrate–salinity diagram for all samples (Fig. 7B) on the joint expedition fell predominantly in the salinity range of 32–32.5‰, and the nitrate varied from about 0.1 to about 40 $\mu\text{g-at/l}$. A few points deviated from this general distribution in low salinity water in the Alaskan Coastal Current that was depleted of nitrate and higher salinity samples from the deep Bering Sea where nitrate concentrations exceeded 50 $\mu\text{g-at/l}$.

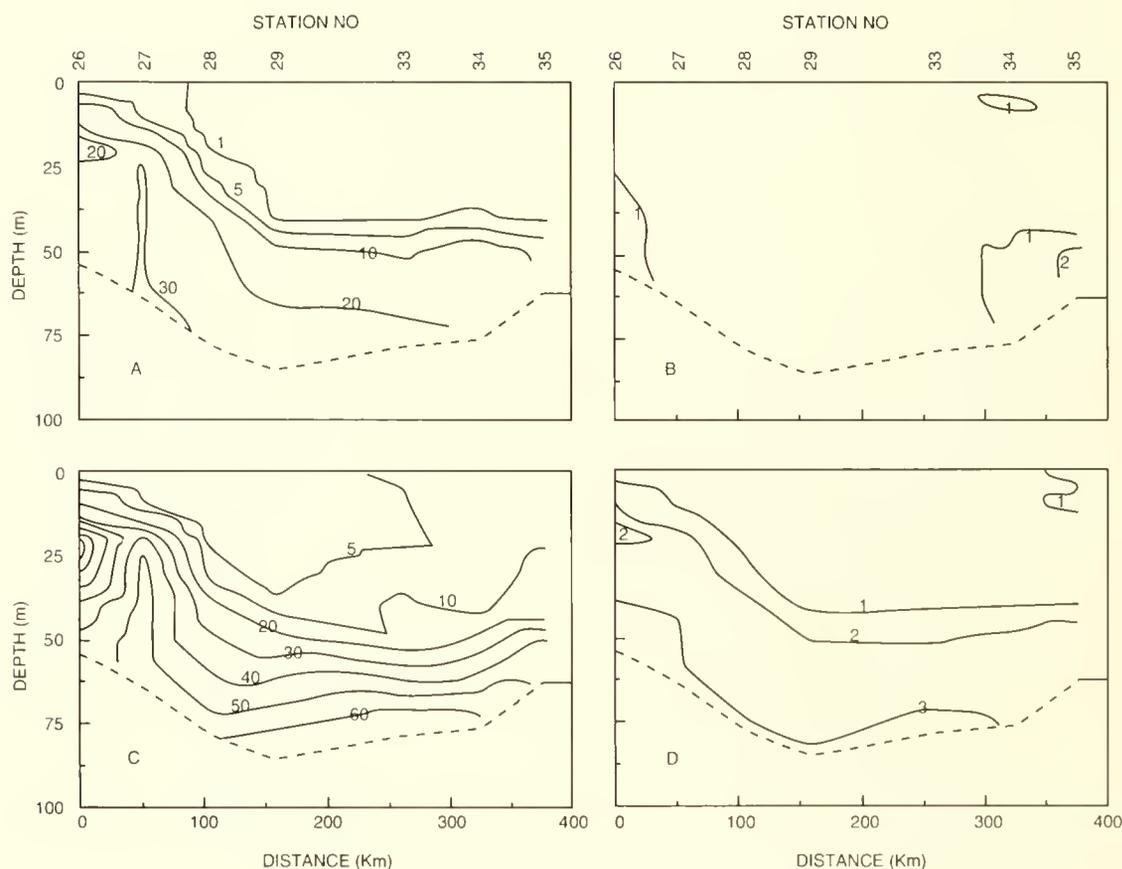


Fig. 4 The distribution of nitrate (A), ammonium (B), silicate (C) and phosphate (D) in a transect of stations across the Gulf of Anadyr. Units are $\mu\text{mole/l}$.

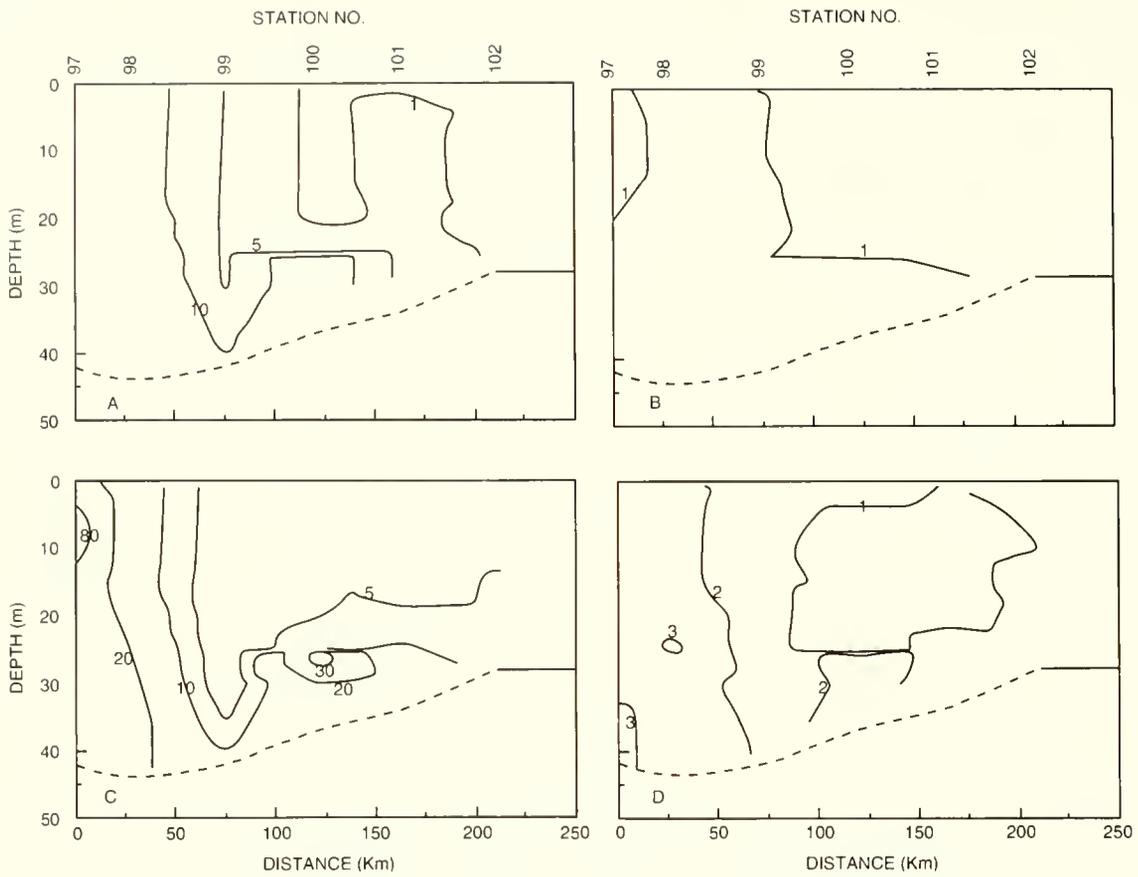


Fig. 5. The distribution of nitrate (A), ammonium (B), silicate (C) and phosphate (D) in a transect of stations across the Chirikov basin. Units are $\mu\text{mole/l}$.

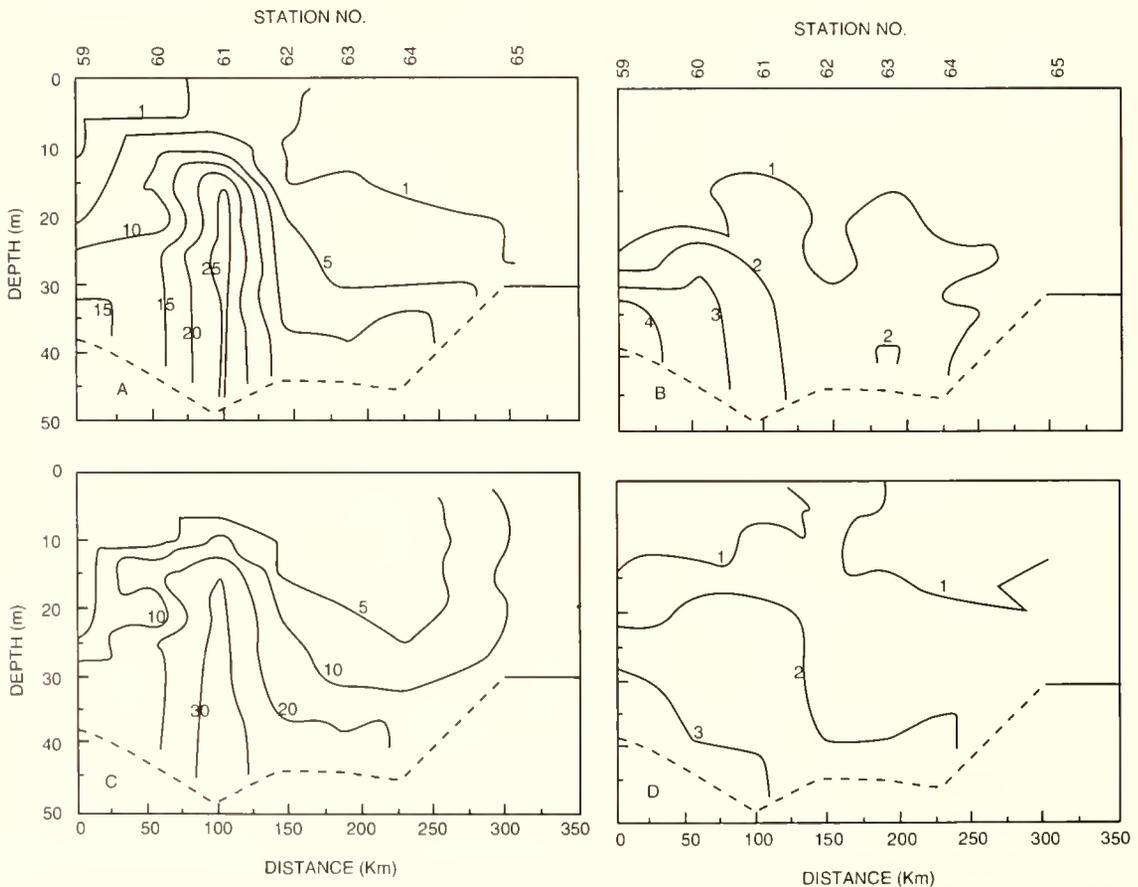


Fig. 6. The distribution of nitrate (A), ammonium (B), silicate (C) and phosphate (D) in a transect of stations across Chukchi Sea. Units are $\mu\text{mole/l}$.

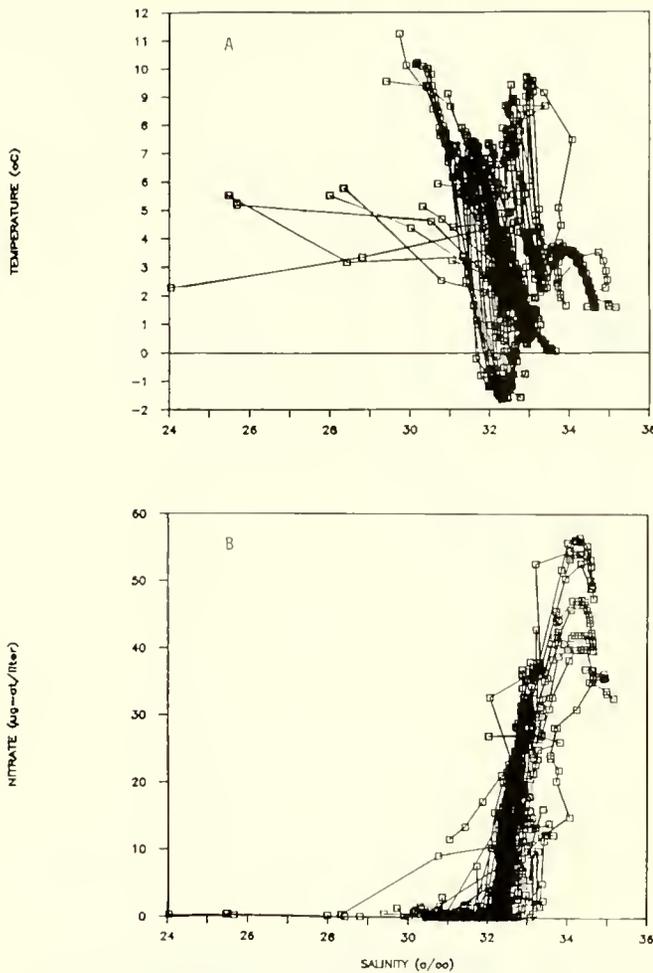


Fig. 7. (A) Temperature ($^{\circ}\text{C}$) and salinity (‰); (B) nitrate ($\mu\text{g-at/l}$) and salinity (‰) plot for all stations sampled in the Bering and Chukchi Seas.

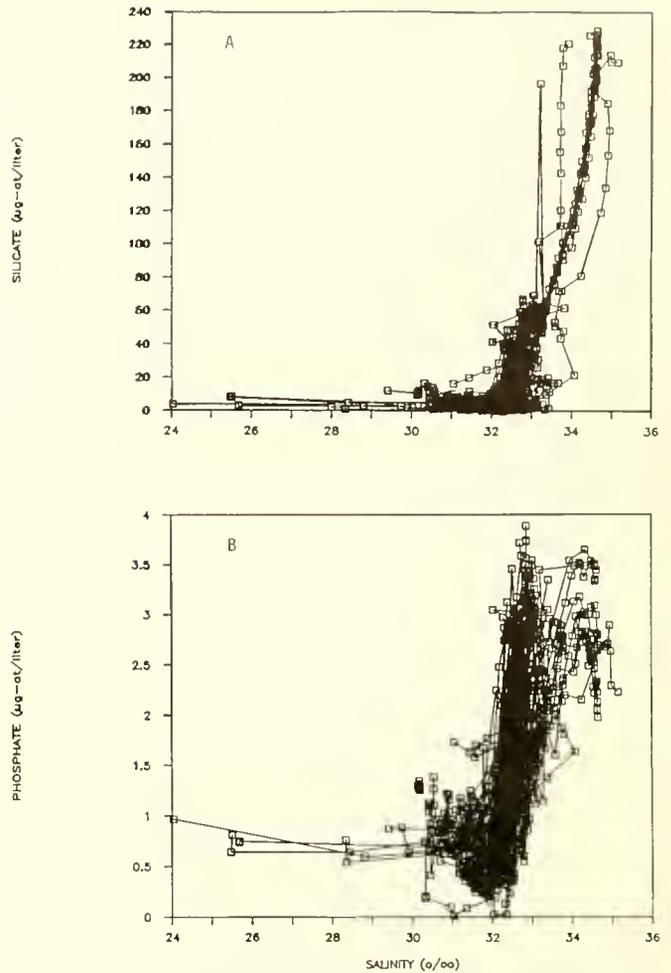


Fig. 8. (A) Silicate ($\mu\text{g-at/l}$) and salinity (‰) plot; (B) phosphate ($\mu\text{g-at/l}$) and salinity (‰) plot for all stations sampled in the Bering and Chukchi Seas.

The silicate–salinity diagram for all samples (Fig. 8A) shows the range of silicate to be between 0.5 and 60 $\mu\text{g-at/l}$ for most samples between 31 and 33 ‰ . The low salinity Alaskan Coastal water had values below 20 $\mu\text{g-at/l}$ and the deep Bering Sea contained concentrations above 230 $\mu\text{g-at/l}$. In contrast, the range of phosphate concentrations (Fig. 8B) was 0.25 to about 3.5 $\mu\text{g-at/l}$. The uniform distribution of phosphate compared to nitrate is probably due to the rapid regeneration of phosphate in the water column.

Deep Bering Sea

The South and East Polygons in the Bering Sea had stations with depths approaching 4,000 m. The vertical profiles of nitrate and silicate (Fig. 9B) provide some insight into the nutrient gradients in the deep Bering Sea. The concentrations of nitrate and silicate were very similar in the upper 100 m between the two polygon locations; however, the East Polygon had larger nitrate and smaller silicate concentrations compared to the South Polygon. The resulting plot of nitrate/silicate ratio with depth (Fig. 9A) clearly shows the differences. The low oxygen concentrations present in the South Polygon (Fig. 11A) are more conducive to denitrification process, so it is likely that the nitrate has been lost from the deep water by this process.

The near-bottom waters near the South Polygon had previously been observed to contain a layer of slightly less saline water near the bottom (Park *et al.*, 1975). The very distinct vertical distributions make further sampling in these regions a necessity.

The vertical phosphate distributions in the deep Bering Sea (Fig. 10B) also tend to be elevated in the East Polygon compared to the South with values greater than 3 $\mu\text{mole/l}$. The dissolved inorganic nitrogen (DIN)/phosphate ratio showed that most deep ocean values were at or above 16:1, especially in near-bottom water where the ratios were $>20:1$.

The vertical distributions of pH (Fig. 11B) and dissolved oxygen (Fig. 11A) in the deep Bering Sea reflect the relatively high rates of primary production in the surface waters and the slow rate of water circulation at depth. These distributions result from the consumption of dissolved oxygen and the respiratory release of carbon dioxide as particulate matter sinks into the deep sea. Since these parameters are both closely associated with the decomposition of organic matter it is not unusual for their relationships with salinity to be similar (Figs. 12A,B). The highest salinity waters in the deep Bering Sea have increased values of both pH and dissolved oxygen and may be related to bottom water renewal processes from the North Pacific Ocean.

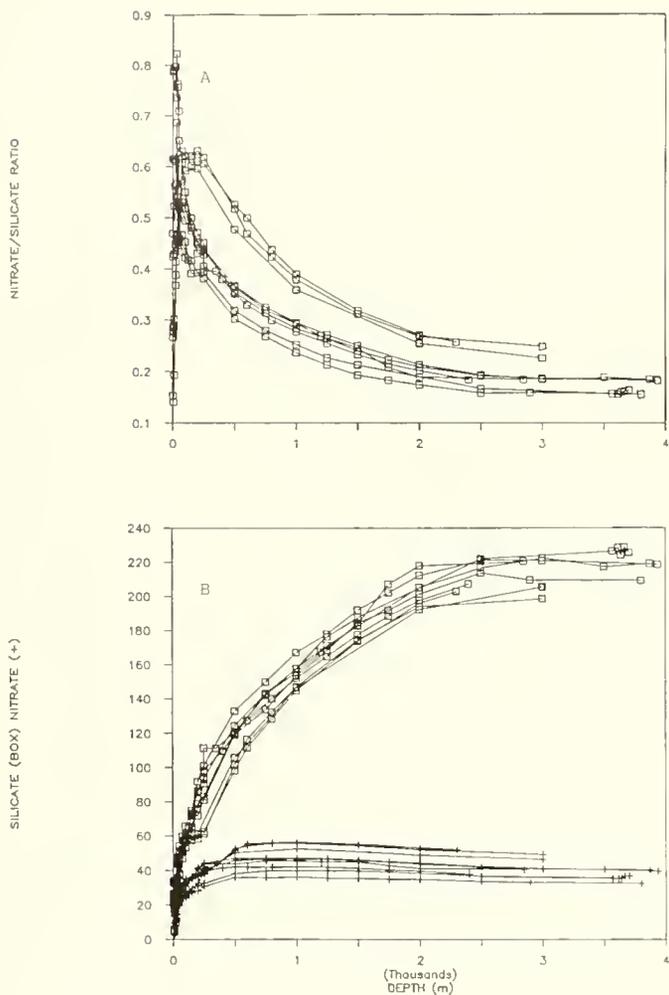


Fig. 9. The vertical distribution of (A) nitrate and silicate (μ mole/l) and (B) the nitrate/silicate ratio for all stations during the joint expedition.

Discussion

The biogenic nutrient content of the Bering Sea is closely coupled to the primary production and regeneration process occurring within its waters. The deep Bering Sea at South and East Polygons have a continued supply of nitrate, silicate, and phosphate to support primary production processes, but a phytoplankton bloom with large chlorophyll concentrations has not been observed. The high nutrients and low chlorophyll are similar to the situation observed in the North Pacific Ocean at Station P. The waters at depth in the deep Bering Sea hold large quantities of nutrients compared to other parts of the world's oceans, which indicates that the Bering Sea is a sink rather than a source. This fact is also true for constituents other than nutrients since there is no apparent ventilation of the deep waters. Future work in the deep Bering Sea should focus on the inputs to the deep water, its age and its level of anthropogenic contamination.

The Gulf of Anadyr receives deep waters from the open Bering Sea and transmits these waters to Anadyr Strait, which separates St. Lawrence Island from the Soviet mainland. The waters in the Gulf of Anadyr are productive, especially near the coastline where upwelling occurs. The resulting phytoplankton

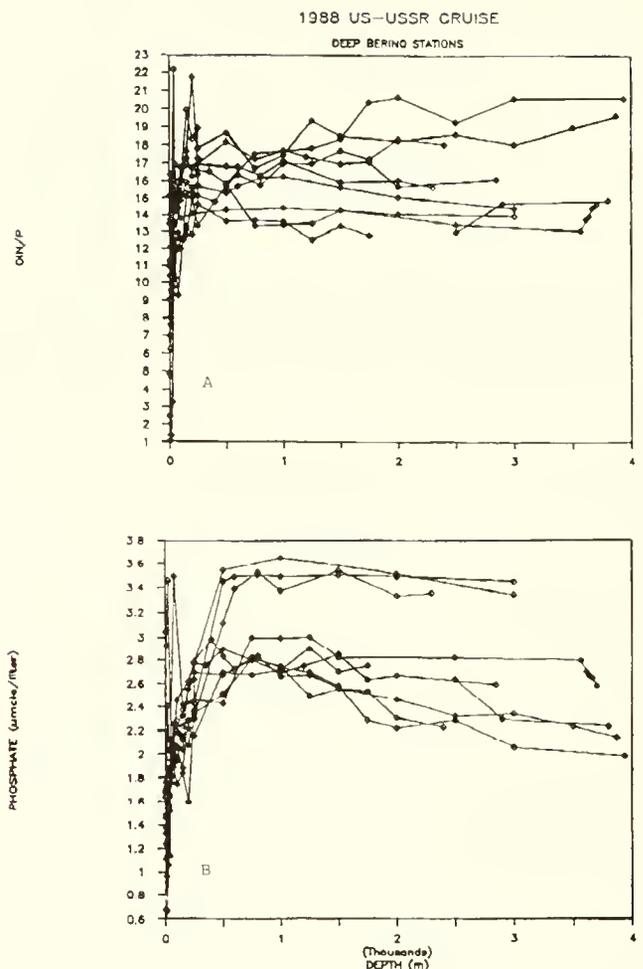


Fig. 10. The vertical distribution of (A) the dissolved inorganic nitrogen/phosphate ratio and (B) phosphate (μ mole/l) for all stations during the joint expedition.

probably act as a seed population for the upwelled water in Anadyr Strait and provide organic matter to support regenerative processes. Note that this nutrient regeneration occurs in the deposition areas depicted by Coachman and Shigaev (Subchapter 2.1, this volume). The bottom water in the central Gulf of Anadyr has the signature of winter water with its extremely cold temperatures of $<0.5^{\circ}\text{C}$. These waters slowly transit through Anadyr Strait while being mixed with open Bering Sea waters.

The Chirikov basin acts as the "chemostat" in the ecosystem by supplying large quantities of nutrients as inflows to ultimately produce organic matter. The transit time through the Chirikov basin may be so small that not all nutrients are utilized, similar to a wash-out condition. The northward transport also includes inner shelf water from the southeast Bering Sea that often produces a separate phytoplankton bloom in the middle of Chirikov basin (Hansell *et al.*, 1989). The majority of organic matter and remaining nutrients advect northward along the western edge into the Chukchi Sea (Hansell & Goering, submitted).

The Chukchi Sea receives the northward flow of nutrients and organic matter and further primary production occurs in the central portion where surface concentrations of nitrate are

greater than 1 $\mu\text{mole/l}$ (Fig. 2A). The organic matter then substantially falls to the bottom to fuel further processes and contributes to the high organic content of the sediments (Walsh *et al.*, 1989).

The extended survey during the 1988 joint expedition encountered an additional source of high-salinity, high-nutrient water near Kolyuchin Bay. The high nitrate content of the southward flowing coastal water (Coachman & Shigaev, Subchapter 2.1, this volume) indicates that additional nitrogen is added to the central Chukchi Sea as it joins the Bering Strait water. There is some speculation about the original source of this southward flowing water but oxygen-18 data indicates that it may have been winter water that previously had passed through Bering Strait (Grebmeier *et al.*, 1990). The importance of this additional nutrient input to the central Chukchi Sea is great because it could supply an additional amount of nutrients to enhance the annual primary production rates. The gains and

losses of the Chukchi Sea are very poorly known but there is some speculation that nutrients utilized here transit to the deep ocean arctic basin.

We would like to acknowledge D. Viedt for technical help in the collection of field samples and its chemical analysis. We would also like to thank Dr. L. K. Coachman and the other US scientists aboard the research vessel (R/V) *Akademik Korolev*. Finally, a special thanks is given to all the Soviet scientists and especially Professor A. V. Tsyban and Captain O. A. Rostovtsev of the R/V *Akademik Korolev*. This project was part of the Third Joint US-USSR Bering & Chukchi Seas Expedition aboard the Soviet R/V *Akademik Korolev*. We express appreciation to the US Fish and Wildlife Service, USA, and the State Committee for Hydrometeorology, USSR, who made our participation possible. This research was mainly supported by Grant No. DPP8605659 from the Division of Polar Programs of the National Science Foundation as part of the ISHTAR program. Contribution No. 766 of the Marine Science Institute, University of Texas at Austin.

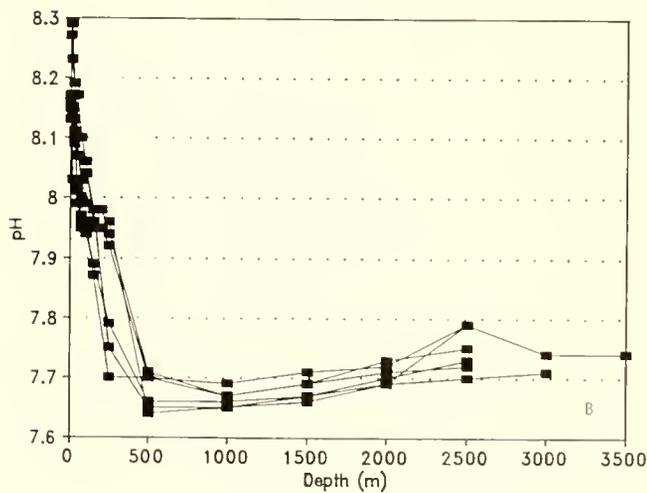
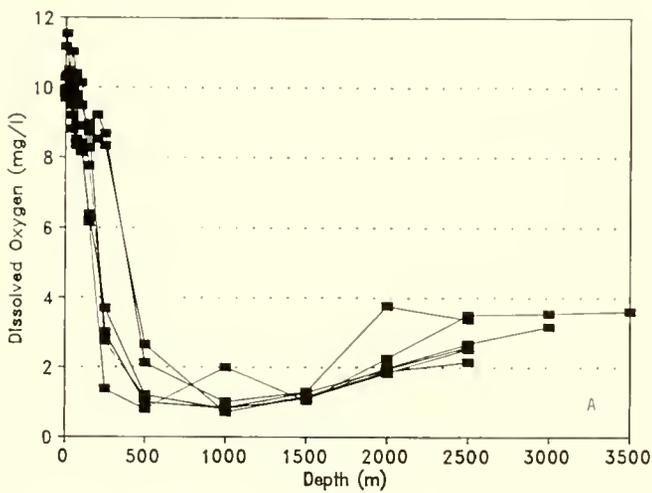


Fig. 11. The vertical distribution of (A) dissolved oxygen (mg/l) and (B) pH for the deep Bering Sea stations.

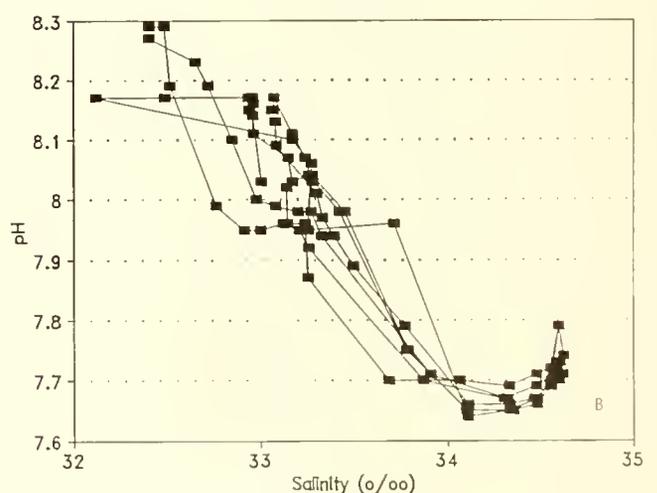
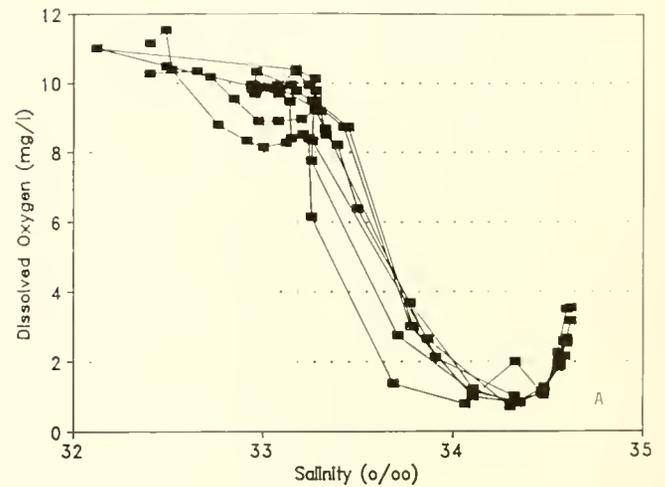


Fig. 12. (A) dissolved oxygen (mg/l) and salinity (‰) plot (B) pH and salinity (‰) plot for the deep Bering Sea stations.

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Chapter 4:

MICROORGANISMS AND MICROBIOLOGICAL PROCESSES

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Subchapter 4.1:

General Characteristics of Bacterial Populations

4.1.1 Total Number, Biomass, and Activity of Bacterioplankton

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Introduction

Until recently, marine microbiologists investigated only general characteristics of heterotrophic microorganisms. However, the development of new techniques (to measure biomass, growth rates, and metabolic activity) (Vieble, 1984), coupled with oceanographic measurements, has made it possible to quantitatively assess the importance of microorganisms in cycling of various organic and inorganic chemicals in the ocean. Such methods are now applied to determine ecotoxicity and resident times of different anthropogenic contaminants.

Investigation of microbiocenoses and quantitative assessment of microbiological processes in marine environment are the most important elements in the evaluation of anthropogenic inputs on marine ecosystem and their assimilation capacities. Information on the assimilation capacity can be obtained from long-term studies conducted across different geographical zones of the World Ocean (Izrael & Tsyban, 1983, 1989).

Long-term microbiological research in the subarctic and arctic seas was started in the early 1980's. Early results (Tsyban *et al.*, 1987b; Izrael *et al.*, 1988) showed that the growth and function of microbiocenoses depended on the hydrological and hydrochemical conditions of the sea. The increase in human population and factors, and the transport of anthropogenic contaminants into the sea, has appreciably affected the growth and activity of marine microflora (Izrael & Tsyban, 1981, 1985a,b; Korsak, 1985).

Materials and Methods

Microbiological studies in the Bering and Chukchi Seas were conducted by the Soviet–American ecological expedition in summer 1988 (see Frontispiece). These studies paid particular attention to specific regions in these seas. In the Bering Sea, research efforts focused on the eastern and southern areas of the deep Bering Sea, the relatively shallow regions of the central area and the Gulf of Anadyr, and the shallow shelf area in the Chirikov basin. All these regions have unique hydrological, chemical, and biological conditions.

To assess total population and biomass of bacteria, 381 samples were assayed in the Bering Sea, of which 320 samples were assessed for dark CO₂ assimilation by bacteria.

Microbiological studies were conducted for the first time in the Chukchi Sea. The study focused on the southern ice-free area of the sea to assess total number and biomass of bacteria; 115 samples were taken. For dark CO₂ assimilation by bacteria, 107 samples were taken at 21 stations.

Total number of bacteria was determined directly on membrane filters “Synpor” with pore diameter of 0.32 μm (Razumov, 1932). A volume of 10 to 20 ml of water was filtered, cells stained with 5% erythrosine, and counted by light microscopy. Counts were done on 10–20 visual fields with a total magnification of ×1,000. The number of bacteria was calculated by the formula:

$$X = \frac{S \times 10^6 \times a}{S_1 \times b \times c}$$

where

X	=	number of bacteria per one ml of water;
S	=	filter area, mm ² ;
10 ⁶	=	coefficient for converting mm ² to μm ² ;
a	=	average number of bacteria counted in 1 visual field “c”;
S ₁	=	area of eyepiece reticular network in μm ² ;
b	=	volume of water filtered, ml;
c	=	number of visual fields, where bacteria were counted over “S ₁ ” area.

The biovolume of bacterial mass was estimated from the average volume and total number of bacteria:

$$V = n \times v_1$$

where

V	=	biovolume of bacterial mass, μm ³ ;
n	=	number of bacteria per liter of water;
v ₁	=	average volume of a single bacterial cell, μm ³ .

The linear dimensions of single bacterial cells were determined (Tsyban *et al.*, 1988) with a calibrated eyepiece micrometer. From such measurements, the average volume of bacterial cells was calculated and equaled to 0.30 μm³.

Bacterial mass was determined (Sorokin & Kadota, 1972; Romanenko & Kusznetsov, 1974) by the formula:

$$P_b = \frac{n \times v \times 15 \times 10^6}{2 \times 100}$$

where

P_b	=	weight of bacterial biomass, $\mu\text{g C/l}$;
n	=	total number of bacterial per l of water;
15	=	percentage of dry residue from raw biomass;
10^{-6}	=	weight of $1 \mu\text{m}^3$ of raw biomass of bacteria (μg) with specific weight equal to unity;
v	=	average biovolume of bacterial mass, μm^3 ;
2	=	carbon content from dry biomass;
100	=	raw biomass, %.

CO_2 dark assimilation by bacteria was assessed by radioisotopic method (Romanenko, 1964; Romanenko & Kuznetsov, 1974). To determine dark CO_2 assimilation by bacteria, the C^{14} sodium carbonate ($\text{Na}_2^{14}\text{CO}_3$; 20.4×10^6) was added to 100 ml of seawater. Water samples were incubated in the dark for 1–3 days at sea surface temperatures. After incubation, water samples were fixed with 40% formaldehyde solution and filtered (pore diameter 0.45 mm). Filters were exposed to 0.1 N HCl vapors and radioactivity of bacteria on filter was measured by liquid scintillation. Rates were calculated by the formula

$$C_{as} = \frac{C_{carb} \times r}{R \times t}$$

where

C_{as}	=	CO_2 assimilation by bacteria, $\mu\text{g C/l}$;
C_{carb}	=	carbonates concentration (mg/l), determined by directly titration (0.1 N HCl in the presence of methyl red indicator);
r	=	radioactivity of bacteria on filters (dpm);
R	=	radioactivity of isotope $\text{Na}_2^{14}\text{CO}_3$ used in experiment, dpm;
t	=	incubation time.

Results and Discussion

Total Number, Biomass, and Dark CO_2 Assimilation by Bacteria in the Bering Sea

Results are shown in Table 1. The growth, distribution, and activity of microflora varied both in time and locality in the Bering Sea. Bacterioplankton numbers, biomass, and activity in 1988 was generally higher than in the summers of 1981 and 1984 (Tsyban *et al.*, 1987). In 1981 and 1984 the total number of bacteria fluctuated between $19\text{--}2,799$ and $73\text{--}380 \times 10^3$ cells/ml. On average, the population and biomass of bacteria in 1988 amounted to 671×10^3 cells/ml and 15.09 mg C/m^3 , respectively. These values were almost twice as high as those found in 1981 and 1984.

Comparing this data to other regions of the World Ocean, for instance, the total number of bacteria in the Barents Sea ranged between 10 and 500×10^3 cells/ml (Baitaz & Baitaz, 1986); in the Scotia Sea, populations of bacterioplankton reached $200\text{--}500 \times 10^3$ cells/ml (Azam *et al.*, 1981); in the Arctic Ocean, concentrations of bacterial population varied

TABLE 1

Numbers, biomass and dark CO_2 assimilation by bacteria in the Bering Sea water, summer 1988.

Sea area	Total bacterial numbers (10^3 cells/ml)	Bacterial biomass ($\mu\text{g C/l}$)	Dark CO_2 assimilation by bacteria, $\mu\text{g C/l/d}$
Bering Sea	<u>283-1050</u> 639	<u>6.37 - 23.62</u> 14.38	<u>0.48 - 1.73</u> 0.98
Northern part of the Sea	<u>276 - 1755</u> 806	<u>6.21 - 39.49</u> 18.13	<u>0.49 - 1.75</u> 1.05
Gulf of Anadyr	<u>381 - 2391</u> 727	<u>8.57 - 53.79</u> 16.38	<u>0.09 - 2.02</u> 0.38
Central part of the Sea	<u>371 - 1601</u> 722	<u>8.35 - 36.02</u> 16.26	<u>0.09 - 2.69</u> 0.53
East Polygon	<u>147 - 3340</u> 655	<u>3.31 - 75.13</u> 14.66	<u>0.26 - 7.11</u> 2.0
South Polygon	<u>122 - 1453</u> 479	<u>2.74 - 32.69</u> 10.78	<u>0.12 - 8.13</u> 1.33
By and large in the Sea	<u>122 - 3340</u> 671	<u>2.74 - 75.13</u> 15.09	<u>0.09 - 8.13</u> 1.04

from 40 to 440×10^3 cells/ml (Dahlback *et al.*, 1982); in the region of Antarctic convergence, numbers varied from 200 to 350×10^3 cells/ml (Hanson *et al.*, 1983); and in oligotrophic areas of the Pacific, the density of bacterial population varied between 10^3 and 10^4 cells/ml (Seki, 1986).

Variations in the growth, number, and distribution of microflora in the Bering Sea with its complex mixture of water masses are specific to various areas in the basin. The maximum density of bacterial population was found on the shallow shelf of the Chirikov basin (Table 1). The total number and biomass of bacteria here were 2.7 times those in 1981. Relatively high bacterial population ($1,755 \times 10^3$ cells/ml) and biomass (39.5 mg C/m^3) in this region were recorded at Station 106, located near St. Lawrence Island. In the northern part of the Chirikov basin, numbers and biomass of microflora were somewhat lower. Thus, at Station 96, the concentration of bacterioplankton was lowest, on average 583×10^3 cells/ml. Nevertheless, even though total bacterial numbers were comparatively low, the microflora activities were high. Daily dark CO_2 assimilation reached on average $1.42 \mu\text{g C/l}$. At other stations the bacterial activity was much lower, suggesting some bacterial cells were dormant.

In the shallow northern part of the sea, a fairly uniform distribution of bacterioplankton and reasonably steady level of activities occurred across the system. The surface microlayer showed relatively low concentrations of bacterioplankton, but bacterial activities were higher than in underlying waters. The bacterial dark CO_2 assimilation in the surface microlayer was, on average, $1.21 \mu\text{g C/l}$ daily, which corresponded to the level of mesotrophic waters.

Thus, the shallow northern part of the Bering Sea exhibited comparatively high total numbers and biomass and moderate activities of microflora and an even distribution of bacterial numbers across water types. From rates of bacterial activities and numbers, the microbiocenoses corresponded to mesotrophic modes.

In contrast to the Chirikov basin, low microbiocenoses growth and absolutely different distribution of bacterioplankton were observed in the south Bering Sea (South Polygon, see Frontispiece). Total numbers and biomass of bacteria in this region comprised, on average, 479×10^3 cells/ml and 10.78 mg C/m^3 . This data is similar to those obtained in 1981 (Tsyban *et al.*, 1987). The moderate concentration of total bacteria and their biomass can be attributed to microorganisms being grazed by protozoa and microzooplankton. According to Mamaeva (1987), the evolutionary stage and metabolic activities of these grazers in the Bering Sea may be high.

The variation in bacterioplankton distribution was clearly seen at South Polygon. The highest density of bacterial numbers (averaging 698×10^3 cells/ml) was found at Station 108; the lowest density (106×10^3 cells/ml) occurred at Station 111. Three bacterial maxima were found in the water column. The first maximum occurred in the surface microlayer. The total number and biomass of bacteria in this layer averaged $1,027 \times 10^3$ cells/ml and 23.32 mg C/m^3 , respectively, which was 1.4 times that in the mixed layer. Microflora flourished in the surface microlayer because of various physical–chemical factors (e.g., particulate aggregates, nutrients, fatty acids and lipids) (Babenzien & Schwartz, 1970), from water–air interaction and from high surface tension. Japanese researchers (Saijo *et al.*, 1974) have demonstrated that concentration of dissolved and suspended organic substances in the surface layer is 2–9 times that in the underlying layer.

The second maximum of bacteria was found in the surface mixed layer (0.5–45 m), a zone of high phytoplankton biomass and photosynthesis. According to Fogg (1971) and Kudryatsev (1973), the excretion of organic matter may constitute more than 20% of the total carbon produced by photosynthesis. The dissolved organic substances that are released by phytoplankton and other biota may be very important for bacterial growth.

The results showed that maximum density of bacterial numbers (942×10^3 cells/ml) and high biomass (21.18 mg C/m^3) occurred at Station 108, and minimum numbers (427×10^3 cells/ml) and low biomass (9.62 mg C/m^3) at Station 112. Below the euphotic zone, total number of bacteria and their biomass gradually declined.

The third layer of high concentration of bacterioplankton occurred in the near bottom layers of water column. Thus, at Stations 110 and 111, near bottom bacterial population and biomass ranged from 510 to 761×10^3 cells/ml and 11.5 to 17.1 mg C/m^3 , respectively.

Bacterioplankton activities also showed several maxima in the water column. In the euphotic zone of the south Bering Sea, bacteria appeared twice as active as those in the shallow northern part. Daily dark CO_2 assimilation by bacteria at South Polygon averaged 1.98 mg C/l , which is similar to bacterial activities in mesotrophic waters.

Bacterioplankton activities in euphotic zone also correlated with the distribution of bacterial numbers. The highest dark CO_2 assimilation by bacteria occurred at Stations 108 and 110, where daily values averaged 2.43 and $2.73 \text{ } \mu\text{g C/l}$, respectively. The lowest rate, $0.95 \text{ } \mu\text{g C/l/d}$, was at Station 109. Bacterioplankton activities declined with depth below the mixed layer in the south Bering Sea. However, between 150 and 2,000 m, relatively high activity of microflora was found, coupled with high dark CO_2 assimilation by bacteria that reached 2.0 – $3.0 \text{ } \mu\text{g C/l/d}$. Thus, south Bering Sea possessed high bacterial activity, particularly in the euphotic zone, and low density of bacteria throughout water column. In this region, bacterial distribution showed considerable variation. Microbiocenoses also varied vertically across water column boundaries.

Another studied region of the sea was the East Polygon (see Frontispiece) located on the eastern slope. At this site, depth of the water column ranged from 135 to 3,000 m and the water column possessed a mixture of water types, dissolved O_2 saturation, and temperature. All these factors undoubtedly influenced the formation and structure of microbiocenoses and distribution of bacteria. Results showed relatively low activities, similar to results reported earlier at this site in 1981 (Tsyban *et al.*, 1987).

Total number and biomass of bacteria at East Polygon varied considerably (Table 1). Values averaged approximately 1.4 times higher than those in the south Bering Sea. Maximum bacterial population ($1,302 \times 10^3$ cells/ml) and high bacterial biomass (29.34 mg C/m^3) occurred at the shallow-water Station 5, and minimum bacterial (873×10^3 cells/ml) and low bacterial biomass (19.65 mg C/m^3) occurred at the deep-water Station 3, where bacterial activities were high. The highest rates of dark CO_2 assimilation by bacteria occurred here, averaging $2.94 \text{ } \mu\text{g C/l}$, approximately 5 times higher than those measured at Stations 4 and 5.

Bacterioplankton in the eastern region declined from the surface microlayer to the bottom. Maximum numbers ($2,174 \times 10^3$ cells/ml) occurred at Station 4 where microbiocenoses showed a maximum stage of development in euphotic zone. The number and biomass of bacteria at East Polygon averaged $1,183 \times 10^3$ cells/ml and 26.62 mg C/m^3 , respectively. Below the euphotic zone, bacteria and their biomass declined to their lowest values (103×10^3 cells/ml and 4.6 mg C/m^3) in near-bottom waters of 2,700–3,000 m. Although microflora activities showed little variation with depth, dark assimilation of CO_2 by bacteria increased from surface layers to the bottom at Stations 2, 4, and 5. At Station 1, maximum bacterial activity occurred in surface waters. Thus, the eastern Bering Sea possessed relatively high numbers, biomass, and activities of bacterioplankton in the surface microlayer and euphotic zone, but values tended to decline with depth.

Microbiocenoses in the central basin and in the Gulf of Anadyr exhibit a position between northern and southern regions. The central basin is relatively shallow (45–145 m), with a sharp thermocline (between 25 and 45 m, temperatures ranging from 6.0 to 1.0°C at Station 9) even though dissolved O_2 saturation remained constant with depth.

The bacterial density and biomass varied considerably between stations. Maximum average values of total numbers ($1,103 \times 10^3$ cells/ml) and bacterial biomass (24.83 mg C/m^3) occurred at Station 6 and minimum values at Station 18, where values averaged 513×10^3 cells/ml and 11.55 mg C/m^3 , respectively.

The distribution of bacterioplankton in the water column also varied with depth (Figs. 1,2). Numbers increased at the thermocline. In contrast to East and South Polygons, the surface microlayer here lacked high concentrations of bacteria. Total numbers and biomass of bacteria averaged 691×10^3 cells/ml and 15.5 mg C/m^3 , respectively. Highest density of bacterioplankton occurred in the euphotic zone, and cell number and bacterial biomass averaged 790×10^3 cells/ml and 17.8 mg C/m^3 , respectively. Bacterial numbers declined with depth, but near the bottom, numbers reached a density of 708×10^3 cells/ml.

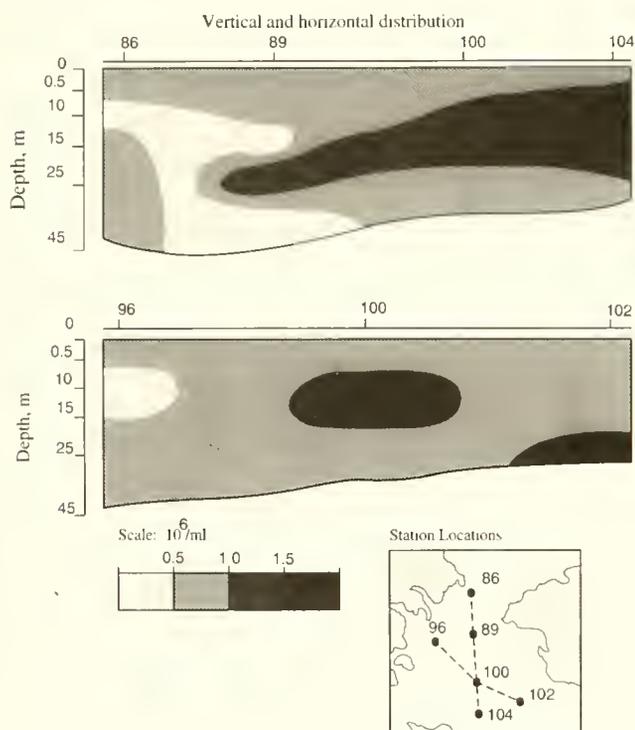


Fig. 1. Distribution of bacterial population in the northern Bering Sea, summer 1988.

Compared to other areas, bacteria in the central basin showed the lowest activity (Table 1), and rates of dark CO_2 assimilation compared with those in oligotrophic waters. Maximum activity of bacterioplankton occurred at Station 7, where rates averaged $1.11 \mu\text{g C/l/d}$. At Stations 6, 18, and 19, all rates varied between 0.20 and $0.30 \mu\text{g C/l/d}$.

In the surface microlayer and euphotic zone, microflora showed similar rates of dark CO_2 assimilation, averaging about $0.50 \mu\text{g C/l/d}$. Near the bottom, rates averaged $0.37 \mu\text{g C/l/d}$. Thus, in the central basin with shallow depths and strong thermocline, the bacteria numbers and biomass are modest but bacterial activity is low.

In the Gulf of Anadyr, river effluence influenced microbiocenoses. The Anadyr River discharges nearly 41 km^3 yearly into the Gulf of Anadyr (Dobrovolski & Zalagin, 1982).

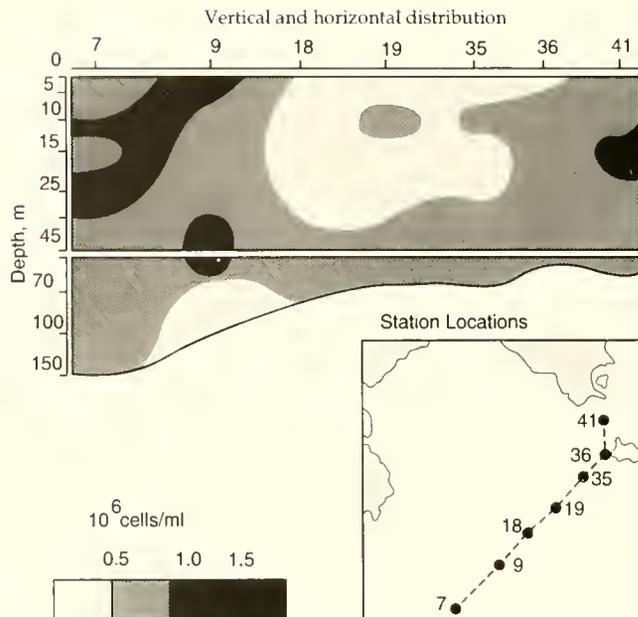


Fig. 2. Distribution of bacterial population in the southern Bering Sea, summer 1988.

During the summer, surface salinities in the gulf waters declined, and terrestrial microorganisms and suspended organic matter of terrigenous origin enter the sea. Consequently, bacteria that absorb to suspended matter may seriously influence the structure of coastal bacterial populations.

Total numbers and biomass of bacterioplankton in the Gulf of Anadyr are high (Table 1) and as high as those in the northern basin. Maximum numbers and biomass occurred at Stations 24 and 26 located in the gulf coastal waters, with minimum values at Station 22 nearest the open sea. Vertical profiles of bacterioplankton showed some increase in both numbers and biomass with depth (Fig. 3). The bulk of bacterioplankton concentrated in the euphotic zone where total numbers and biomass averaged 910×10^3 cells/ml and 20.5 mg C/m^3 , respectively. Near-bottom waters contained the lowest density of bacteria in the water column.

Bacterioplankton in the Gulf of Anadyr showed the lowest activity relative to other studied areas. This suggests that most of the microflora were dormant. The highest activity of microbiocenoses occurred at Station 26, the lowest activity at Station 11. Dark CO_2 assimilation by bacteria at those stations averaged 1.11 and $0.17 \mu\text{g C/l/d}$, respectively, and distributed evenly throughout the water column. Dark CO_2 assimilation in the surface microlayer, euphotic zone, and near the bottom ranged between 0.48 and $0.50 \mu\text{g C/l/d}$. Thus, high density of bacterioplankton and low activities of microbiocenoses characterized the shallow Gulf of Anadyr with its sharp thermocline and low surface salinity. Generally speaking, bacteria remained constant with depth, although at Stations 15 and 22, highest numbers and activities of bacterioplankton occurred at the thermocline.

In conclusion, by studying bacteria in the Bering Sea in summer 1988, it was possible to assess the status and variance of total number, biomass, and activities of bacterioplankton in relation to different hydrological and chemical conditions and

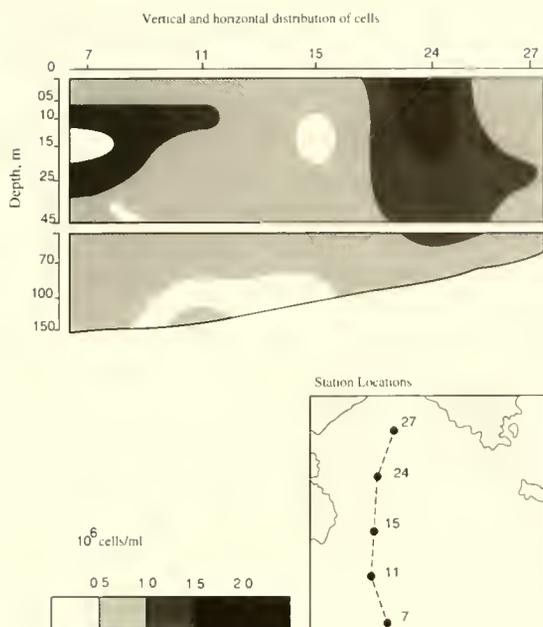


Fig. 3. Distribution of bacterial population in the Gulf of Anadyr of the Bering Sea, summer 1988.

to compare them with the data obtained in previous years. Relating bacterial numbers, biomass, and activities with other oceanographic parameters, it was possible to analyze the microbiological conditions with increasing anthropogenic load in the Bering Sea ecosystem.

Total Number, Biomass, and Activity of Bacterioplankton in the Chukchi Sea

Until recently, there has been no microbiological studies in the Chukchi Sea ecosystem. The first investigations, conducted in summer 1988, focused on bacterioplankton, their distribution, and biological status of the microbiocenoses. Microbiological studies included variance across the region, vertical distribution of bacterial number, biomass, and activity.

The Chukchi Sea is one of many adjacent seas of the Arctic Ocean. It freely communicates with cold waters to the north and limitedly with the Pacific. Nevertheless, every year 30,000 km³ of water flow into the Chukchi Sea from the Pacific through the Bering Strait (Dobrovolski & Zalogin, 1982). Sea water temperatures depend mostly upon solar warming and autumn–winter cooling. The space–time scales for salinity depend on the inflow of Pacific waters and river waters from coastal areas. The horizontal and vertical variance of dissolved oxygen and biogenic elements affect the formation and growth of microbiocenoses.

The analysis of results (Table 2) shows that total number of bacteria and their biomass in the Chukchi Sea varied across locality and depths. In coastal waters of Chukchi and Alaska, maximum numbers and biomass of bacteria occurred. These regions are strongly influenced by both river effluence and Pacific Ocean waters. Deep-ocean waters from the Pacific, which are warm and enriched with biogenic nutrients, penetrate through the Bering Strait and mix with Chukchi Sea, resulting in varied growth and distribution of microbiocenoses across the Chukchi Sea. The activity of Chukchi littoral bacteria was

high and equal to that of mesotrophic waters. Bacterioplankton showed the lowest activity in Alaskan waters. The distribution of bacterioplankton along sections across different water types (Fig. 4) can be attributed to water depths (0–45 m), temperature (0.1–5.2°C), salinity (30.6‰ to 33.6‰), and dissolved oxygen (from 51% to 98%).

TABLE 2

Assessments of population, biomass and dark CO₂ assimilation by bacteria in Chukchi Sea Waters, summer 1988.

Sea regions explored	Total population of bacteria 10 ³ cells/ml	Bacterial biomass (μg C/l)	Dark CO ₂ assimilation by bacteria, μg C/l/d
Sea northern region	<u>443 - 1987</u> 913	<u>9.97 - 44.71</u> 20.55	<u>0.13 - 2.79</u> 1.00
Alaska coastal region	<u>443 - 1908</u> 923	<u>9.97 - 42.93</u> 20.97	<u>0.12 - 1.23</u> 0.66
Sea central part	<u>496 - 1718</u> 875	<u>11.16 - 38.65</u> 19.69	<u>0.47 - 4.01</u> 1.61
Chukchi coastal area	<u>305 - 1385</u> 967	<u>6.86 - 31.16</u> 21.76	<u>0.47 - 3.67</u> 1.57
On the whole over the Sea	<u>305 - 1987</u> 919	<u>6.86 - 44.71</u> 20.69	<u>0.12 - 4.01</u> 1.21

Maximum density of bacteria (averaging 997 × 10³ cells/ml) occurred near the bottom in the Chukchi Coastal waters. In the euphotic zone and surface layer bacteria and their biomass were almost 1.5 times lower than those near the bottom.

In the Alaska littoral zone, bacterioplankton were most abundant between 0 and 25 m. In this layer, numbers and biomass averaged 921 × 10³ cells/ml and 17.92 mg C/m³. In the surface microlayer and near the bottom bacterioplankton were somewhat lower than the euphotic zone.

Due to mixing in the northern area of the sea, bacteria remained constant with depth as did hydrological and chemical factors. In the Chukchi Sea, the growth of bacteria equalled that of mesotrophic waters. The highest number of bacterioplankton occurred at Station 46, where bacteria and their biomass averaged 1,154 × 10³ cells/ml and 25.96 mg C/m³, respectively. High bacterial activity also occurred at Station 45. The highest daily dark CO₂ assimilation by bacteria was averaged (2.08 μg C/l) at Station 50, where bacterial numbers and biomass average 765 × 10³ cells/ml and 17.01 mg C/m³, respectively. Vertically, total number, biomass, and activity of bacterioplankton increased from the surface microlayer to the bottom (Fig. 3).

The waters in the central basin of the Chukchi Sea showed variable temperatures and dissolved oxygen. Waters mixing over this area distributed bacteria within specific localities. Maximum numbers occurred at Stations 55 and 74, and numbers and biomass of bacteria averaged 1,028 and

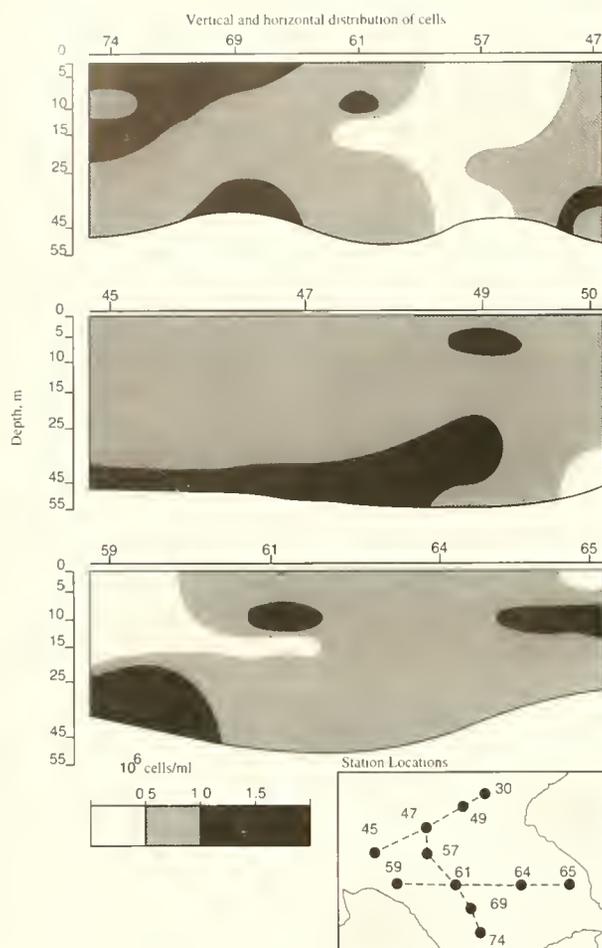


Fig. 4. Distribution of bacterial population in the Chukchi Sea, summer 1988.

$1,108 \times 10^3$ cells/ml and 23.14 and 24.94 mg C/m³, respectively. Minimum numbers and their biomass occurred at Station 57, where values averaged 446×10^3 cells/ml and 10.49 mg C/m³.

In the central basin, highest bacterial activity compared with the other study sites. Maximum dark CO₂ assimilation by bacteria occurred at Station 64, where the rates equaled that of eutrophic waters. Minimum values occurred at Station 74. Vertically, numbers and biomass of bacterioplankton peaked between 0.5 and 25 m thick relative to values in the microlayer and near-bottom waters.

In conclusion, microbiological studies were made for the first time in the Chukchi Sea. Water masses of the Chukchi Sea showed a high level of microbiocenoses growth comparable to mesotrophic waters. Additionally, bacterial numbers, biomass, and activity in the waters of the Chukchi Sea exceeded those found in the Bering Sea.

4.1.2 Thymidine Incorporation, Frequency of Dividing Cells, and Growth Rates of Bacterioplankton

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Introduction

The Third Joint US-USSR Bering & Chukchi Seas Expedition offered a comparative regional and depth analysis of bacterioplankton in the ice-free Chirikov basin and the south Bering Sea during late July and early August 1988. This study focused primarily on the Chirikov basin, the region between the St. Lawrence Island and the Bering Strait. Two deep-water stations in the south Bering Sea ecosystem were also examined.

The principal objectives were to characterize the spatial distribution and potential growth rate of bacterioplankton, to estimate bacterioplankton productivity, and to assess their importance relative to primary production in the western and eastern Chirikov basin. The results from this study provided some essential, first time estimates of bacterioplankton production, growth rate, and biomass in the shallow ecosystem of the northern Bering Sea and in deep waters of the south Bering Sea.

Materials and Methods

Study Area and Station Locations

The second leg of the 1988 US–USSR cruise aboard the research vessel *Akademik Korolev* focused primarily on the shallow Chirikov basin (<50 meters), the region between St. Lawrence Island and the Bering Strait (see Frontispiece). In the Chirikov basin, three major water types occur and are bathymetrically steered northward across this northern Bering Shelf.

Anadyr water (AW) is located in Soviet waters along the western boundary of the system. The Bering Shelf water (BSHW) is restricted to the central basin; and Alaskan Coastal water (ACW) is located near the Alaskan coast and forms the eastern boundary of the northern shelf ecosystem. These waters are identified by temperature/salinity profiles and bottom water properties. In the summer, AW is characterized with salinities >32.5‰ and temperatures ≤1.5°C, BSHW with salinities of 31.8 to 32.5‰, and temperatures of 0–1.5°C, and ACW with salinities of <31.8‰ and temperatures of ≥4°C (Walsh *et al.*, 1989).

Two additional areas were also made in deep water of the south Bering Sea basin near the Aleutians (see Frontispiece). Bacterioplankton dynamics were measured at Station 110 in the South Polygon (53°9'N, 175°9'W) and at Station 113, the old GEOSECS station in the eastern Bering Sea basin (53°2'N, 177°3'W).

Physical Measurements

Salinity, temperature, and depth data were collected using a Sea-Bird SBE9 CTD/General Oceanic Rosette System. This information was used to select water depths for bacterioplankton samples.

Bacterioplankton Measurements

On the shallow Bering Sea Shelf, water samples for bacterioplankton measurements were collected from 5 depths at 12 stations using 1.7-l Niskins bottles on the rosette. Sample depths were chosen to represent surface mixed waters, hydrographic conditions within the region (i.e., thermohalocline or midwater column), and near-bottom waters. In the deep Bering Sea at Stations 110 and 113, water samples were collected from 12 depths: 6 depths in the upper 250 m of the water column and 6 depths over the remaining water column down to the bottom.

Bacterioplankton measurements included [³H-methyl]thymidine incorporation, bacterial numbers and frequency of dividing cells, and empirical growth experiments. For thymidine incorporation (Fuhrman & Azam, 1982), unaltered 50-ml water samples were transferred to an 8-oz sterile Whirl Pak bag. [³H-methyl]thymidine (84.8 Ci mmol⁻¹) was added to obtain a final concentration of 20 nmoles l⁻¹. Water samples were incubated in the dark at *in situ* surface temperatures. After 3 h, samples were chilled in an ice bath and ice-cold trichloroacetic acid (TCA) was added to a final concentration of 5% TCA. After 30 min on ice, 25-ml replicate samples were filtered on 25-mm Millipore cellulose acetate filters of 0.45 μ pore size. The filters were rinsed with cold 5%

TCA and were dissolved in Aquasol. Radioactivity, corrected for counting efficiency using an internal ³H standard, was determined by liquid scintillation.

Bacteria in 10-ml water samples were preserved with 0.2 μm filtered formaldehyde (2% final concentration) and stored at 5°C. One to 3 weeks following the cruise, bacteria were stained with Acridine Orange and filter on 0.2 μm Nuclepore filters for counting total bacteria in 10 microscopic fields filter⁻¹ (Hobbie *et al.*, 1977), along with dividing cells in 20 microscopic fields filter⁻¹ (Hagstrom *et al.*, 1979). The frequency of dividing cells were calculated relative to the total number of single plus dividing cells. Bacterial numbers and dividing cells were determined by epifluorescence microscopy.

Estimates of cell production and growth rates in natural populations of bacteria were calculated using two different techniques: thymidine incorporation into DNA material using the theoretical conversion factor of 2 × 10¹⁸ cells mole⁻¹ thymidine incorporated (Fuhrman & Azam, 1982) and the frequency of dividing cells using the empirical relationship between FDC and specific growth rate (u) of ln u = 0.81 (FDC) - 3.73 for southern ocean bacterioplankton (Hanson *et al.*, 1983).

Growth rates were calculated from estimates of cell production divided by standing stocks of bacteria. To convert cell production and standing stocks to carbon, an estimate of cell carbon was assumed to be 10 femtogram C cell⁻¹ based on estimates from Antarctica and British Columbia (Fuhrman & Azam, 1980; Fuhrman, 1981).

Statistics Analysis

Data transformation and statistics analysis (i.e., correlations, slope analysis, t-test, ANOVA) were computed with SAS, Inc., software.

Results and Discussion

Bacterioplankton, Thymidine Incorporation, and Frequency of Dividing Cells

Anadyr water (AW): Rates of thymidine incorporation by bacterioplankton along the western boundary of the Chirikov basin remained constant with depth, except at Station 86 where rates reflected the thermohalocline in the Bering Strait (Frontispiece, Figs. 1a,b). Rates averaged 1.37 pmoles l⁻¹ h⁻¹ in AW (Table 1). Salinity profile at Station 86 characterized low-salinity ACW in the upper 15 m and high-salinity AW below 30 m. Rates of thymidine incorporation correlated strongly with temperature but not with the index of the population growth rate (i.e., specific activity of thymidine incorporation) (Fig. 2, Table 2).

Bacterial populations were generally more abundant in surface waters in AW and averaged 3.7 × 10⁸ cells l⁻¹. Highest numbers occurred in the surface waters of the Bering Strait (Station 86, Fig. 1a). Bacteria in these waters correlated with the narrow range in water temperatures (Fig. 3, Table 2). This relationship to the index of population growth rate was similar to that found for ACW (Fig. 2, Table 2).

The frequency of dividing cells, an index of cellular growth rate, ranged from 4 to 8% dividing cells in surface

waters at all stations. Below the minimum frequency of dividing cells (<4%), dividing cells again increased with depth to 5.1% near the bottom (Figs. 1a,b). The frequency of dividing cells averaged 4.4% dividing cells over the water column. The specific activity of thymidine uptake, population growth rate, averaged 4.04×10^{-21} moles cell⁻¹ h⁻¹ (Table 2) and showed no relation to the frequency of dividing cells, cellular growth rate, except at Station 86. Both indices of growth rates showed no relation to temperature (data not shown).

Alaskan Coastal water: With the exception of Station 91 where the water column was isothermal (10°C), ACW showed a strong thermocline near 10 m (Figs. 4a,b; 5a,b). Rates of thymidine incorporation along the eastern boundary of the Chirikov basin averaged 1.55 pmoles l⁻¹ h⁻¹ but not significantly different (P = 0.05) from the rates measured along the western boundary (Table 1). At Station 84 in the Bering Strait and Station 91, thymidine incorporation varied little with depth, whereas at Station 92, the highest rates occurred within the thermocline. At Station 102 northeast of St. Lawrence Island, thymidine incorporation increased in the high salinity bottom waters (Fig. 4b).

Rates of thymidine incorporation were related inversely with temperature and positively with the index of the population growth rate (Fig. 2, Table 2). Rates measured in the bottom waters of the eastern Bering Straits clustered with rates measured in the waters of the western boundary of the Chirikov basin (AW, see Fig. 2), suggesting similar bottom waters flowing through the eastern and western sides of the Bering Strait.

Bacterial populations averaged 3.6×10^8 cells l⁻¹ (Table 1) and were also similar to population densities in AW. Highest densities occurred above the thermocline at Stations 92 and 102 and were approximately constant with depth at Stations 84 and 91 (Figs. 4a,b; 5a,b). Bacterial populations in ACW showed no relation to temperature.

The frequency of dividing cells in ACW averaged 0.037 (3.7% dividing cells) (Table 1). The highest frequency of dividing cells (5.0%) occurred near the thermocline and declined towards the bottom, except at Station 91 where dividing cells remained constant over the water column. The specific activity of the population averaged 4.85×10^{-21} moles cell⁻¹ h⁻¹ (Table 1) and was similar to the specific activity measured in AW. The specific activity showed no relationship to dividing cells except at Station 84 in the Bering Strait. Similar observation was seen at Station 86 in the western Bering Strait.

Bering Shelf water: Waters at Stations 89, 100, 104, and 106 characterized BSHW (Figs. 2,3). Waters at Stations 89 and 106 nearest to the western boundary of the system typify AW with bottom temperatures <2°C, whereas low-salinity ACW dominates surface waters near the eastern boundary at Stations 100 and 104. Rates of thymidine incorporation averaged 1.70 pmoles l⁻¹ h⁻¹ (Table 1). Highest rates in BSHW occurred at Station 104, northeast of St. Lawrence Island (Fig. 3). Rates were highly variable with temperature (P > 0.05) but correlated significantly with the specific activity (Fig. 2, Table 2).

Bacterioplankton populations averaged 5.2×10^8 cells l⁻¹ (Table 1) and were significantly higher than the Anadyr and ACW's (ANOVA, P < 0.05). The highest densities occurred

TABLE 1

Vertical distribution of averaged bacterioplankton parameters from the three water types measured in the Chirikov basin. Units: N = number of samples averaged at each depth, depth = meters, Thymidine Incorporation = pmoles l⁻¹ h⁻¹, Bacteria = 10⁸ cells l⁻¹, Specific Activity of thymidine incorporation = 10⁻²¹ moles cell⁻¹ h⁻¹.

Anadyr Waters					
N	Depth	Thymidine Incorp.	Bacteria	Freq. Dividing	Specific Activity
4	05	1.66	4.2	0.035	4.02
4	10	1.46	4.7	0.056	3.01
3	15	1.31	3.3	0.038	3.95
3	20	1.07	1.9	0.032	6.04
2	25	1.26	4.4	0.053	2.92
4	40	1.31	3.6	0.051	4.23
average		1.37 ± 0.11	3.7 ± 0.3	0.044 ± 0.004	4.04 ± 0.36
Alaskan Coastal Waters					
N	Depth	Thymidine Incorp.	Bacteria	Freq. Dividing	Specific Activity
4	05	1.39	3.1	0.036	4.66
4	10	1.53	4.4	0.050	3.48
4	15	1.55	3.5	0.038	4.69
2	20	1.81	3.9	0.033	4.96
4	25	1.58	3.9	0.026	4.82
2	30-35	1.54	2.3	0.035	6.55
average		1.55-0.09	3.6-0.2	0.037-0.003	4.85-0.54
Bering Shelf Waters					
N	Depth	Thymidine Incorp.	Bacteria	Freq. Dividing	Specific Activity
3	05	1.89	5.1	0.051	3.94
3	10	1.87	4.7	0.044	3.71
4	15	1.97	5.7	0.044	3.52
4	20	1.58	6.1	0.034	2.96
3	25	1.57	5.0	0.029	3.33
3	30-40	1.30	3.8	0.027	3.41
average		1.70-0.19	5.2-0.5	0.038-0.003	3.45-0.28
overall mean		1.54-0.08	4.1-0.2	0.040-0.002	4.11-0.24

above or within the thermocline. Bacteria numbers were also highly variable with temperature and specific activity (Fig. 3, Table 2).

The frequency of dividing cells averaged 0.038 (3.8% dividing cells) (Table 1). In general, frequency of dividing cells decreased from 5.1% in the surface to 2.9% below the thermocline. The specific activity averaged 3.45×10^{-21} moles cell⁻¹ h⁻¹ (Table 1), which was significantly

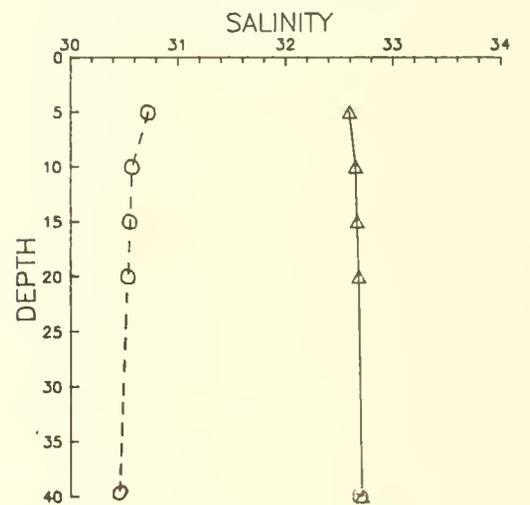
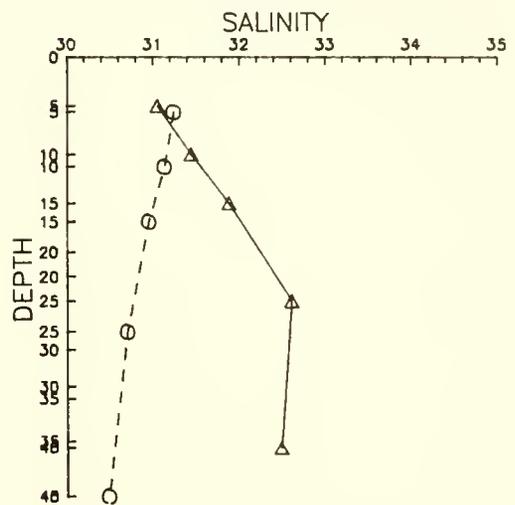
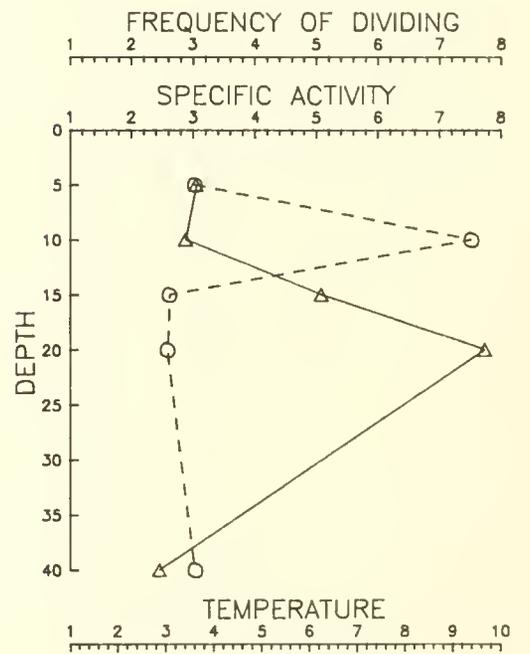
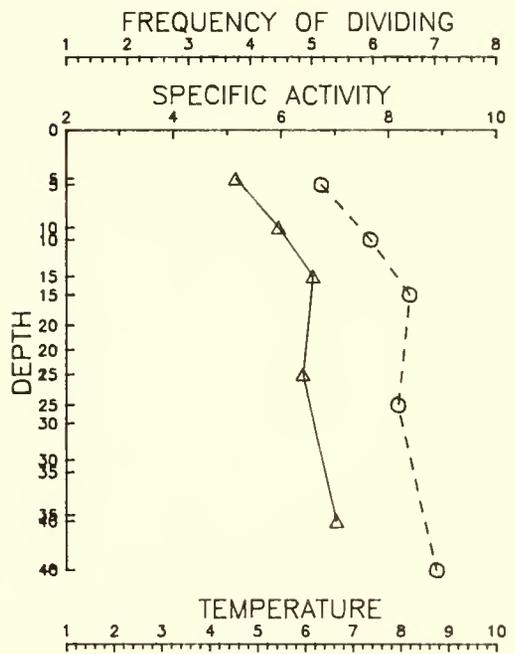
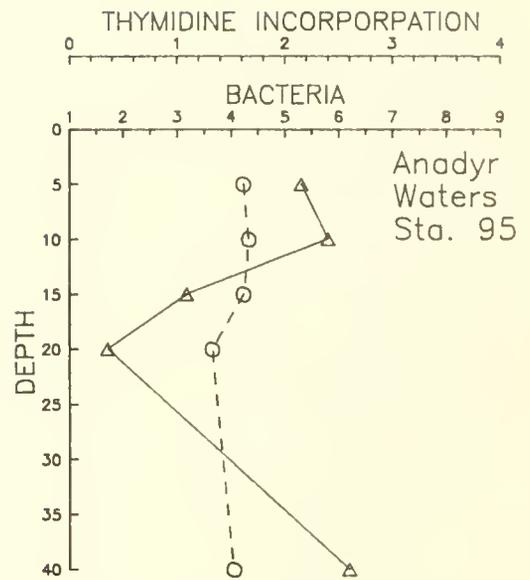
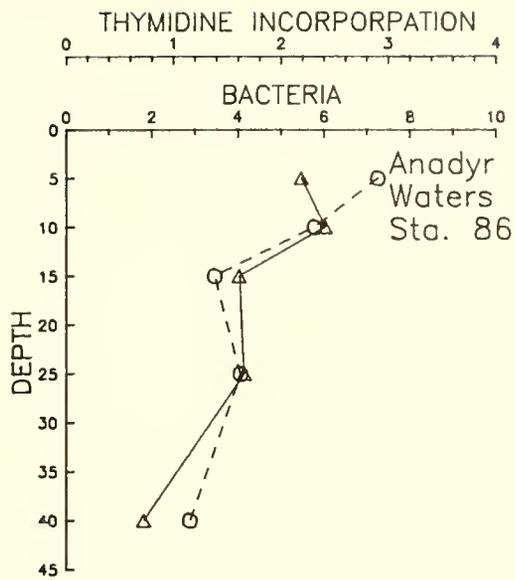


Figure 1a. The vertical distribution of thymidine incorporation (pmoles l⁻¹ h⁻¹), bacteria (10⁸ cells l⁻¹), frequency of dividing cells (% of total bacteria), specific activity of thymidine incorporation (10⁻²¹ moles cell⁻¹ h⁻¹), temperature (°C), and salinity (‰) at Stations 86 and 95 (AW).

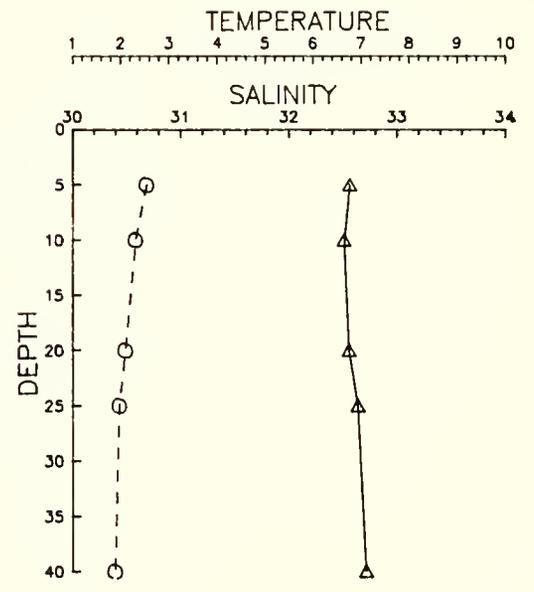
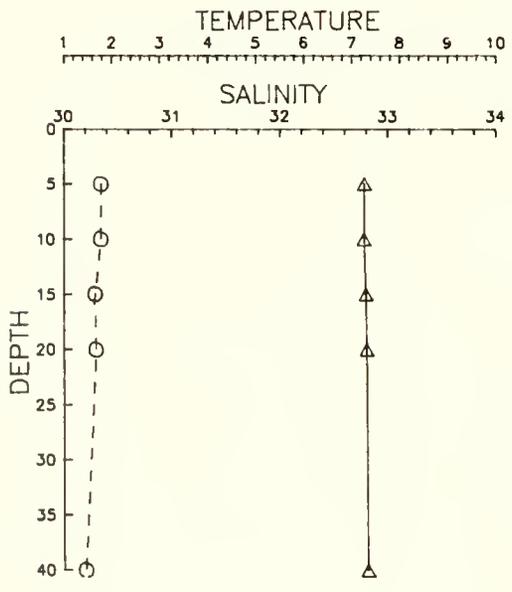
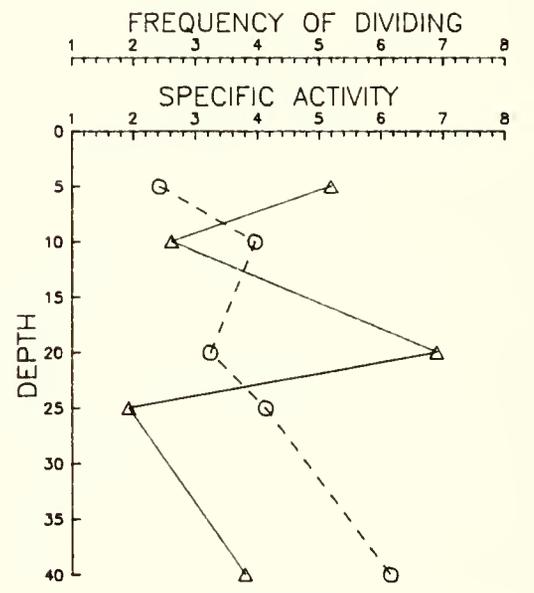
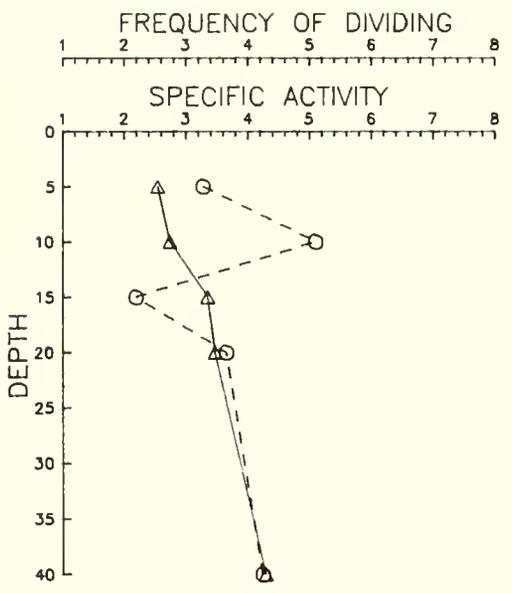
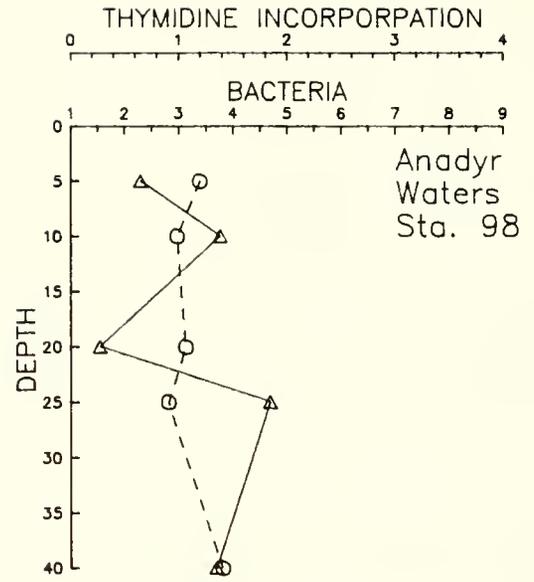
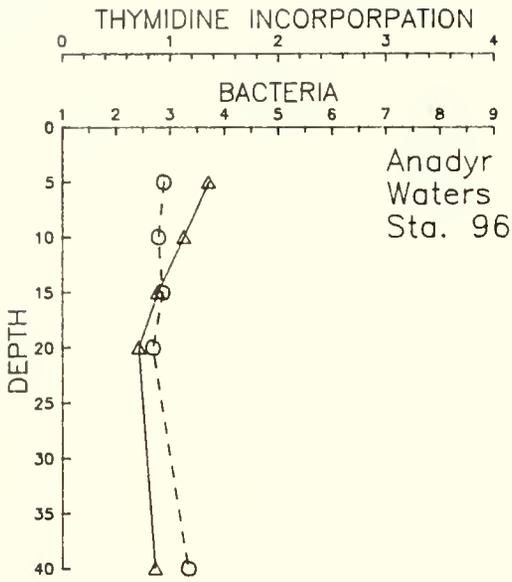


Figure 1b. The vertical distribution of thymidine incorporation, bacteria, frequency of dividing cells, specific activity, temperature and salinity at Stations 96 and 98 (AW's).

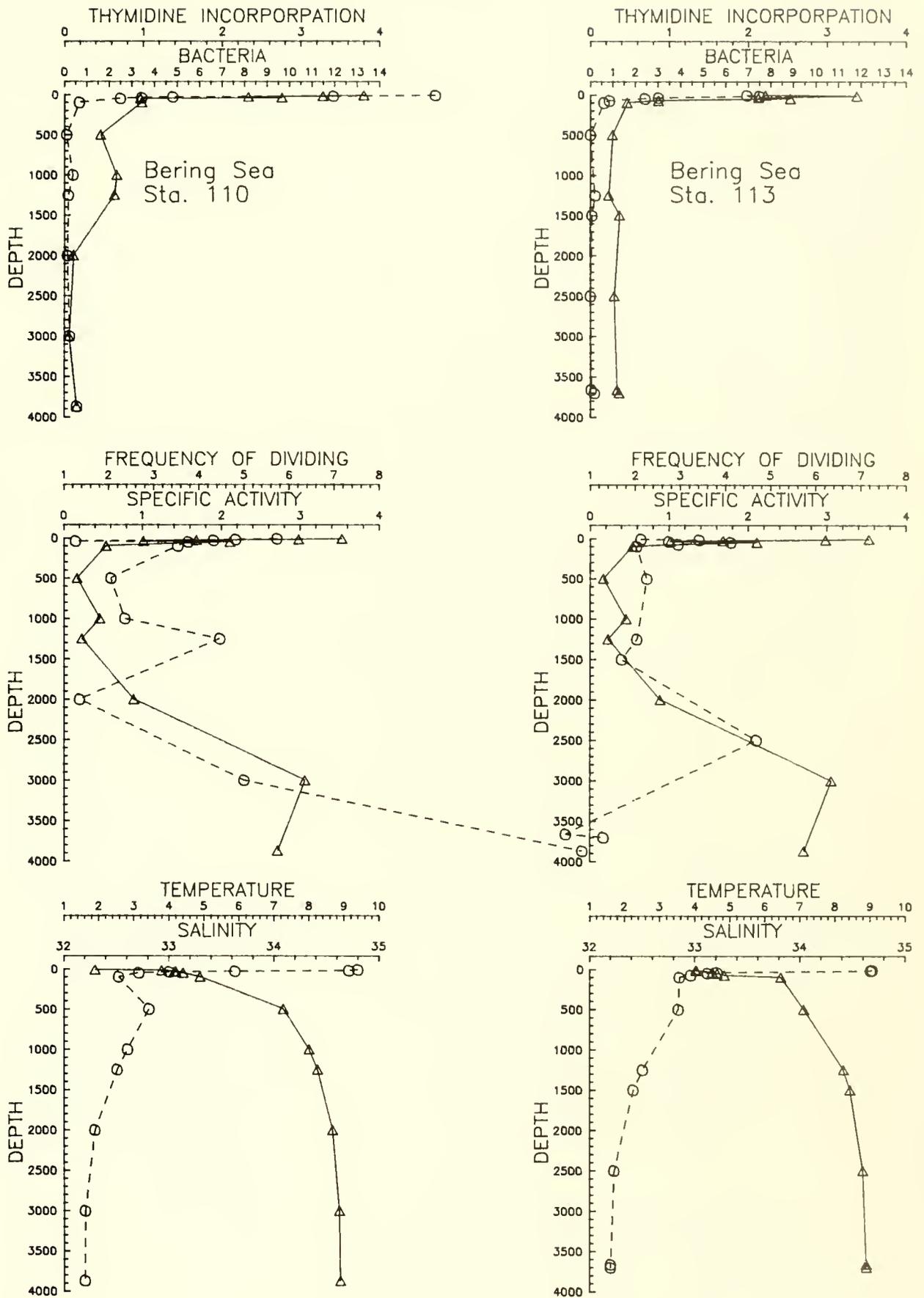


Figure 2. The vertical distribution of thymidine incorporation (pmoles $l^{-1} h^{-1}$), bacteria (10^8 cells l^{-1}), frequency of dividing cells (% of total bacteria), specific activity of thymidine incorporation (10^{21} moles cell $^{-1} h^{-1}$), temperature ($^{\circ}C$), and salinity (‰) at Stations 110 and 113 in the south Bering Sea.

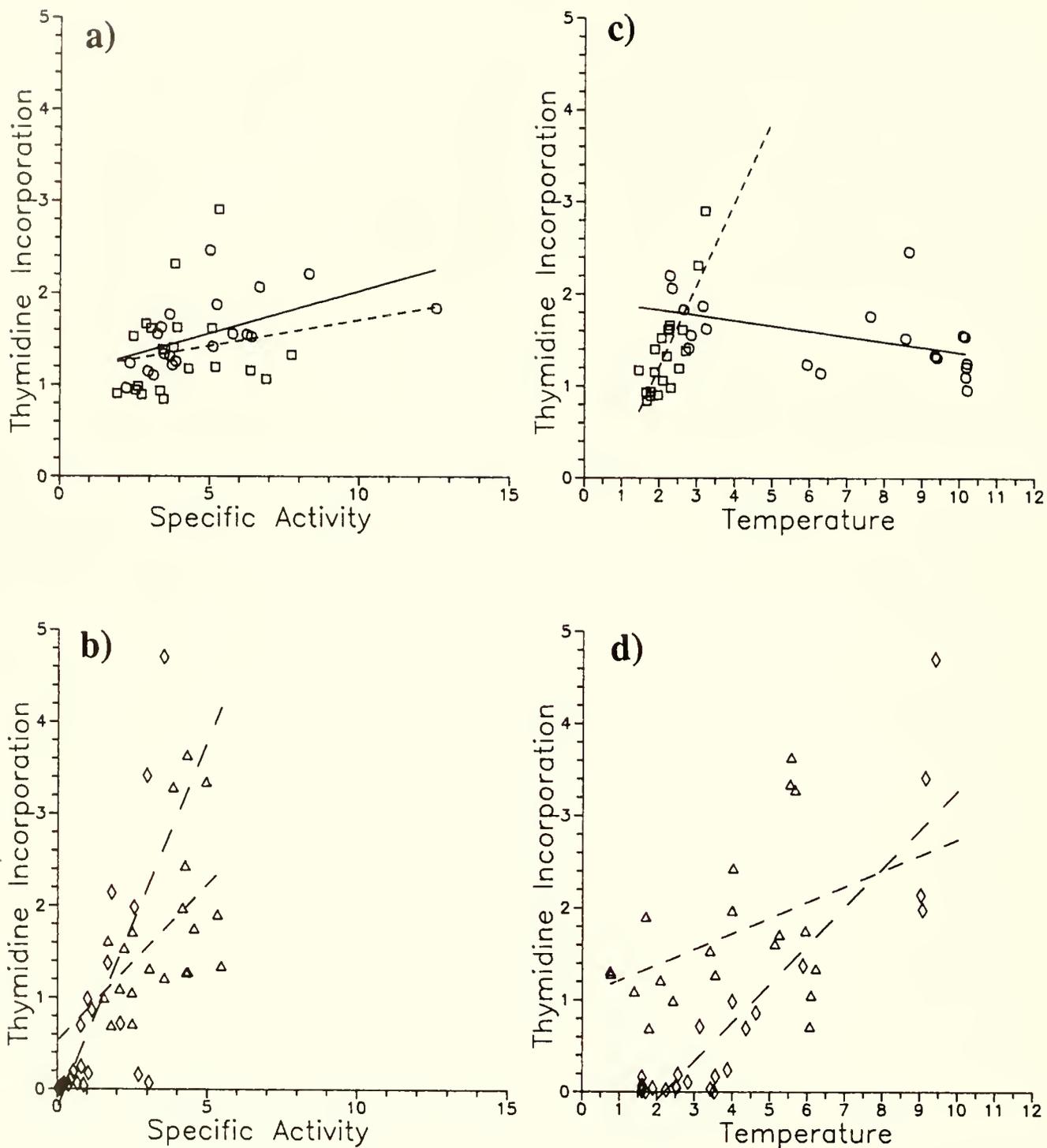


Figure 3. Linear regression of thymidine incorporation plotted against specific activity (a,b) and temperature (c,d). Figs. 3a and 3c show data from ACW's (circles) and AW's (squares), and Figs. 3b and 3d show data from BSHW's (triangle) and BSW's (diamond). Statistics for linear regressions are given in Table 2.

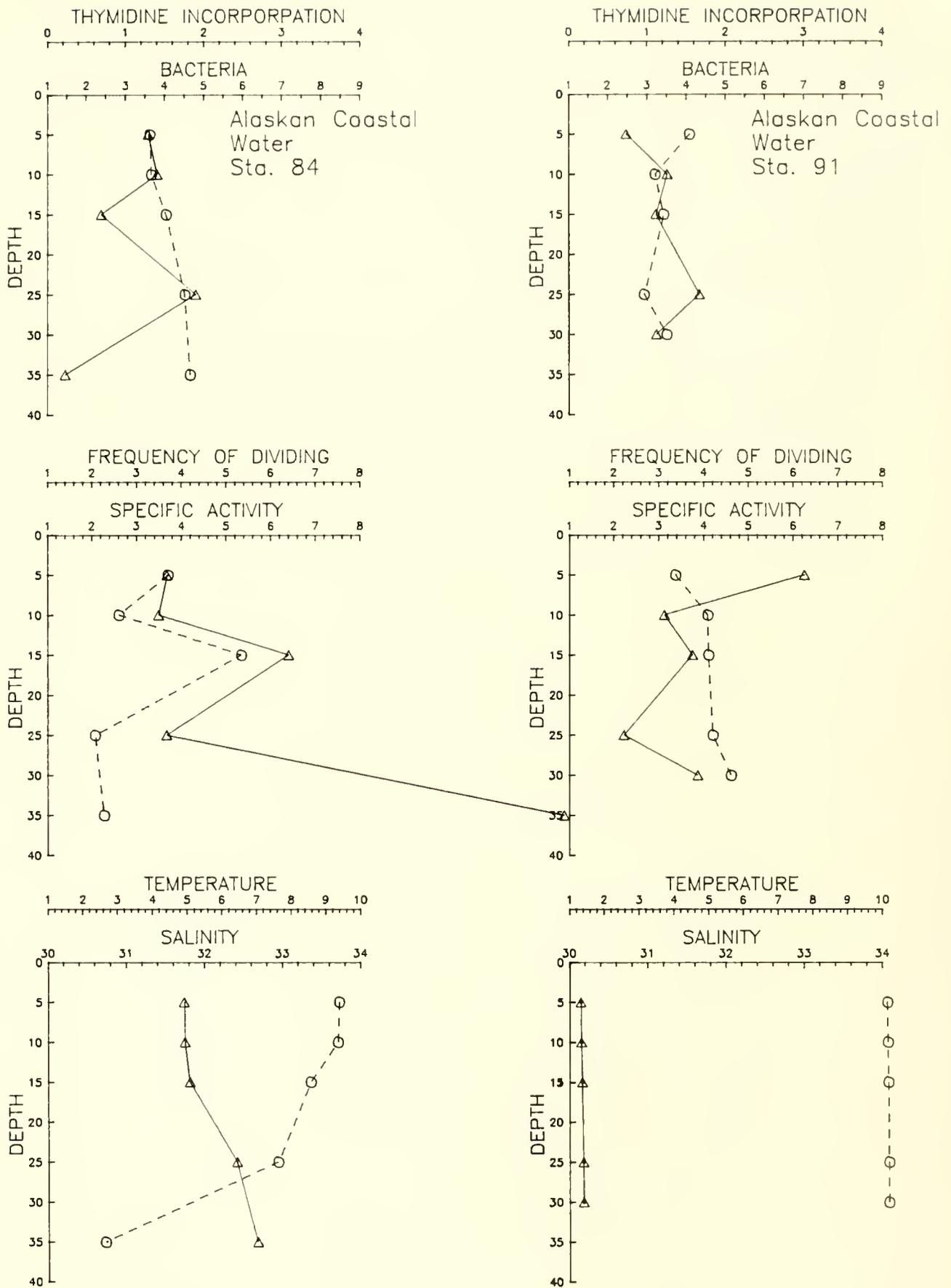


Figure 4a. The vertical distribution of thymidine incorporation (pmoles $l^{-1} h^{-1}$), bacteria (10^8 cells l^{-1}), frequency of dividing cells (% of total bacteria), specific activity of thymidine incorporation (10^{21} moles cell $^{-1} h^{-1}$), temperature ($^{\circ}C$), and salinity (‰) at Stations 84 and 91 (ACW's).

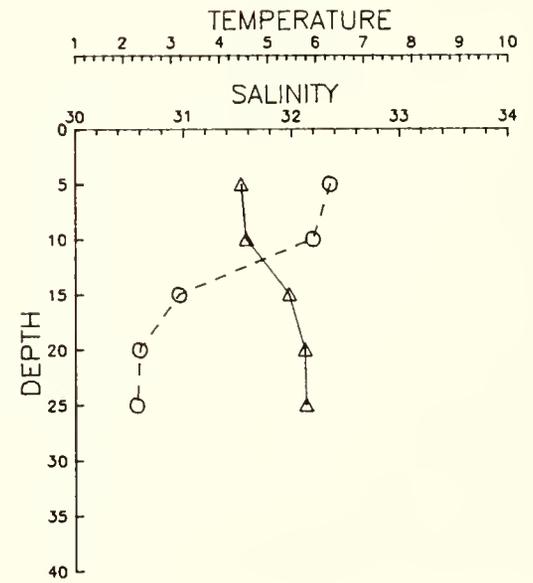
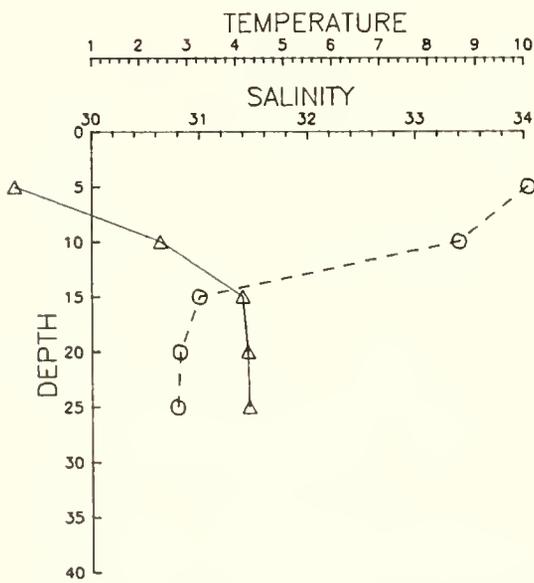
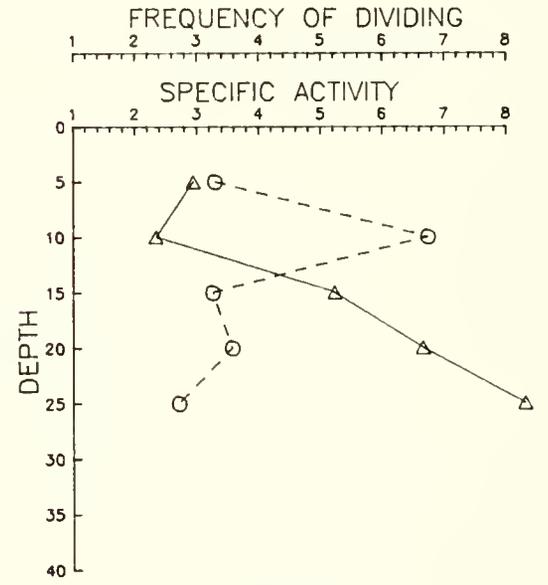
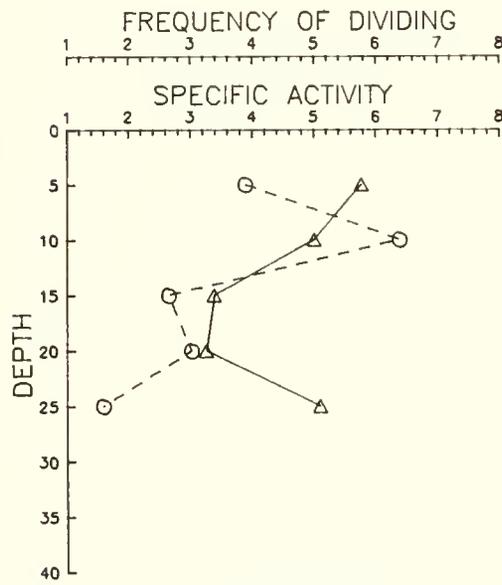
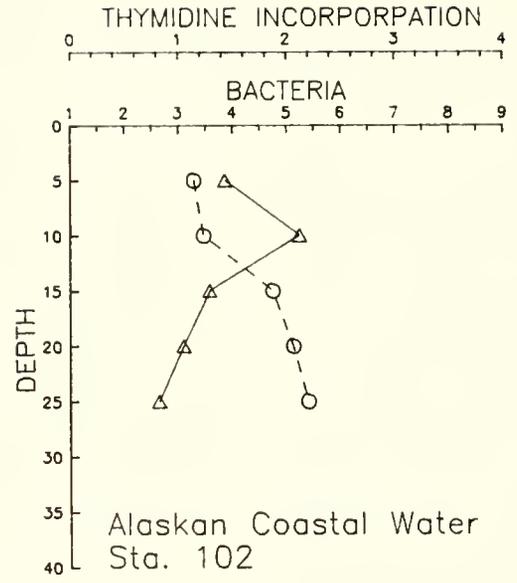
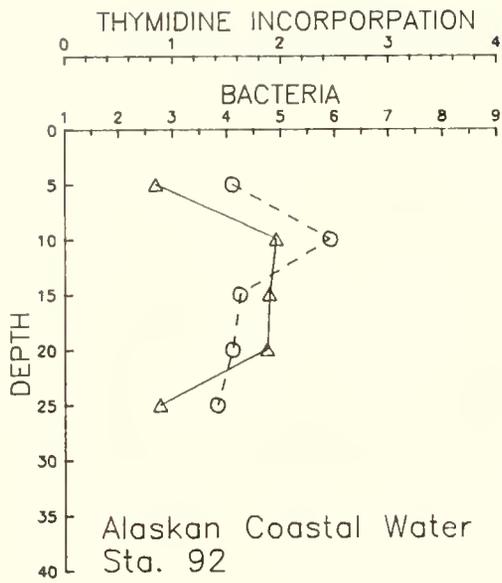


Figure 4b. The vertical distribution of thymidine incorporation (pmoles l⁻¹ h⁻¹), bacteria (10⁸ cells l⁻¹), frequency of dividing cells (% of total bacteria), specific activity of thymidine incorporation (10⁻²¹ moles cell⁻¹ h⁻¹), temperature (°C), and salinity (‰) at Stations 92 and 102 (ACW's).

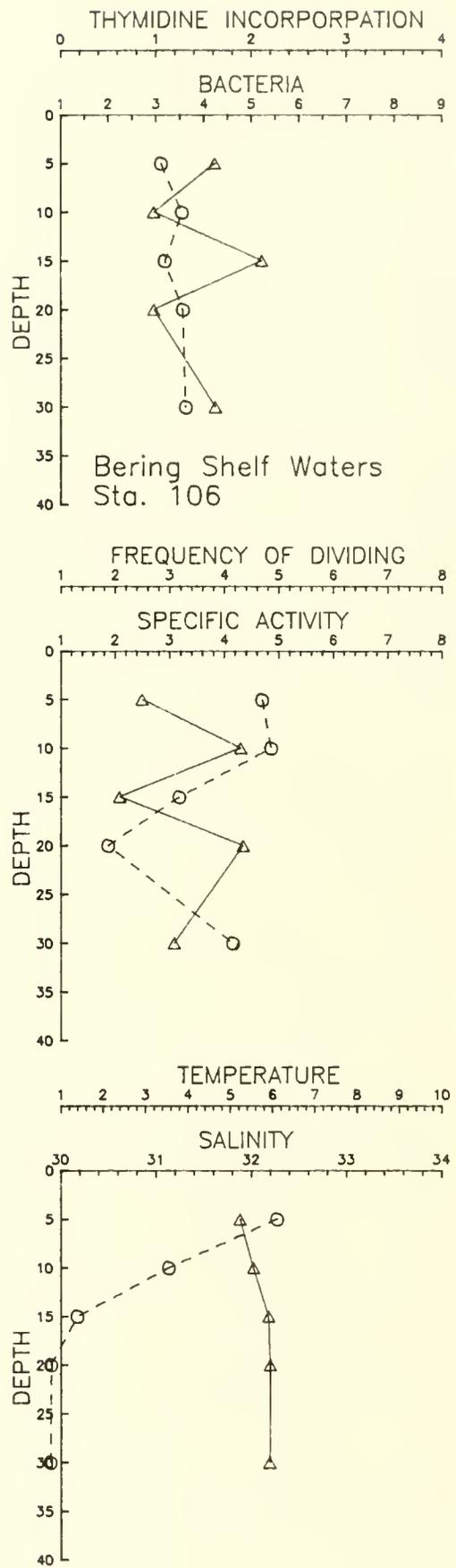
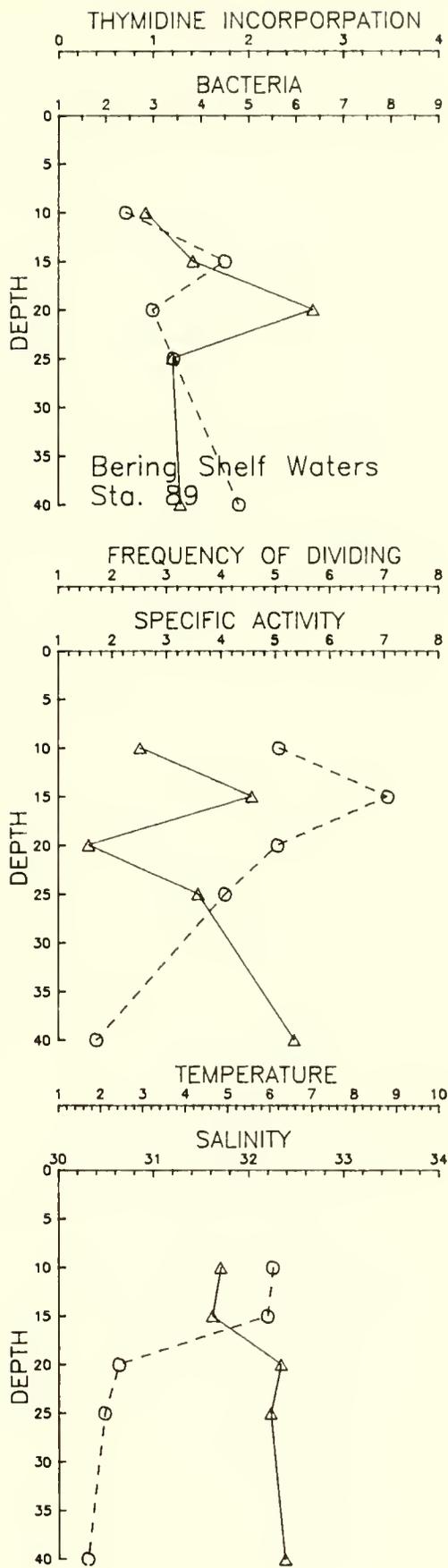


Figure 5a. The vertical distribution of thymidine incorporation ($\text{pmoles l}^{-1} \text{h}^{-1}$), bacteria ($10^6 \text{ cells l}^{-1}$), frequency of dividing cells (% of total bacteria), specific activity of thymidine incorporation ($10^{21} \text{ moles cell}^{-1} \text{h}^{-1}$), temperature ($^{\circ}\text{C}$), and salinity (‰) at Stations 89 and 106 (BSHW's).

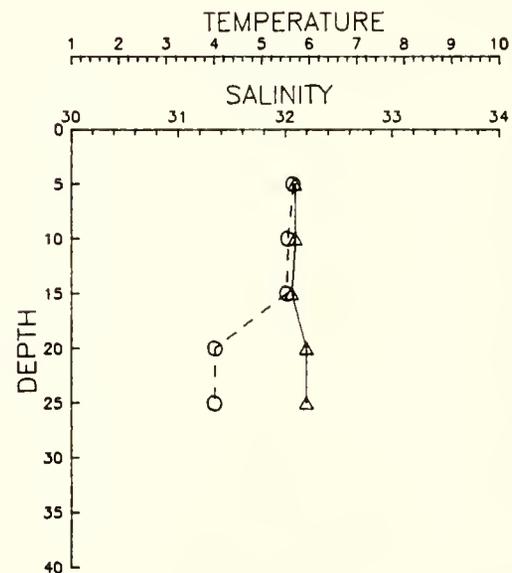
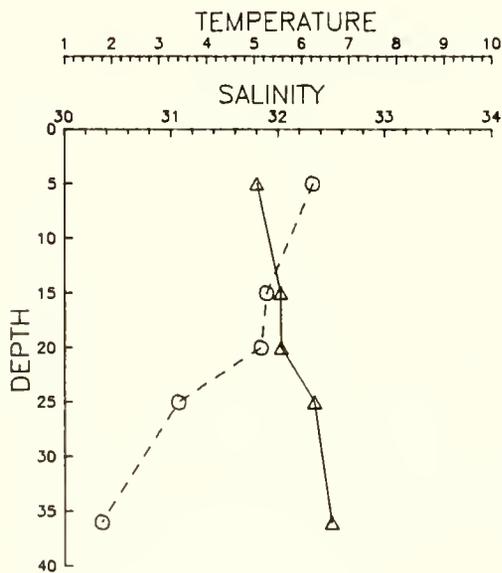
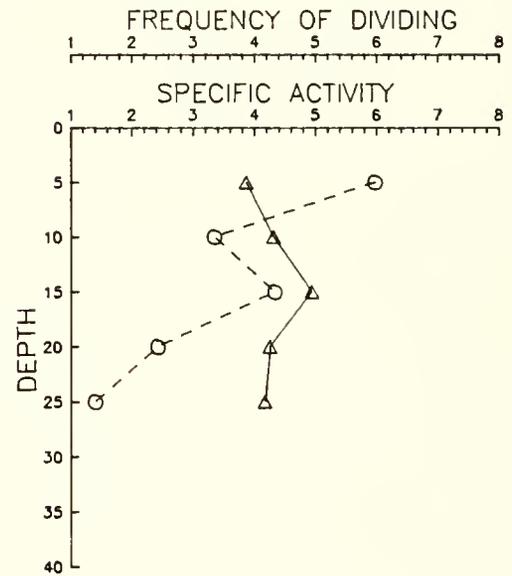
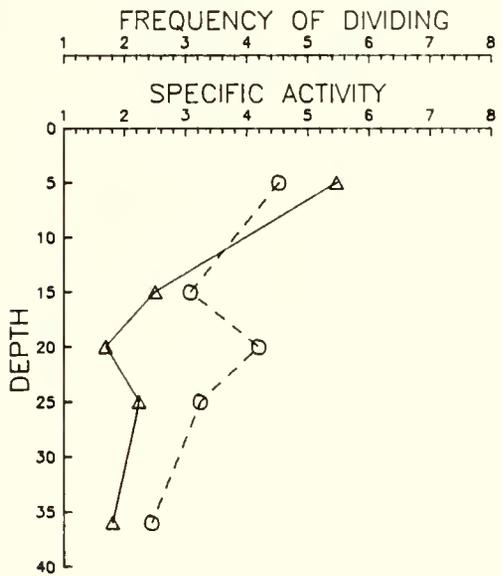
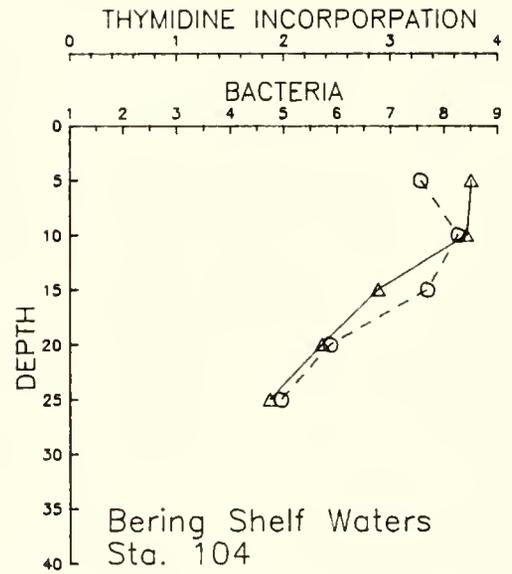
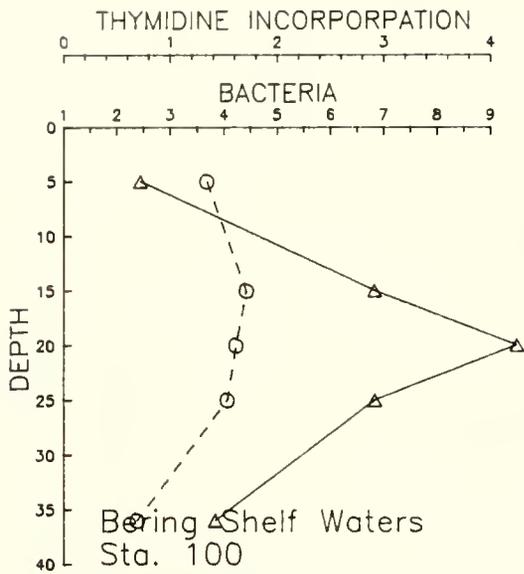


Figure 5b. The vertical distribution of thymidine incorporation (pmoles l⁻¹ h⁻¹), bacteria (10⁸ cells l⁻¹), frequency of dividing cells (% of total bacteria), specific activity of thymidine incorporation (10⁻²¹ moles cell⁻¹ h⁻¹), temperature (°C), and salinity (‰) at Stations 100 and 104 (BSHW's).

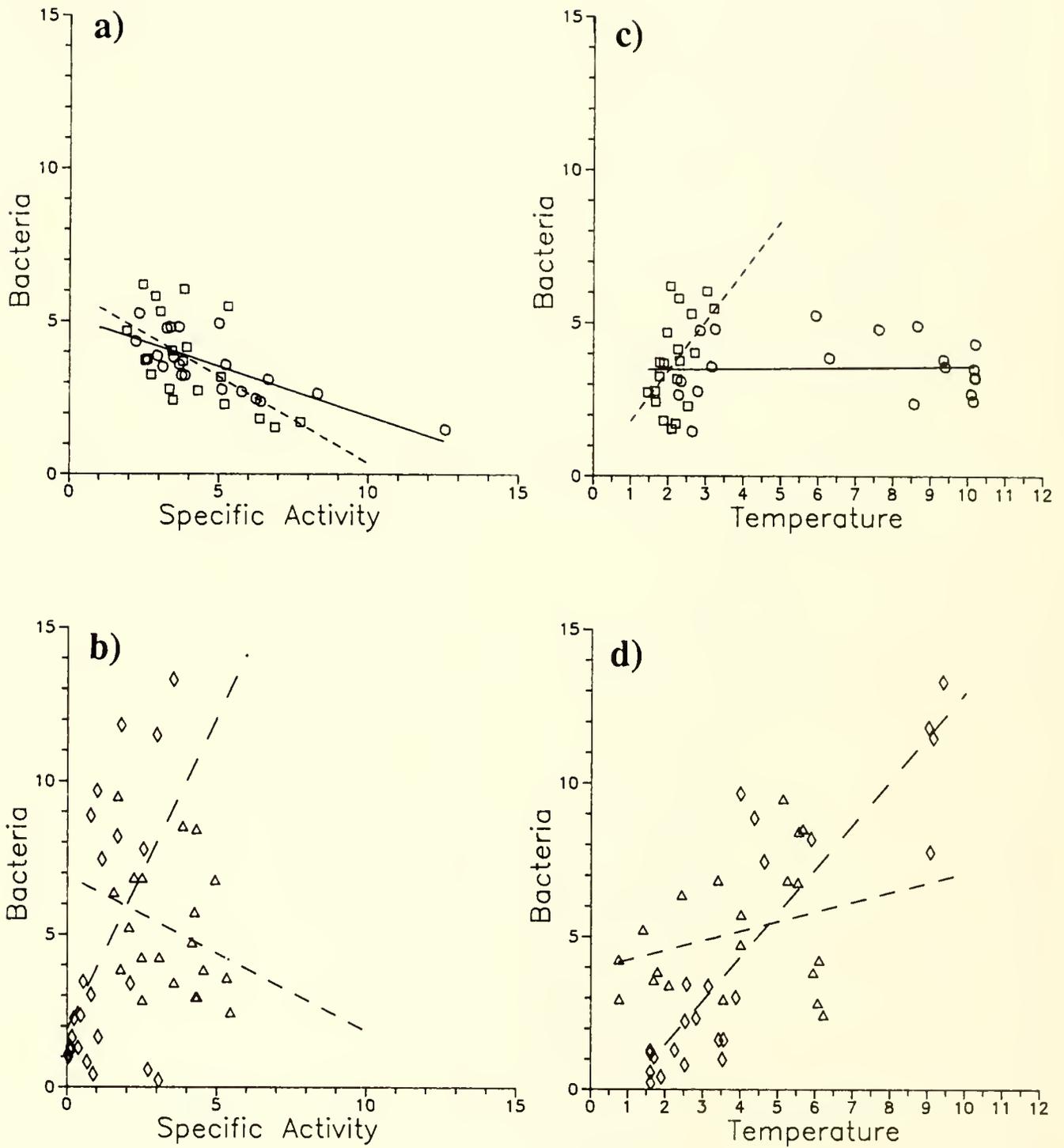


Figure 6. Linear regression of bacteria plotted against specific activity (a,b) and temperature (c,d). Fig. 6c shows data from ACW's (circles) and AW's (squares), and Figs. 6b and 6d show data from BSHW's (triangle) and BSW's (diamond). Statistics for linear regressions are given in Table 2.

TABLE 2

Statistical analysis for linear regressions of plots in Figs. 5 and 6.

Variable abbreviations: Thy (thymidine incorporation), Bac (bacteria), T (temperature), and Spa (specific activity of thymidine incorporation) are the parameters for the regression analysis.

Statistics Abbreviations: F-value (value for data variance), r^2 (correlation coefficient), C.V. (coefficient of variation), Intercept (y-intercept), Slope (slope of the best linear regression), T-test (test of null hypothesis (Ho), Slope >0).

Anadyr Waters

Regres.	F value	r^2	C.V.	Intercept	Slope	T-test
Thy*T	5.6	0.23	22.7	1.94	-0.058	0.03
Thy*Spa	8.8	0.33	21.3	1.09	0.092	0.008
Bac*T	0.1	<0.01	29.3	3.44	0.015	NS
Bac*SPA	26.2	0.59	18.7	5.11	-0.322	0.0001

Alaskan Coastal Waters

Regres.	F value	r^2	C.V.	Intercept	Slope	T-test
Thy*T	33.4	0.64	22.7	-0.56	0.887	0.0001
Thy*Spa	0.5	0.03	37.9	1.14	0.056	NS
Bac*T	6.5	0.26	34.7	0.17	1.625	0.02
Bac*Spa	10.7	0.37	32.2	6.00	-0.564	0.004

Bering Shelf Waters

Regres.	F value	r^2	C.V.	Intercept	Slope	T-test
Thy*T	3.2	0.15	47.3	1.04	0.169	NS
Thy*Spa	6.2	0.25	44.2	0.50	0.347	0.02
Bac*T	1.6	0.09	40.1	3.93	0.315	NS
Bac*Spa	1.8	0.09	39.9	6.91	-0.507	NS

Bering Sea water

Regres.	F value	r^2	C.V.	Intercept	Slope	T-test
Thy*T	98.2	0.82	70.1	-0.92	0.418	0.0001
Thy*Spa	23.4	0.51	114.1	-0.21	0.797	0.0001
Bac*T	79.2	0.78	46.4	-1.37	1.433	0.0001
Bac*Spa	8.4	0.27	84.5	1.87	2.038	0.008

lower than Anadyr and ACW's (T-test, $P < 0.05$). The specific activity again was unrelated to frequency of dividing cells (T-test, $P > 0.05$).

Bering Sea water: The highest rates of thymidine incorporation and numbers of bacterioplankton were measured in the surface mixed layer of the south Bering Sea (Fig. 6). Incorporation rates ranged from 5 pmole $l^{-1} h^{-1}$ above the thermocline to less than 1 pmole $l^{-1} h^{-1}$ below the thermocline and less than 0.2 pmoles $l^{-1} h^{-1}$ below 100 m. Rates were strongly correlated with temperature and specific activity (Fig. 2, Table 2). However, this strong relation could be attributed to any number of factors (e.g., phytoplankton productivity or biomass in the upper mixed layer).

Surface mixed layer processed the highest number of bacterioplankton (1×10^9 cells l^{-1}), and numbers decreased to less than $1-2 \times 10^8$ cells l^{-1} below 100 m (Figs. 5a,b). Likewise, bacteria correlated strongly with temperature and specific activity (Fig. 3, Table 2).

Surface waters also had the highest frequency of dividing cells (4 to 7% dividing), but frequency of dividing cells decreased with depth to less than 2% dividing below 500 m (Fig. 6). At Station 110, bacterioplankton showed a secondary peak in dividing cells at 1,500 m, and below 2,000 m dividing cells increased with depth to nearly 12% dividing cells. Specific activity showed a similar distribution to frequency of dividing cells in the water column. In the mixed layer, specific rates averaged 2.5×10^{-21} mole cell $^{-1} h^{-1}$ (Table 1) and decreased to 0.11×10^{-21} mole cell $^{-1} h^{-1}$ below 500 m. At Station 110, both specific activity and the frequency of dividing cells increased with depth below 1,500–2,000 m. At Station 113, specific activity, but not frequency of dividing cells, increased with depth below 1,500 m (the old GEOSECS Station).

Spatial Distribution of Bacterioplankton

In the Chirikov basin, bacterioplankton dynamics showed considerable variability through the water column and across the water types. The regional depth distribution of bacterioplankton parameters are summarized in Table 1. In nutrient-rich AW, the highest rates of thymidine incorporation occurred in the surface and near bottom waters. Bacterioplankton, frequency of dividing cells, and specific activity, generally covaried with the rates of thymidine incorporation, even though the water column was isothermal.

In nutrient-poor ACW, the thermocline was generally a dynamic region in the water column for bacterioplankton activity. Bacterioplankton, thymidine incorporation, frequency of dividing cells, and specific activity peaked within the region of the thermocline at water depths of 10–20 m, whereas in BSHW, the upper mixed layer contained highest bacterioplankton activity.

Like BSHW, the highest bacterioplankton activity occurred in the upper mixed layer in the deep waters of the south Bering Sea. Below the thermocline, bacterioplankton uptake of thymidine diminished greatly even though measures of population growth rate increased with depth in bottom waters. In these deep waters, bacterioplankton populations were an order of magnitude or two lower than upper mixed layer.

Comparison to other Marine Ecosystems

Thymidine incorporation data reported here for Chirikov basin and south Bering Sea (0.0 to 4.7 pmoles $l^{-1} h^{-1}$) fell within the range of values reported for other coastal-shelf waters and adjacent and marginal seas in both high and low latitudes of the Northern and Southern Hemispheres. In polar waters of McMurdo Sound and the ice edge zone of the Ross Sea, Antarctica, where temperatures range from -1.8 to 5°C year round, Fuhrman and Azam (1980) found similar rates of thymidine incorporation of 0.2 to 11.3 pmoles $l^{-1} h^{-1}$ (calculated from values in Table 1, Fuhrman & Azam, 1980).

Within the Antarctic Polar Front (2.5°C) of the Drake Passage, rates were also on the order of 0.1 to 10 pmoles $l^{-1} h^{-1}$ over the upper mixed layer, but within the productive marginal ice edge zone (-1 to 2°C) off the Palmer Peninsula, rates as high as 200 pmoles $l^{-1} h^{-1}$ were measured (Hanson & Lowery, 1983). In northern latitudes off Nova Scotia, Canada, Douglas *et al.* (1987) found thymidine

incorporation rates ranging from 1.4 pmoles $l^{-1} h^{-1}$ in coastal waters with temperatures of 6.5°C to rates of 4.7 pmoles $l^{-1} h^{-1}$ at the shelf break with temperatures of 7.5–10°C. In the Celtic Sea where water-column temperatures varied from 8 to 15°C, thymidine rates ranged from 0.24 to 0.81 pmoles (values converted from data given in Table 3 in Joint & Pomroy, 1983). In coastal shelf waters off NW Spain with temperatures of 10–18°C, rates of 0.1 to 10.1 pmoles $l^{-1} h^{-1}$ were reported (Hanson *et al.*, 1986a; Hanson *et al.*, accepted). In other temperate waters, rates ranged from 0.1 to 20 pmoles $l^{-1} h^{-1}$ for California Coastal waters (calculated from data in Table 1 in Fuhrman *et al.*, 1980) and for southeastern US shelf waters (Hanson *et al.*, 1988). Therefore, results from the Chirikov basin and surface waters of the south Bering Sea show that bacterioplankton during this late summer period appeared as productive as bacterioplankton on many continental shelves and oceanic ecosystems in northern temperate and southern polar regions.

Bacterioplankton are the most abundant group of marine organisms in pelagic communities, yet the least understood in regard to population structure, function, and interaction with other pelagic communities in marine food webs. Total bacterioplankton counts varied little with water type on the north Bering Sea Shelf (overall $4.2 \times 10^8 \pm 0.2$ [S.E.] cells l^{-1}). The highest density of bacterioplankton occurred in the surface waters of the south Bering Sea (about 1.3×10^9 cells l^{-1}). These densities are quite similar to values reported for other polar or subpolar regions (Fuhrman & Azam, 1980, 1982; Hanson *et al.*, 1983; Garrison *et al.*, 1986; Pomeroy & Deibel, 1986; Douglas *et al.*, 1987; Kottmeier & Sullivan, 1987).

Estimate of Bacterioplankton Productivity and Growth Rates

Because of the uncertainty in the proportion of bacterioplankton that use thymidine for DNA synthesis relative to total metabolically active cells (Douglas *et al.*, 1987), we can only estimate the productivity of the bacterioplankton in the Bering Sea ecosystem. Our estimates are based on a theoretical conversion factor of 2×10^{18} cells produced (mole of thymidine incorporated) $^{-1}$ (Fuhrman & Azam, 1982), the accuracy of which depends on a number of assumptions that have been discussed previously (Fuhrman & Azam, 1982; Ducklow & Hill, 1985; Douglas *et al.*, 1987).

Empirically derived CF's generally range 1 to 5×10^{18} cells produced (mole of thymidine incorporated) $^{-1}$ (Kirehman *et al.*, 1982; Riemann *et al.*, 1984, 1987; Ducklow & Hill, 1985). Acknowledging the relative accuracy of the theoretical CF, we applied the theoretical CF and report the productivity of the bacterioplankton in the Chirikov on the order of $1-5 \times 10^6$ cells produced $l^{-1} h^{-1}$, average 3×10^6 cells $l^{-1} h^{-1}$ (Table 3). These rates of cell productivity in the Chirikov basin are on the same order as rates measured in other high and low latitude ecosystems. In McMurdo Sound and the Ross Sea, Antarctica, Fuhrman and Azam (1980) estimated cell productivity ranging from <0.1 to 21×10^6 cells $l^{-1} h^{-1}$ (rates adjusted 1.54 times; a theoretical CF of 1.3×10^{18} cells [mole of thymidine incorporated] $^{-1}$ was originally applied to thymidine incorporation for cell productivity estimates).

TABLE 3

Bacterioplankton production (mg carbon $m^{-2} d^{-1}$), biomass (g carbon m^{-2}), growth rate (u, d^{-1}), and doubling time ($\ln 2/u$, days) in the Chirikov basin and south Bering Sea, August 1988. Bacterioplankton production based on estimates from thymidine (Thy) incorporation and frequency of dividing cells (FDC).

N	Production		Biomass	Growth Rate	Doubling Time
	Thy	FDC			
<u>Anadyr Waters</u>					
20	263	855	1.48	0.18	3.8
<u>Alaskan Coastal Waters</u>					
20	223	623	1.08	0.21	3.3
<u>Bering Shelf Waters</u>					
20	245	1050	1.82	0.14	4.9
<u>Bering Sea Waters (upper mixed layer)</u>					
6	387	1770	3.00	0.13	5.3

Dividing-cell productivity by the total number of bacterioplankton, an estimate of the specific growth rate of bacterioplankton population can be calculated. Specific growth rates in the three water types in the Chirikov basin are given in Table 3. Growth rates were not significantly different across the basin. Rates averaged 0.18 day^{-1} (or a population doubling time of roughly 5 days). The doubling time of 5 days is similar to the doubling times reported for temperate coastal and shelf waters (1 to 4 days, Fuhrman & Azam, 1982; 4 days, Joint & Pomroy, 1983; 0.8 to 10 days, Hanson *et al.*, 1986b, 1988).

Assuming a thymidine-active subpopulation of 50% of the total number of bacterioplankton in the Chirikov basin, the doubling time of this subpopulation is 2.5 days. The doubling time of the thymidine-active bacterioplankton in Canadian Shelf waters off Nova Scotia ranged from 0.5 to 1.2 days (Douglas *et al.*, 1987). Thus, mean growth rate for bacterioplankton of high latitude ecosystems are in general comparable to rates calculated for bacterioplankton in low latitude environments.

Hagstrom *et al.* (1979) proposed a frequency of dividing cells (FDC) method to estimate bacterioplankton growth rates without incubation and radioactive organic substrates. Theoretical consideration and empirical evidence have shown that the frequency of cells in the dividing state is proportional to the growth rate of the population (Newell & Christian, 1981; Larsson & Hagstrom, 1982; Hanson *et al.*, 1983). To calculate growth rates by the FDC technique, a basic assumption is that all cells are metabolically active. But because of inactive cells in the population, FDC values underestimate the growth state of the active population. Thus, estimates of bacterioplankton growth rates using FDC error conservatively.

The FDC values in this study ranged from 1 to 12% of the cells dividing (averaged 4%), not much different from values reported elsewhere. Using the empirical relationship between FDC and specific growth rate, u ($\ln u = 0.81[\text{FDC}] - 3.73$), (Hanson *et al.*, 1983), for southern ocean bacterioplankton, we calculated a specific growth rate of 0.58 day^{-1} , a doubling time of 1.7 days. Growth rates estimated from the FDC method in the Chirikov basin were generally lower than those made from thymidine incorporation. A similar conclusion was made by Riemann *et al.* (1984), although Newell and Fallon (1982) found lower results for thymidine incorporation compared with FDC. The results shown here for thymidine incorporation and FDC procedures indicate doubling times between 2 and 5 days. Correcting for inactive cells, bacterioplankton growth rates probably range on the order of 1 to 3 days during the late summer period in the Chirikov and south Bering Seas.

In summary, bacterioplankton carbon production in the Chirikov basin and the surface waters of the south Bering Sea was estimated based on an average carbon content of 10 femtograms carbon per cell (Fuhrman & Azam, 1980). From thymidine-based cell productivity estimates, bacterioplankton production averaged $245 \text{ mg C m}^{-2} \text{ d}^{-1}$ in the Chirikov basin and $387 \text{ mg C m}^{-2} \text{ d}^{-1}$ in the upper mixed layer of the south Bering Sea (Table 3). Frequency of dividing cells-based production was 2 to 5 times the thymidine-based estimates (Table 3). The large difference between both estimates is attributed to the relative accuracy of the theoretical conversion factor and the empirically derived FDC equation. Thus, a comparison of bacterioplankton production and phytoplankton production in the Chirikov and south Bering Seas suggests that bacterioplankton production ranges between 5 and 33% of the phytoplankton production (Table 4). If we assume that the average growth yield of marine bacteria is about 50% of the organic matter consumed, then bacterioplankton in these waters may consume upwards to 70% of the total phytoplankton production, but it is probably much less. Future bacterial studies need to evaluate the incorporation of thymidine into cellular components, growth kinetics, active cells, and empirical relationships of thymidine incorporation and frequency of dividing cells.

The authors thank the US Fish and Wildlife Service (USFWS) and Division of Polar Programs (NSF) for travel and shipping assistance and Mr. Steven Kohl (USFWS) for logistical arrangements that

TABLE 4

Comparison of bacterioplankton and phytoplankton production ($\text{mg carbon m}^{-2} \text{ h}^{-1}$) in the Chirikov basin and south Bering Sea, August 1988. Bacterioplankton production estimated from thymidine incorporation and frequency of dividing cells (see Table 3).

	<u>Bacterioplankton Production</u>	<u>Phytoplankton Production</u>	<u>Percent Bacterioplankton</u>
<u>Anadyr Waters</u> (0-40 meters)	10.9-35.6	175	6-20
<u>Alaskan Coastal Waters</u> (0-35 meters)	9.3-25.9		
<u>Bering Shelf Waters</u> (0-40 meters)	10.2-43.8	209	5-21
<u>Bering Sea Waters</u> (0-30 meters)	16.1-73.8	221	7-33
range	9-74	175-221	5-33

allowed the authors to participate in the Third Joint US-USSR Bering & Chukchi Seas Expedition. Mr. Harold J. O'Connor (USFWS), the US Project Leader, and Dr. Alla Tsyban, the USSR Project Leader, represented the bilateral US-USSR Environmental Agreement under Activity 02.07-2101. Dr. Terry Whitledge and Dr. Alla Tsyban acted as chief scientists for the Americans and Soviets on the Soviet's R/V *Akademik Korolev*. The authors acknowledge the cooperation and assistance of the captain, crew, and Soviet scientists during the research cruise aboard the R/V *Akademik Korolev*.

4.1.3 Bacterial Production and Destruction of Organic Matter

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Introduction

Bacteria play an important role in mineralization and detoxication of anthropogenic materials (e.g., oil hydrocarbons, pesticides, anionic surfactants, and heavy metal compounds) (Larsson & Lemkemeier, 1981; Tsyban, 1981; Bernard & George, 1986; Braginsky, 1986; Sahasrabudhe & Modi, 1987; Tsyban *et al.*, 1987d; Kirso *et al.*, 1988; O'Connor & Huggett, 1988). While considerable data have been published on the processes and mechanisms of organic matter destruction, the extent of biological self-purification have not been studied thoroughly enough, especially in subarctic and arctic areas of the World Ocean. In these regions, characterized by low temperatures and increasing anthropogenic load, the role of microbial transformation of contaminants becomes considerably more important. In this regard, the assessment of bacterial production, destruction of organic matter, and the transformation of toxic organic compounds of anthropogenic origin is very important to determine the assimilation capacity, self-purification of organic contaminants, and prognosis of marine ecosystems.

Materials and Methods

The production–destruction process affected by bacteria in the Bering and Chukchi Seas was studied in July–August 1988 during the third Soviet–American ecological expedition. Bacterial production and the rate of organic matter (OM) destruction was measured in the Gulf of Anadyr, Bering and Chukchi Seas (Fig. 1).

Dark CO₂ assimilation was measured by the Romanenko and Kuznetsov (1974) method. Details are given in *Methodical Foundations of Integrated Ecological Monitoring of the Ocean* (Tsyban *et al.*, 1988) and Kuznetsov and Dubinina (1989). To determine dark CO₂ assimilation, water samples were taken from standard hydrological depths with Niskin bottles and added to 100-ml stoppered bottles. The bottles were filled in the same way as samples taken for soluble oxygen (i.e., flushed with 3 water volumes). The bottles, filled with water, were placed in dark sacks and 0.5 ml of Na¹⁴C₃ (specific activity about 20 × 10⁶ counts/min) were added. Bottles were stoppered without air bubbles under the stopper. Duplicate samples were taken from each depth. Two reference bottles were included at each station and, apart from radioactive sodium carbonate, 1 ml of 40% formaldehyde solution was added. Bottles inside the sack were tightly closed to light and incubated at surface seawater temperature.

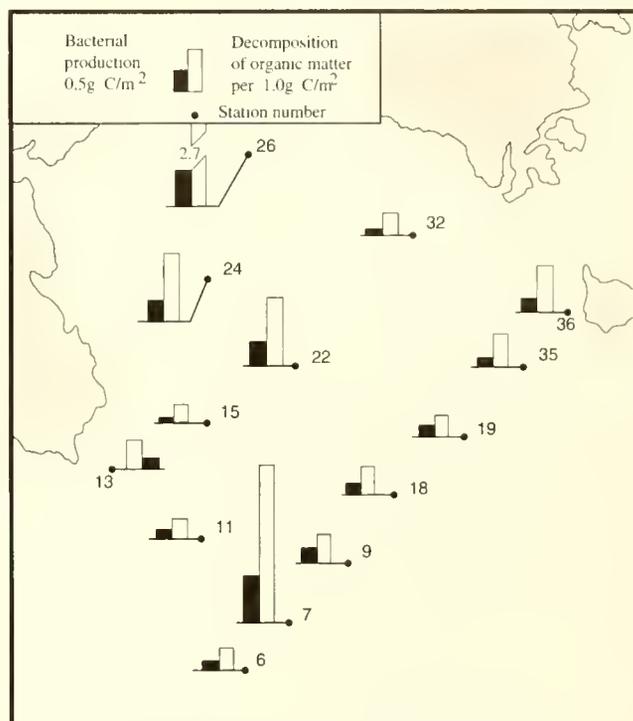


Fig. 1. Bacterial production and decomposition of organic matter in the 0.5 to 45 m layer in the Gulf of Anadyr, and central Bering Sea, summer, 1988.

After suitable exposure, depending on temperatures, formalin (1 ml) was added to each bottle. Water samples were filtered through a "Sinpor" membrane filter having pore diameter 0.35 or 0.45 μm and immediately treated with 1% hydrochloric acid to remove residues of radioactive carbonate. Radioactivity was measured by means of liquid scintillation. Dark CO₂ assimilation was calculated by the following formula:

$$C_{as} = \frac{C_{carb} \times r}{R \times t}$$

where

- C_{as} = dark CO₂ assimilation, μg C/l/d;
- r = radioactivity on filters, dpm/min;
- C_{carb} = carbonate contents in the water, mg C/l (determined by direct titration with 0.1 HCl in the presence of methyl red tracer);
- R = isotope added to each bottle, dpm/min;
- t = incubation time, 24 hours

Bacterial production was calculated by the formula

$$P_B = C_{as} \times 16.6,$$

where

- P_B = bacterial production, $\mu\text{g C/l/d}$;
 C_{as} = quantity of 14 CO_2 assimilated, $\mu\text{g C/l/d}$;
 16.6 = relationship of total biomass carbon and biomass synthesized from carbon dioxide (100:6).

To assess mineralization processes of organic matter, biochemical oxygen demand (BOD) is usually used. In practice, BOD is more often determined after 24 hours of exposure under *in situ* conditions. Presently, there is no single and reliable technique for BOD determination. "Bottle" technique over-estimates the oxygen demand of bacteria and is labor intensive. Apart from that, the effectiveness of the oxygen technique in eutrophic waters to determine destruction of organic matter in waters with low temperature and primary production is difficult. In mesotrophic and oligotrophic waters, the radioisotope technique is extensively used to measure destruction of organic matter which is more sensitive and less labor intensive. The application of this technique is due to the relationship between oxygen demand and heterotrophic assimilation of CO_2 by bacteria (Romanenko, 1965), where 7 mg C/CO_2 is assimilated per mg of oxygen used for bacterial respiration. Hence, there is a coefficient to determine the quantity of oxygen consumed by bacteria relative to heterotrophic assimilation of CO_2 .

Oxygen used by bacterial respiration was calculated by the formula

$$O_2 = C_T/7,$$

where

- O_2 = oxygen demand for organic matter destruction, $\text{mg O}_2/\text{l/d}$;
 C_T = dark CO_2 assimilation, $\mu\text{g/l/d}$;
 7 = Coefficient between oxygen demand and CO_2 assimilation.

Results and Discussion

Bacterial Production and Organic Matter Destruction in the Bering Sea

The change in bacterial numbers and biomass does not determine their biological state and role in marine ecosystems. These questions can be assessed by means of a sensitive radiocarbon technique to measure the bacterioplankton respiration.

The data obtained in summer 1988 (Table 1) show considerable variance in the rate of bacterial production (1.5–135 $\mu\text{g C/l/d}$) and destruction of organic matter (4.8–435.0 $\mu\text{g C/l/d}$). Production in the Bering Sea averaged 17.3 $\mu\text{g C/l/d}$ or 28.4 $\mu\text{g C/m}^2$. The destruction of organic

TABLE 1

The rates of bacterial production and destruction of organic matter in the Bering Sea in summer 1988.

Investigated sea areas	Bacterial production		Organic matter destruction		P/B
	$\mu\text{g C/l/d}$	g C/m^2	$\mu\text{g C/l/d}$	g C/m^2	
Bering Strait	8.0-28.9 16.4	0.7	25.7-92.7 52.7	2.4	1.1
Northern Bering Sea (Chirikov basin)	8.2-29.2 17.6	0.8	26.2-97.7 56.5	2.5	1.0
Anadyr Bay	1.5-33.7 6.4	0.9	4.8-108.2 20.7	2.9	0.4
Central Bering Sea	1.5-44.8 8.9	1.3	4.8-144.1 28.5	4.1	0.5
East Polygon	4.3-118.5 33.4	100.2	13.8-380.9 107.3	321.9	2.3
South Polygon	2.0-135.5 22.2	66.6	6.4-435.5 71.2	213.6	2.1
Total for the Sea	1.5-135.5 17.3	28.4	4.8-435.5 55.7	91.2	1.2

matter averaged 55.7 $\mu\text{g C/l/d}$ or 91.2 $\mu\text{g C/m}^2$. These rates are 20 times higher than similar estimates obtained in summer 1981 and 1984 (Tsyban *et al.*, 1987a). These rates also equalled production and destruction processes in mesotrophic marine ecosystems (Sorokin, 1980).

High rates of bacterial production and destruction of organic matter occurred in eastern and south Bering Sea (e.g., East and South Polygons). Maximum rates, found at Stations 3 and 108, averaged 47.8 and 153.7 $\mu\text{g C/l/d}$, respectively.

Low rates of bacterial production occurred between 0.5–45 m at Stations 5 and 109, where rates averaged 8.3 and 15.8 $\mu\text{g C/l/d}$, respectively. Rates of organic matter destruction at these stations averaged 26.8 and 50.9 $\mu\text{g C/l/d}$. These rate processes in 1988 are 10 times higher than those measured in 1981. The rates of bacterial production and organic matter destruction varied considerably across the eastern and south Bering Sea areas (Table 1). Thus, southern and eastern Bering Sea were characterized by high but variable rates of bacterial production and organic matter destruction across the basin. A high production/biomass (P/B) coefficient was also observed in eastern Bering Sea (Table 1).

In the central basin and in the Gulf of Anadyr, low rates of production and destruction occurred even though the total numbers of bacterioplankton in these areas were higher than in the southern and eastern Bering Sea (Tsyban *et al.*, Section 4.1, this volume). The rate of bacterial production and organic

matter destruction in euphotic zone averaged $8.4 \mu\text{g C/l/d}$, and $26.9 \mu\text{g C/l/d}$, respectively. Lower rates occurred in the Gulf of Anadyr.

Maximum activity of microflora and high rates of bacterial production of 25.5 and $18.7 \mu\text{g C/l/d}$ and organic matter destruction of 81.9 and $60.0 \mu\text{g C/l/d}$ were found at Stations 7 and 26 (Fig. 1; Subchapter 4.2.1, this volume). The lowest rates of bacterial production of 4.2 and $2.8 \mu\text{g C/l/d}$ and organic matter destruction of 13.4 and $9.1 \mu\text{g C/l/d}$ were found at Station 6 in the deep central part of the Bering Sea, and at Station 11 in the Gulf of Anadyr. These results are similar to those obtained for stratified waters in the vicinity of frontal zone of the Irish Sea (Turley & Lochte, 1985).

The results showed that the highest rates of bacterial production and organic matter destruction occurred in the surface microlayer and near-bottom waters in the deep central basin of the Bering Sea, higher than rates measured in the zone of phytoplankton photosynthesis. In Gulf of Anadyr, rates gradually decreased with depth, and in bottom waters, rates of bacterial production and organic matter destruction were two times lower than in the surface microlayer.

In general, the central part of the Bering Sea and Gulf of Anadyr were characterized by the low bacterioplankton activity, the low rates of bacterial production and organic matter destruction, as well as by low production/biomass coefficient.

Because of its distinct hydrological and hydrochemical characteristics, the northern part of the Bering Sea is much different in other areas in the sea. Shallow depths, intensive water exchange and unstratified water column produced a uniform distribution of bacterioplankton and microflora activity. The rates of bacterial production and organic matter destruction were high (Table 1) in this part of the sea. The average daily rate was about $18 \mu\text{g C/l}$. Organic matter destruction amounted to about $56.6 \mu\text{g C/l}$, which is about 3 times higher than in the Gulf of Anadyr. Integrated over the water column, the rate of bacterial production was 0.8 g C/m^2 and destruction of 2.5 g C/m^2 .

The highest microflora activities and diurnal rates of bacterial production of $12.1 \mu\text{g C/l/d}$ or 0.85 g C/m^2 were found at Station 96 and the lowest rates at Station 92. The rate of organic matter destruction at Station 96 was $68.0 \mu\text{g C/l/d}$ or 2.7 g C/m^2 , whereas at Station 92 destruction was two times lower (Fig. 2; Subchapter 4.2.1, this volume).

The distribution of microflora activity in the Chirikov basin was independent of the uniform distribution of bacterioplankton. The rates of bacterial production and organic matter destruction in the surface microlayer decreased with depth. The daily rate averaged about $20 \mu\text{g C/l}$ of bacterial biomass in the surface microlayer while organic matter destruction averaged to $65.1 \mu\text{g C/l/d}$.

Thus, the shallow waters of the northern Bering Sea was characterized by high rates of bacterial production and organic matter destruction, the integrated rates being much lower than in deep water areas of the sea. In addition, microflora activity varied horizontally and vertically, and P/B coefficient averaged 0.97 in the northern Bering Sea.

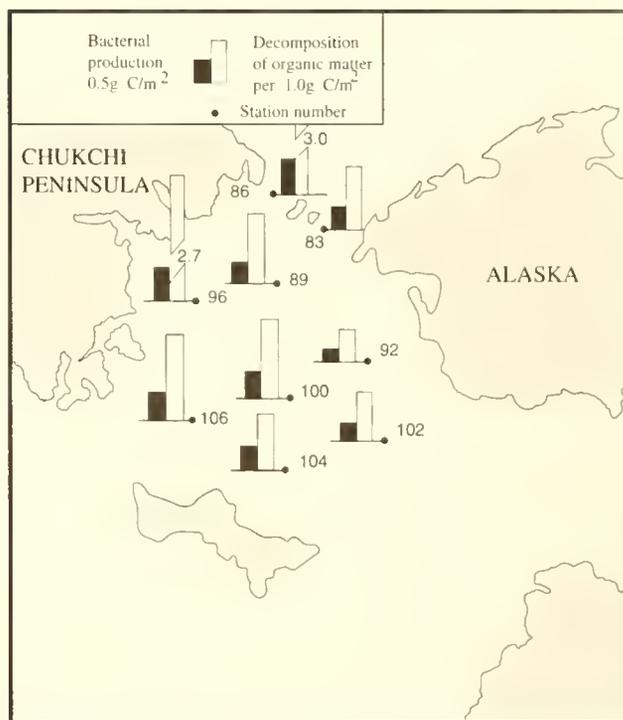


Fig. 2. Bacterial production and decomposition of organic matter in the 0.5 to 45 m layer in the northern Bering Sea, summer 1988.

In summary, this investigation of microbiological processes in the Bering Sea allowed us to assess the scales of some links in production and transformation of organic matter. It was shown that CO_2 assimilation by heterotrophic microorganisms contributes to the production of organic carbon in the system. Microflora contribution to the total production via CO_2 fixation is sufficiently high and can amount to about 30% of the primary production. In addition, microflora contributes to the destruction of organic matter. The rate of destruction processes was determined based on the activity of bacterial population, trophic ability level, and hydrological and chemical conditions in the sea.

Bacterial Production and Organic Matter Destruction in the Chukchi Sea

The rates of bacterial production and organic matter destruction were measured in the Chukchi Sea for the first time. The results (Table 2) show that a relatively high rate of production and destruction occurs in the water column. The average rate of bacterial production was about $20 \mu\text{g C/l/d}$, or 0.8 g C/m^2 . The rate of organic matter destruction was about $64.9 \mu\text{g C/l/d}$, or 2.5 g C/m^2 . These rates are slightly higher than those in the Bering Sea. They agree with the rates of production and respiration in mesotrophic waters, such as temperate seas, regions of equatorial divergence, upwelling areas where daily production of bacterioplankton biomass varied from 5 to $20 \mu\text{g C/l}$ and respiration from 10 to $60.0 \mu\text{g C/l}$ (Sorokin, 1985).

Based on microflora activity, rates of bacterial production, organic matter destruction, and bacterial respiration, some areas in the sea differed from other areas. The highest microflora

TABLE 2

The rates of bacterial production and organic matter destruction in the water column of the Chukchi Sea, summer 1988.

Investigated sea areas	Bacterial production		Organic matter destruction	
	$\mu\text{g C/l/d}$	g C/m^2	$\mu\text{g C/l/d}$	g C/m^2
Northern part of the Sea	<u>2.2-46.5</u> 16.7	0.7	<u>6.9-149.5</u> 53.6	2.4
Coastal Alaska Area	<u>2.0-20.6</u> 11.0	0.3	<u>6.4-65.9</u> 35.4	1.0
Central part of the Sea	<u>7.9-66.9</u> 26.8	1.1	<u>25.2-214.8</u> 86.4	3.4
Coastal Chukotka Area	<u>7.9-61.3</u> 26.2	1.0	<u>25.2-196.6</u> 84.3	3.2
Total for the Sea	<u>2.0-66.9</u> 20.2	0.8	<u>6.4-214.8</u> 64.9	2.5

activity was found in the central basin of the Chukchi Sea (Fig. 3; Subchapter 4.2.1, this volume). In coastal waters of the Chukchi, rates of bacterioplankton production and organic matter destruction averaged 2–3 times higher than the rates of production and organic matter destruction in Alaskan Coastal waters.

The daily rate of bacterial production averaged $26.8 \mu\text{g C/l}$ or 1.1 g C/m^2 ; bacteria respiration rate was $86.4 \mu\text{g C/l}$ or 1.3 g C/m^2 ; P/B coefficient was 1.3. A low microflora activity was observed in coastal areas of Alaska. Diurnal rates of bacterial production averaged 0.3 g C/m^2 , respiration rate 1.0 g C/m^2 , and P/B coefficient was the lowest, 0.5; measured in the region.

Although the rates of bacterial production and organic matter destruction varied in the water column, microflora activity and organic matter destruction gradually increased from surface layers towards the bottom of the water column.

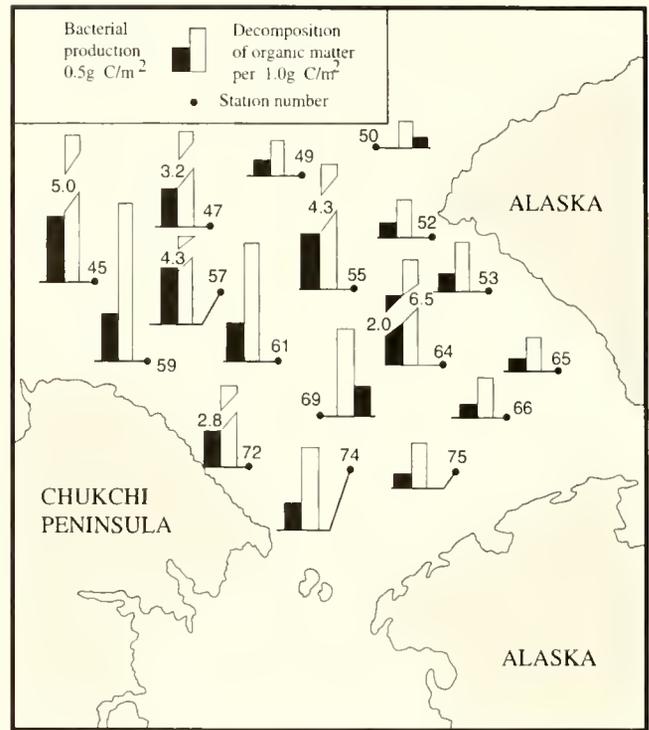


Fig. 3. Bacterial production and decomposition of organic matter in the 0.5 to 45 m layer of the Chukchi Sea, summer 1988.

In the northern Chukchi Sea, rates of bacterial production in layer 25–45 m were 1.7 times higher than rates measured in water layer 0.5–25 m. Total production of bacterial biomass in bottom waters averaged $27.8 \mu\text{g C/l/d}$, while in euphotic waters production was $20 \mu\text{g C/l/d}$.

In conclusion, the study of microflora and microbiological processes in the Chukchi Sea allowed us to identify specific features of formation and function of microbiocenoses in this Arctic Sea. In addition, the activity of microflora and rates of bacterial production was determined and the role of bacterioplankton assessed in the transformation of organic matter. The results showed that the rates of bacterial production and organic matter destruction in the Chukchi Sea equaled rates in mesotrophic waters.

Subchapter 4.2:

Heterotrophic Saprophytic Microflora

4.2.1 Distribution of Indicator Groups of Marine Heterotrophic Microorganisms

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Introduction

Over the last few decades, the attention over ocean pollution has become one of the most urgent problems in applied oceanography and is drawing great attention by world scientific communities (Goldberg, 1970; Bernhard & Zattera, 1975; Izrael & Tsyban, 1981, 1985a, 1989; Pravdic, 1981; Gesamp, 1982; Kullenberg, 1984). Today's anthropogenic impact on the World Ocean creates a tense ecological situation. Pollutants are becoming not only a continuously active ecological factor (Izrael & Tsyban, 1985), but also an evolution factor by affecting sea organisms (Izrael & Tsyban, 1989). Pollutants getting into the sea environment, including xenobiotics, cause rapid change in sea organisms and, due to directional selection, result in active growth of certain hydrobionts and disappearance of others that are not able to tolerate the action of foreign substances. Organisms, which have adapted to new chemical compounds that pollute the sea environment and then take a dominant position in the biocenosis structure, are named after the chemical substance. There are grounds to suggest that the development of these hydrobionts is a function biological response to the chemical pollutants of the world's oceans (Izrael & Tsyban, 1981, 1985a, 1989). Biological significance of indicator types is determined by their special designation. Some fill a critical gap in biocenoses, others help to restore the natural backgrounds while still others determine the immunity of the sea ecosystem (Izrael & Tsyban, 1989). The latter include sea microorganisms.

Microorganisms have high rates of reproduction and extensive range of constitutive and inductive enzymatic activity. The latter characteristic stipulates their ability to transform and utilize practically all naturally occurring organic compounds. For this reason, these organisms are distinguished for their unique ability to rapidly adapt to changing environmental conditions. For example, an accidental oil spill in the world's oceans would result in rapid and abrupt increase of hydrocarbon oxidizing bacteria by 3–5 orders of magnitude (Gunkel, 1968; Atlas *et al.*, 1976; Le Petet *et al.*, 1977; Oppenheimer *et al.*, 1977; Atlas, 1981).

The possibility of using microorganisms that are capable of oxidizing oil as indices of the degree of hydrocarbon oxidation under natural conditions and indicators of oil pollution was shown in the 1950's (Izjurova, 1950; Voroshilova & Dianova, 1950, 1952). According to Voroshilova and Dianova (1950, 1952), the number of oil-oxidizing bacteria in clean pools did not exceed 100 cells/ml, and in 50% of the cases, less than 10 cells/ml. Another parameter used as an index of the degree of water pollution with oil products is the ratio of the

numbers of oil-oxidizing to heterotrophic bacteria (Voroshilova & Dianova, 1950; Gavrishova, 1969; Mironov, 1970). Atlas (1981) used the ratio between oil oxidizing microorganisms and total bacterial number as an index of oil pollution.

The concept of using microbes as indicative of organic pollutants in the World Ocean has been most actively developed during the last 20 years. It was shown (Tsyban *et al.*, 1985) that, depending on the phenomena under consideration, microbial cenoses may act not only as indicators of physicochemical and biological processes but also as a powerful biotic factor, facilitating pollutants' elimination from the sea environment.

At present, physiological and biochemical potential of microbial populations is at the stage of active developments. However, these important fields of marine microbiology have not investigated the distribution in different parts of the World Ocean or with depth of heterotrophic bacteria using or transforming various organic substances. Bacteria using high-molecular toxic compounds (e.g., benzo(a)pyrene [BaP] and polychlorinated biphenyls [PCB's]), are an important characteristic of the world ecosystems state under the conditions of increasing anthropogenic influence.

Materials & Methods

Investigations of indicator microflora in the Bering Sea began in 1981 (Izrael *et al.*, 1987) and continued during the period of the Second Joint US–USSR Expedition on board the research vessel (R/V) *Akademik Korolev* in 1984 (Izrael *et al.*, 1988; 1989; 1990). These investigations were continued in 1988 during the Third Joint US–USSR Bering & Chukchi Seas Expedition on the *Akademik Korolev*. It should be noted that in 1988 observations were carried out not only in the same areas of the Bering Sea as in 1981 and 1984 but also covered some new areas: the Gulf of Anadyr, the Chirikov basin, the Bering Strait, and the southern part of the Chukchi Sea. All together, 82 stations were studied in the Bering Sea and 31 stations in the Chukchi Sea.

Water samples from the near-surface microlayer 0–2 cm thick were taken with sterile water microsamplers, with sterile bottles, or with plastic Niskin Water samplers, presterilized with 96% ethanol. These samples were immediately analyzed to reveal indicator bacteria, including the following forms: saprophytic bacteria (SB), hexadecane oxidizers (HDB), benzo(a)pyrene transformers (BaPB), and polychlorobiphenyl transformers (PCBB). The determination of bacterial indicator groups is viewed as a study of physiological activity of indigenous sea microflora prior to their isolation from the habitat.

Numbers were determined by the method of ultimate dilutions, described as early as 1927 by Razumov (1927), which is widely used in similar works (Gunkel, 1967; Atlas, 1981; Platpira, 1982, 1985; Shtukova, 1990). The method consists of adding into two to three rows of test tubes, containing a liquid medium or "sea potassium-yeast medium" (SPY). These media were supplemented with hexadecane, BaP, or PCB as the only source of carbon. Dilutions were made in measured volumes of analyzed seawater so that the initial sample in the first test tubes was diluted 1:10, and followed by 1:100, 1:1,000, 1:10,000 (etc.) times accordingly. After incubation, test tubes were checked for maximum dilution of the sample that showed growth of the bacterial physiological group under study. Growth was determined visually by change in transparency and color of the medium. A special statistical McCredy table was used to determine the numbers of bacterial cells per milliliter. When using the method of ultimate dilutions, we assumed that the observed bacterial growth occurred when at least one actively dividing bacterial cell was transferred during inoculation.

To study SB, fish broth made with seawater from investigated areas was used as a liquid medium, prepared from 0.5 kg of fish cooked in 1 liter of water, and diluted 10 times with the same seawater. The medium was poured into test tubes and sterilized in an autoclave with pressure 1 atm (1.01×10^5 Pa) for 20 minutes. To determine the number of other indicator bacteria groups, a liquid SPY medium was used (Tsyban, 1970; Seki, 1986) containing K_2HPO_4 (1 g), NH_4Cl (1 g), yeast extract (0.5 mg), and seawater (1,000 ml). These media were poured into test tubes and autoclaved. Sterile substrate, hexadecane, BaP, PCB, or Aroclor 1232 (0.01–1%) was added into test tubes after inoculation.

The SPY medium, as an elective media, has found extensive application in the practice of marine microbiology (Seki, 1982; Tsyban *et al.*, 1985; Izrael & Tsyban, 1989).

The statistical method of prismatic ecograms was used to analyze the results (Tsyban, 1970).

Results and Discussion

Saprophytic Bacteria in the Bering and Chukchi Seas

In the central Bering Sea (East Polygon), the MPN of SB varied within the range of $0-1.8 \times 10^3$ cells/ml, 222–440 cells/ml for the investigated stations. These bacteria varied with depth at Stations 1, 2, and 3 of about 3,000 m deep. Maximum concentrations of more than 1,000 cells/ml occurred at depths 10–25 m (thermoline), 150, 500, and 2,500 m. The above bacterial groups were not discovered at Station 1, 15 m and 3,000 m; at Station 2, 2,000 m; Station 3, surface microlayer; or Station 4, 25 m. At shallow-water stations (Stations 4 and 5), SB increased only in deep-water and near-bottom layers of waters deeper than 100 m. Such distribution of microflora reflected water masses heterogeneity in this sea area. Compared to 1984 (Izrael *et al.*, 1988; Tsyban *et al.*, 1990), the number of SB at East Polygon remained constant ($0-10^4$ cells/ml), but their vertical distribution varied with depth.

In the northwest Bering Sea at the sections near St. Lawrence Island, SB distribution was also variable. Maximum concentrations (10^3 cells/ml) occurred at depth and in the near bottom layers of Stations 7, 18, and 19. Overall, the vertical distribution of this group of microorganisms showed an increase in numbers with increase in depth. At Station 36, not far from the St. Lawrence Island, the SB (10^2 cells/ml) remained constant over the entire water column from 15 m to the bottom. At other stations SB in the upper layers of water (0, 5, and 10 m) ranged from 10^0 to 10^3 cells/ml.

Distribution analysis of mean SB number showed that maximum mean MPN values were typical for Station 7 (2.4×10^3 cells/ml). At other stations of the section (with the exception of Station 35), mean values for saprophytes varied between 105 and 360 cells/ml. At Station 35, the SB mean was about 96 cells/ml.

First studies of microflora of the Gulf of Anadyr were made during this cruise. Numbers varied across a very wide range from zero to 1.8×10^4 cells/ml. Maximum values occurred at Stations 24 and 27. At Station 11, SB did not range greatly—0–300 cells/ml, mean 56 cells/ml. At Station 41, situated between the Gulf of Anadyr and Chirikov basin, SB averaged 7.1×10^3 cells/ml. Vertical distribution of saprophytes was variable, with a trend towards increasing concentration with depth (Fig. 1).

In the Chirikov basin and Bering Strait, SB varied vertically and horizontally. Overall, concentrations ranged between 0 and 1.8×10^4 cells/ml. At Stations 96, 100, 102, and 104, cell

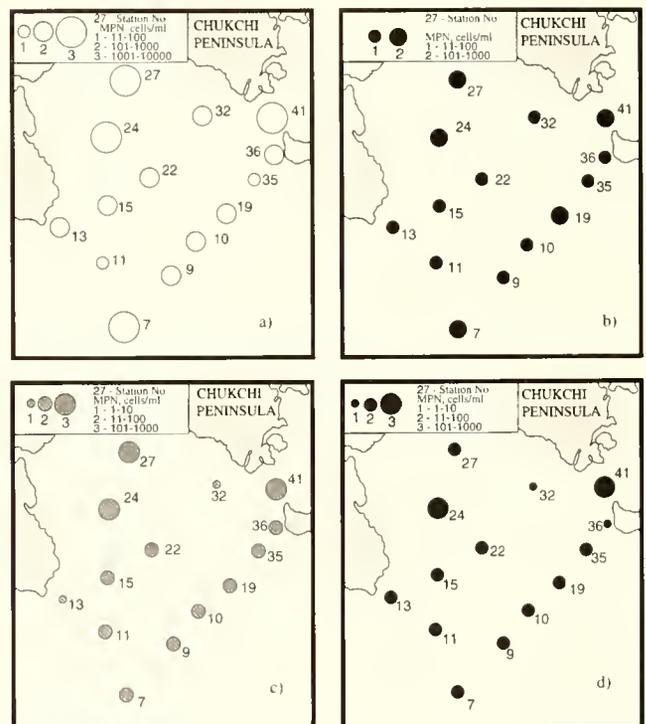


Fig. 1. Vertical distribution of mean values of the most probable number (MPN) of heterotrophic-saprophytic (a), hexadecane oxidizing (b), benzo(a)pyrene transforming (c) and PCB-transforming (d) bacteria at stations in the northwestern Bering Sea and the Gulf of Anadyr in summer 1988.

numbers averaged 10^2 cells/ml, and at Stations 89, 92, and 104, numbers averaged 10^3 cells/ml. At Station 102, in the southeastern part of the basin, SB averaged only 170 cells/ml, but near the Alaskan shore (Station 92) we found the largest concentrations (4.4×10^3 cells/ml) in the Bering Sea.

In the deep Bering Sea (South Polygon), SB ranged from 0 to 1.8×10^3 cells/ml, but mean values (per station) were higher, $1.3\text{--}2.6 \times 10^3$ cells/ml. Compared to 1984 (Izrael *et al.*, 1988; Tsyban *et al.*, 1990), the numbers of SB increased slightly. In 1984, they were within the range of $0\text{--}3.0 \times 10^3$ cells/ml. The mean values were also higher in 1988. Distribution of these bacteria varied over water column depth. Saprophytic microflora in the near-surface microhorizon (0–2 cm thick) were absent or in extremely low numbers at Stations 108, 110, and 112.

In summer 1988, the first microbiological survey in the southeastern Chukchi Sea was made. The area was characterized by two large sources of biogenous elements. Here, inorganic nitrogen compounds were being advected through the Bering Strait and along the coastal Siberian Current. Biogenous elements also originated from the Chukchi and Alaska Rivers. Through the combination of these flows, a wide area with high rates of primary production of organic matter by phytoplankton, was formed in the southeastern Chukchi Sea. In the process of photosynthesis, phytoplankton excrete newly synthesized organic matter that is substrate for bacterioplankton. Extensive growth of phytoplankton is usually accompanied by increased numbers of SB (Gocke, 1977; Rheinheimer, 1977, 1985).

Indeed, our results show that the numbers of SB were higher in the Chukchi Sea than in the northwestern and northern parts of the Bering Sea. The number of SB varied between 1.8 and 2.0×10^4 cells/ml, with averages between 0.4 and 16.6×10^3 cells/ml. Highest mean numbers of SB occurred in the coastal zone of Alaska (Station 66, 11.2×10^3 cells/ml; Station 67, 16.6×10^3 cells/ml). High mean numbers of SB also occurred at Station 55, 10.3×10^3 cells/ml. At other stations in the Chukchi Sea, mean values varied between 0.4×10^3 cells/ml (Station 74) and 9.6×10^3 cells/ml (Station 57; Fig. 2). Vertical distribution of bacteria varied little over depth. At Stations 50, 55, 61, 67, and 69, SB distribution remained constant with depth and varied by no more than one order of magnitude at Stations 50, 61, and 69 ($10^2\text{--}10^3$ cells/ml). At other stations, SB varied by 2–3 orders of magnitude. The largest variation was observed at Station 49 ($3\text{--}1.8 \times 10^4$ cells/ml).

Analysis of SB in the Bering and Chukchi Seas Relative to Temperature and Salinity

During the time of expedition in the Bering Sea, water temperatures varied from -1.6°C to $+10.1^\circ\text{C}$ and salinity ranged from 29.73‰ to 34.64‰. For analysis, we grouped samples to both temperature and salinity (Fig. 3a). In the Bering Sea, 27% of the water samples fell in the temperature range between -2 and $+2^\circ\text{C}$; 40% between $+2$ and $+6^\circ\text{C}$; and 33% between $+6$ and $+10^\circ\text{C}$. The waters of the Chukchi Sea, in comparison with the Bering Sea, was colder. The majority of samples (65%) fell within the temperature range between $+2$ and $+6^\circ\text{C}$, and only 10% of samples had temperatures exceeding $+6^\circ\text{C}$.

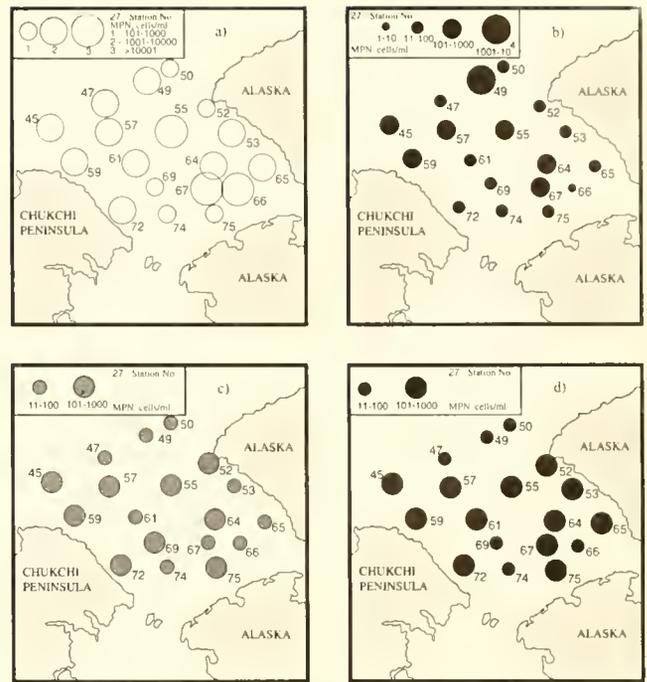


Fig. 2. Vertical distribution of mean values of saprophytic (a), hexadecane oxidizing (b), BaP-transforming (c), and PCB-transforming (d) bacteria at stations in the Chukchi Sea in summer 1988. Numbers near symbols are station numbers.

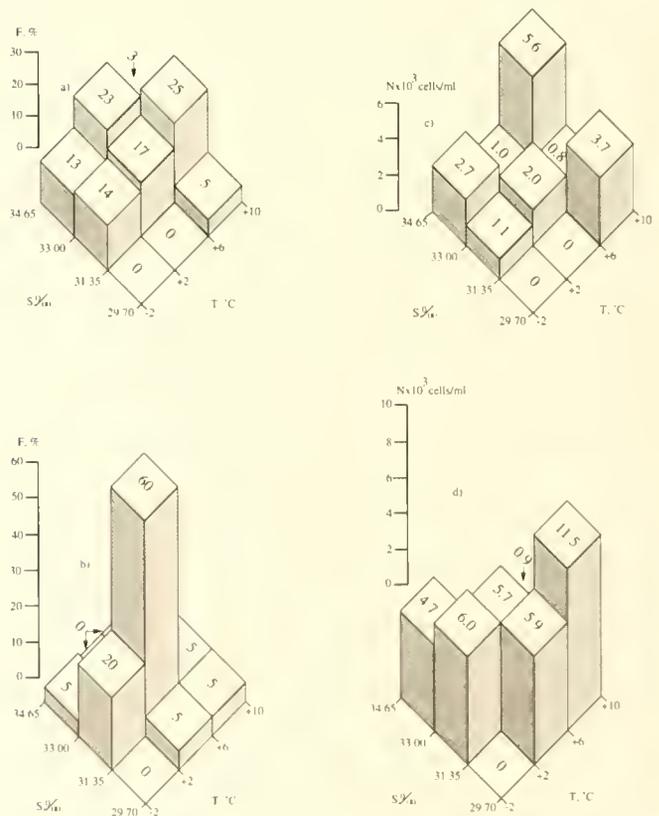


Fig. 3. Occurrence rate (%) of samples with various combinations of temperature and salinity in pairs in the Bering (a) and the Chukchi (b) Seas in summer 1988, and mean values of heterotrophic saprophytic bacteria number in the above samples from the Bering (c) and Chukchi (d) Seas. Number of bacteria are 10^3 cells/ml.

In the Chukchi Sea, waters appeared less saline (24.04 to 33.66%) than the Bering Sea, and only 5% of the stations had salinities greater than 33%. Salinities less than 29.70% were included in the 29.70–31.35% for analysis (Fig. 3b).

In the Bering Sea, the highest mean number of SB (3.7×10^3 cells/ml) occurred in warm waters, with temperatures $+6^\circ\text{C}$ and salinity between 33.00 and 34.65%, which represented a small percentage (3%) of the total number of analyzed samples. These samples dominated the surface 25 m in the southern Bering Sea (South Polygon and Station 113).

Water samples from the Bering Sea with temperatures higher than 6°C and salinity 31.31–33.00% represented 25% of samples. These samples were usually taken from the surface 25 m in the central, northwestern, and northern areas of the sea and contained about 8.0×10^2 SB cells/ml (Fig. 3). Mean values of SB number with other pair combinations of temperature and salinity grouped close to each other, 1.0 to 3.7×10^3 cells/ml (Fig. 4).

In the Chukchi Sea, the highest mean number of SB (1.15×10^4 cells/ml) also grouped in relatively warm waters ($> +6^\circ\text{C}$), but in contrast to the Bering Sea, less saline waters ($>31.35\%$). The lowest mean number of SB (5.7×10^3 cells/ml) was similar to other pair combinations of temperature and salinity, 4.7 to 6.0×10^3 cells/ml (Fig. 3).

Ecogram analysis showed that during the cruise in the Chukchi Sea, the saprophytic microflora grew rapidly as maximal mean SB in the Chukchi Sea (1.15×10^4 cells/ml) occurred in warm, low salinity waters, typical of southeastern water (Stations 65 and 66). An area affected by river flow from the Alaska coast (Fig. 2).

Hexadecane-oxidizing Bacteria in the Bering and Chukchi Seas

The most probable number of HDB in the central Bering Sea, East Polygon, in summer 1988, varied between 0 and 1.8×10^3 cells/ml. Maximum numbers occurred only at Station 3, at depths of 45 and 150 m. At other stations, HDB varied less—0–30, 0–180, and 0–300 cells/ml.

In the South Polygon, HDB ranged between 0 and 180 cells/ml at Station 112 (average 90 cells/ml). At the other stations, HDB ranged from 0– 1.8×10^3 cells/ml (averaged between 180 and 700 cells/ml). Samples with maximum HDB represented $>10\%$ of the total number of samples in this deep-sea area (Fig. 4).

This bacterial group varied vertically. The greatest vertical variation occurred at a station nearest the St. Lawrence Island, where HDB increased with depth, with practically no hexadecane-oxidizing microflora in the near surface microlayer.

Mean numbers of HDB in the section ranged between 10 and 100 cells/ml. Only at two stations, 7 and 19, did DB numbers exceed 10^2 cells/ml. Generally, in the southeastern Bering Sea, including the Gulf of Anadyr, HDB varied between 0 and 1.8×10^3 cells/ml. Hexadecane-oxidizing microflora occurred in 72% of the samples.

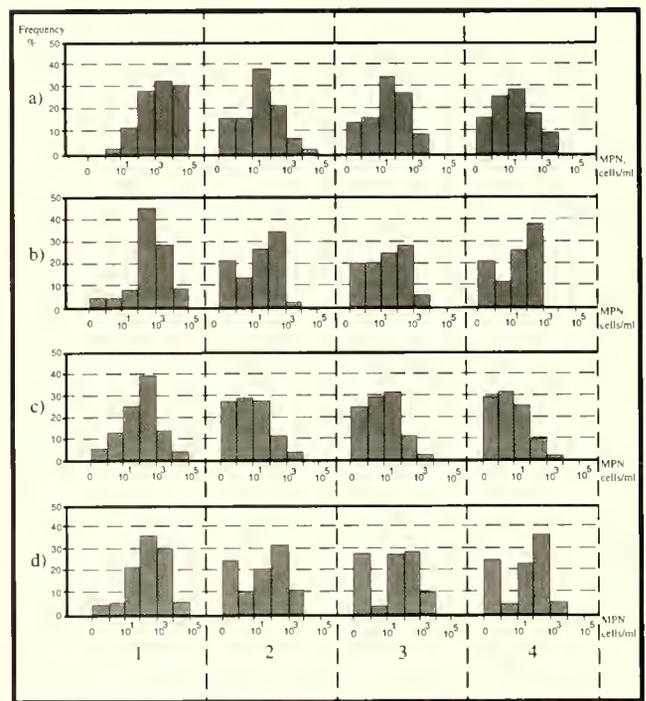


Fig. 4. Occurrence rate (%) of various values of the most probable number (MPN, cells/ml) of heterotrophic saprophytic and other functions of groups in the Bering and Chukchi Seas in summer 1988: (a) southern Chukchi Sea; (b) northern Bering Sea (Chirikov basin) and the Bering Strait; (c) the Gulf of Anadyr; and (d) central and southern Bering Sea.

In the Chirikov Basin, HDB also varied between 0 and 1.8×10^3 cells/ml, averaging between 10 and 100 cells/ml. HDB increased at Station 83 in the Bering Strait and at Station 89 (Fig. 5). In general, the HDB distribution in the Chirikov basin resembled the distribution in the open sea (Fig. 4).

In the Chukchi Sea, HDB varied between 0 and 1.8×10^4 cells/ml. Their distribution appeared extremely variable. Thus, at Station 66, only a few cells/ml occurred, while at Station 49, they ranged up to 3.4×10^3 cells/ml (Fig. 2). Generally, HDB occurred in 62% of the samples, but at only 10 cells/ml; waters that are characteristic of nonpolluted seas (Fig. 4). A relatively high number (10^2 cells/ml) of HDB occurred in 21% of the samples. This may be explained by the fact that microorganisms of this group also use aliphatic hydrocarbon as a source of carbon and energy. The source may be anthropogenic, but aliphatics also seep into the sea from underwater oil fields, and are synthesized and subsequently released by some seaweed.

Prismatic ecogram analysis (Figs. 6,7) showed that the largest mean numbers of HDB (7.1×10^3 cells/ml) in the Bering Sea occurred in waters with high concentration of SB; that is, waters with relatively high temperatures ($>6^\circ\text{C}$) and salinities ($>33\%$) (Fig. 6). Such combinations of temperature and salinity occurred in only 3% of the total number of analyzed samples (Fig. 6). However, the numbers of hexadecane-

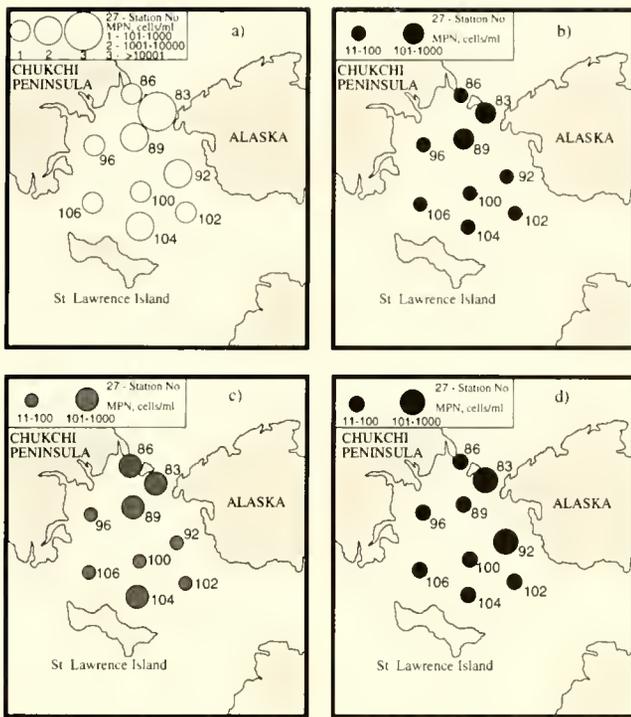


Fig. 5. Vertical distribution of mean values of saprophytic (a), hexadecane oxidizing (b), BaP-transforming (c), and PCB-transforming (d) bacteria at stations in the northern Bering Sea (Chirikov basin) in summer 1988.

oxidizing microflora were also high in waters with temperatures $<6^{\circ}\text{C}$, but with relatively high salinity ($>33\%$) (Fig. 6). In the Chukchi Sea, the highest mean number of DB (6.6×10^2 cells/ml) (Fig. 7) were found in waters with temperatures between $+2^{\circ}\text{C}$ and $+6^{\circ}\text{C}$ and salinity between 31.35% and 33.00% . Such conditions occurred in 60% of all the samples (Fig. 7).

This analysis of hexadecane-oxidizing microflora in the waters of the Bering and the Chukchi Seas confirms that these waters remain relatively unpolluted. The waters of the northern, central, and especially southern areas of the Bering Sea have experienced aliphatic hydrocarbon inputs of natural or anthropogenous origin.

Benzo(a)pyrene Transforming Bacteria in the Bering and Chukchi Seas

Mean numbers of BaPB in the northwestern Bering Sea, including the Gulf of Anadyr, averaged about 10^3 cells/ml. The highest concentration of BaPB occurred at Stations 24 and 27 near the coastal zone and at Station 41 between the Gulf of Anadyr and the Chirikov basin (Fig. 1).

The vertical distribution of BaP-transforming microflora followed a similar distribution for hexadecane-oxidizing microflora. However, in the Chirikov basin, high mean numbers of BaPB were not only found at Stations 83 and 89, but also at Stations 86 and 104 (Fig. 5). Similar numbers occurred in the Chukchi Sea (Fig. 2).

In the central and southern Bering Sea, BaPB varied between $0-3.0 \times 10^3$ cells/ml, but most often values fell between 10 and 100 cells/ml (28% of all the samples) and 100–1,000 cells/ml (29% of all the samples), respectively

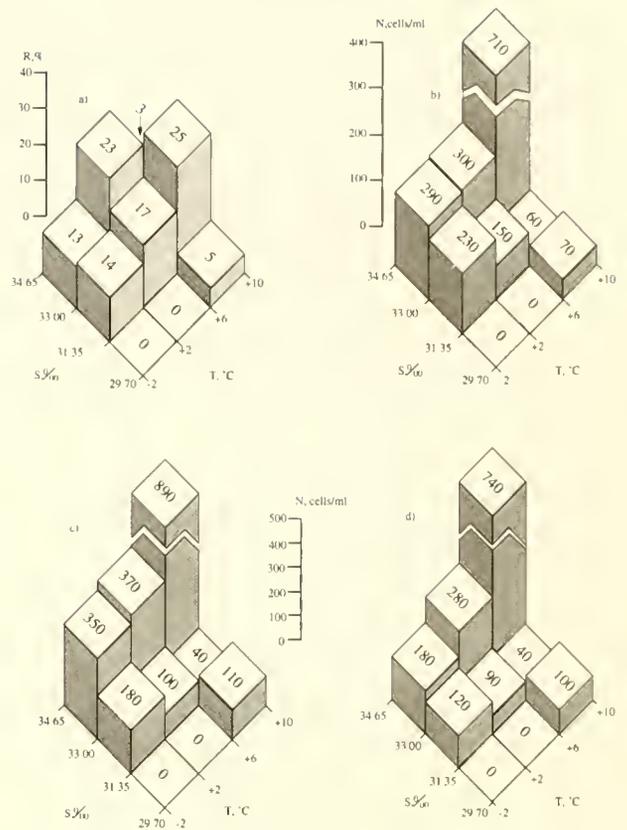


Fig. 6. Occurrence rate (R, %) of samples with various pair combinations of temperature and salinity in Bering Sea in summer 1988 (a), and mean numbers of hexadecane oxidizing (b), BaP-transforming (c), and PCB-transforming (d) bacteria (cells/ml) in the above samples.

(Fig. 4). As for BaPB distribution, the open waters in the central and southern Bering Sea differed from other areas. Here, 40% of samples possessed low BaPB numbers, whereas only 11% of samples contained more than 1,000 cells/ml (Fig. 4). Water samples with relatively high temperatures ($>6^{\circ}\text{C}$) and salinity ($>33\%$) in the southern Bering Sea again contained the highest mean numbers of BaP transforming microorganisms, 8.9×10^2 cells/ml (Fig. 6).

In the Chukchi Sea, highest mean numbers of BaPB (6.0×10^2 cells/ml) occurred in water samples with relatively low salinity ($<31.35\%$) and temperatures between 2°C and 6°C . Such conditions exist in the surface waters at Stations 45 and 59, a coastal area affected by the Siberian rivers outflow, and at Station 53 in Alaska Coastal waters (Figs. 2,7). Compared to 1984 and, as far back as 1981, the number of BaP-transforming microflora in the Bering Sea in 1988 has increased at a number of stations, and their distribution has become more extensive.

Polychlorinated Biphenyls-transforming Bacteria in the Bering and Chukchi Seas

In 1981, research in the Bering Sea began on the number and distribution of heterotrophic bacteria that transform PCB's and has continued in summers 1984 and 1988.

At the East Polygon, in the central Bering Sea, the PCBs varied between 0 and 180 cells/ml. Maximal concentration, 3.0×10^3 cells/ml, was measured at only 150 m at Station 1. The distribution of this bacterial group varied with depth, but

peaked at 0.5–10 m, 150–200 m, and 1,500 m at the deep-water stations. At shallow-water Stations 4 and 5, highest concentrations occurred at 0.5, 15, and 45 m. Compared to 1984, the numbers of PCB-transforming bacteria had not increased and their vertical distribution remained constant (Fig. 8).

Vertical variations of PCBB in the northwestern Bering Searesembled the distribution of both hexadecane and especially BaP-transforming bacteria. Maximum numbers of PCBB (10^2 cells/ml) occurred in near-bottom waters. At Station 7, which is the farthest from St. Lawrence Island, only 10 cells/ml were measured. At Station 35, the density of PCB-transforming bacteria increased to 180 cells/ml at 25 m.

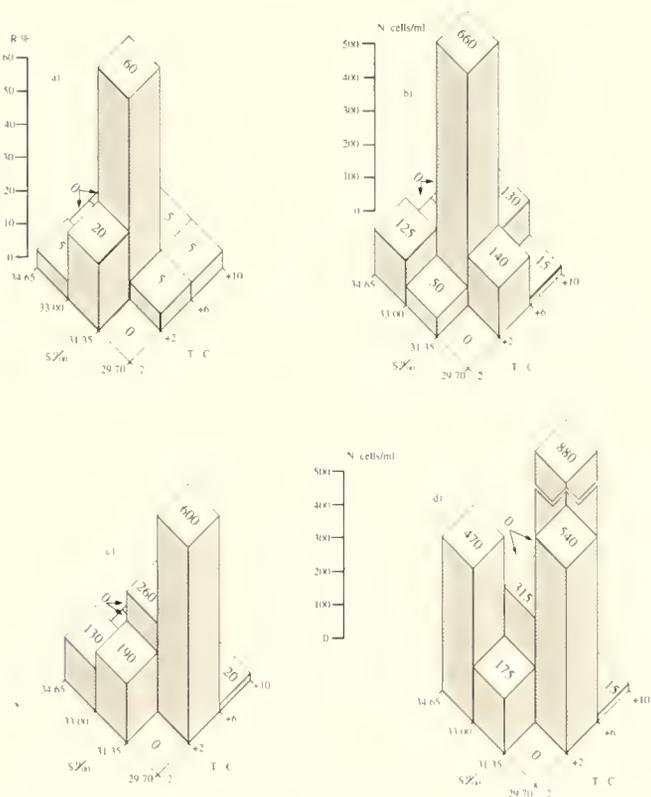


Fig. 7. Occurrence rate (%) of samples with various pair combinations of temperature and salinity in the Chukchi Sea in summer 1988 (a) and mean values of numbers (cells/ml) of hexadecane oxidizing (b), BaP-transforming (c), and PCB-transforming (d) bacteria.

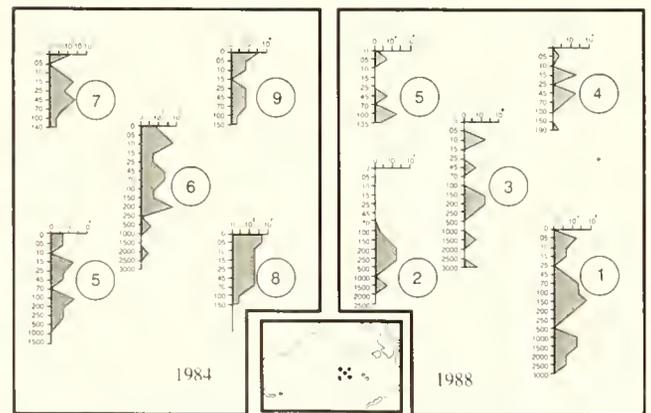


Fig. 8. Vertical distribution of PCB-transforming bacteria in the central Bering Sea (East Polygon) summer 1984 and 1988. The insert shows location of stations.

The horizontal distribution of PCBB in the northwestern Bering Sea, including the Gulf of Anadyr, was highly variable. Mean numbers ranged between 1 and 10 cells/ml at Stations 32 and 36; 11–100 cells/ml at Stations 7, 9, 10, 13, 19, 27, and 35; and 101–1,000 cells/ml at Stations 24 and 41 (Fig. 1). The variation of PCBB was generally greater than for HDB, but similar to the BaP-transforming microflora (Fig. 1).

Compared to 1981, the numbers of PCBB in 1988 increased 2–3 times, from 100 cells/m in 1981 to 180 and 300 cells/ml in 1988. The distribution of PCBB also became more extensive in 1988 (Fig. 9).

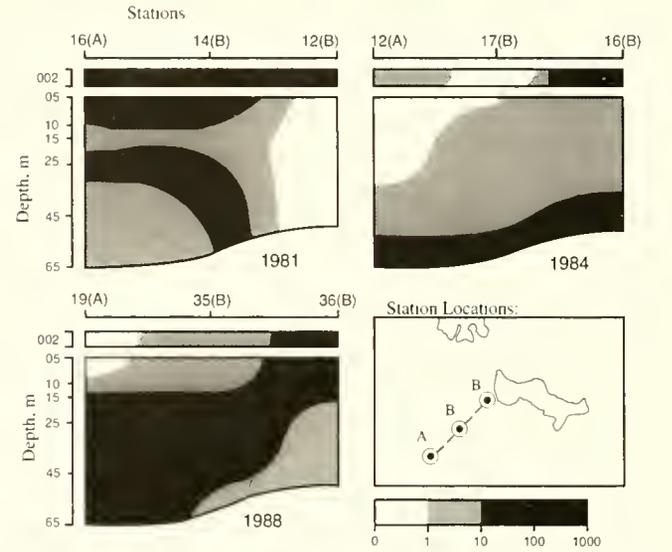


Fig. 9. Vertical distribution of PCB-transforming bacteria at three stations of North Polygon in the northern Bering Sea near St. Lawrence Island in summer 1981, 1984, and 1988. X - axis = station numbers and indices of stations; and Y - axis = depth (m).

In the Chirikov basin and the Bering Strait, PCBB varied between 0 and 180 cells/ml, with 39% of all the samples containing 180 cells/ml (Figs. 4,5). Due to significant vertical variability, mean numbers for the various stations never exceeded 100 cells/ml. Only at Station 83 in the Bering Strait, the mean number of PCBB averaged more than 100 cells/ml, ranging from 180 to 690 cells/ml. Distribution of PCBB showed high numbers at 0.5, 45, 250, and 2,500 m.

In the southern Chukchi Sea, PCBB also varied between 0 and 3.0×10^3 cells/ml (Fig. 2), but concentrations most often fell within the range of 10–100 cells/ml in 29% of all the samples (Fig. 4a).

Although the mean numbers of PCB-transforming microflora ranged between 10 and 1,000 cells/ml (Figs. 2,6), PCBB at 6 out of 18 stations under investigation rarely exceeded 100 cells/ml. At the remaining 12 stations, PCBB fell within range of 10 and 100 cells/ml (Fig. 2). In the Chukchi Sea, 10% of samples contained PCB-transforming microflora with more than 10^3 cells/ml (Fig. 4a). These bacteria were absent in 16% of all those analyzed whereas, in the Bering Sea, as much as 30% of the samples had no PCBB (Fig. 4).

PCB-transforming bacteria showed similar distribution ecograms as other indicator groups in the Bering Sea. Maximum mean numbers of PCB-transforming bacteria (7.4×10^2 cells/ml) occurred at stations with high temperatures,

6–10°C, and salinities >33‰ in surface water. In the Chukchi Sea, the ecograms differed between Stations (Fig. 7). The largest mean number of PCB (8.8 × 10³ cells/ml) again found in the waters with salinities of 31.35–33.00‰ and temperatures >6°C (Fig. 7).

The resemblance of ecograms between the Chukchi and Bering Seas (Fig. 6) indicates the variety of functional groups that exist in these seas and that these groups are widely distributed and comprise an integral part of the ecosystem. These ecograms illustrate again the variability and patchiness of these groups in these seas.

In summary, from the results on the number and distribution of saprophytic, hexadecane-oxidizing, BaP- and PCB-transforming bacteria in the Bering and Chukchi Seas, and comparison with investigations conducted in 1981 and 1984, we found:

1. In the summer of 1988, SB were ubiquitous, albeit highly variable, in the Bering and Chukchi Seas. In the Bering Sea, these bacteria occurred most frequently at hundreds of cells/ml, whereas in the Chukchi Sea, they exceeded 10³ cells/ml. Based on boreal concentrations of SB, the Bering Sea can be characterized as oligomesotrophic and the Chukchi Sea as mesotrophic.

2. Hexadecane bacteria were also highly variable in the Bering and Chukchi Seas. In the Bering Sea, maximum numbers changed little since 1984 and were most abundant in

the Bering Sea (South Polygon) where significant concentrations of anthropogenic hydrocarbons occurred.

3. Benzo(a)pyrene-transforming bacteria were also variable in the Bering and Chukchi Seas. These bacteria were widely dispersed in the Chukchi Sea, generally at 10 cells/ml. Although the distribution of BaP-transforming bacteria was also patchy in the Bering Sea (the Chirikov basin, the Bering Strait, South and East Polygons), BaPB were most abundant at 100 cells/ml.

4. PCB-transforming bacteria covaried with the distribution of BaP-transforming bacteria.

5. Relative to 1981 and 1984, numbers in each functional group and their distribution increased significantly in summer 1988, suggesting that the Bering Sea ecosystem is experiencing anthropogenic inputs.

6. From characterizing the number and distribution of each functional bacterial group (in particular, PCB-transforming bacteria) in the Bering and Chukchi Seas, we conclude that there exists an anthropogenic effect on the ecosystems. The degrees of eutrophication varies with each region. In the central Bering Sea, as well as in the Gulf of Anadyr, anthropogenic impact is minimal. However, in the northern Bering Sea and in the southern Chukchi Sea, anthropogenic influences are evident. Because of the remoteness of the area from big industrialized centers, the presence and distribution of PCB- and BaP-transforming bacteria indicates the global propagation of organic pollutants via atmospheric processes.

4.2.2 Taxonomic Composition of Heterotrophic Bacteria

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Introduction

The study of the morphologic characteristics and taxonomic composition of microorganisms of the Bering Sea was started in 1981 and 1984, and continued in 1988 during the Third Joint US–USSR Bering & Chukchi Seas Expedition. In 1988, investigations included microbial structure (microbial population including taxonomic diversity) of the Chukchi Sea. It is noteworthy that these microbiological investigations were conducted over extensive areas of the Bering and Chukchi Seas and that they included the taxonomic determination of heterotrophic bacteria that were isolated from different sites of the marine environment.

Methods and Materials

The taxonomic investigation included 829 strains of bacteria isolated from different sites of the marine environment (the water column, bottom sediments, and biota): 432 strains isolated from the Bering Sea in summer 1981; 320 strains isolated from the Bering Sea in summer 1984; and 77 strains isolated from the Chukchi Sea in 1988. In addition, the results are compared to bacterial cultures isolated from the Baltic Sea impact region of the World Ocean.

Bacteria from the marine environment and their culture were isolated using fish broth and fish peptone agar prepared with fresh seawater (Tsyban, 1980). The inocula were incubated at 28°C.

To characterize the cultures according to morphologic and phenotypic traits, generally accepted methods were used (Gerhardt, 1983; Yegerov, 1983). Taxonomic position of the strains was investigated using the schemes of marine Gram-negative bacteria and the 8th edition of Bergey's determinant (Shewan *et al.*, 1960; Pallroni, 1975; Sieburth, 1979; Buchanan & Gibbons, 1982; Oliner, 1982).

Results and Discussion

The morphology of 432 isolates of heterotrophic microorganisms from the Bering Sea environment in 1981 showed that rods accounted for 81.4% of the bacterial representatives. The cocci accounted for 18.6% of the isolates (Table 1). The length and width of the rods ranged from 0.7 to 2.0 and from 0.3 to 1.5 μm , respectively. Their diameter varied from 0.5 to 1.5 μm .

Most bacterial isolates (87.4%) possessed mobility (see Table 1). Peritrichs and monotrichs accounted for 74.5% and 25.5%, respectively. The presence of spores was found in 82 of 297 isolates, which accounted for 27.6% (see Table 1).

For comparison, among 66 isolates from the Baltic Sea in 1982, the cocci were far less than in the Bering Sea, only 4.5% of the investigated isolates. The rest, 95.5%, were motile

peritrich rods (see Table 1). The number of spores formed (13.6%) in the composition of Baltic microflora were also lower than in Bering Sea flora (see Table 1).

One of the most important morphologic and systematic traits of microorganisms is affinity to the Gram Stain. The test of 297 isolates from the Bering Sea bacteria showed that most isolates (70.8%) were Gram-positive; the remaining 29.2% were Gram-negative. It is interesting to note that among 66 isolates from the Baltic Sea, 60.5% of microorganisms were Gram-negative, and only 39.5% were Gram-positive (see Table 1).

Visual pigments occurred in 59.2% of 432 bacterial isolates from the Bering Sea. Pigmentation of Bering Sea isolates ranged from white to red: 16.9% pink; 11.8% creamy; 9.3% yellow; 5.6% beige; 3.7% grey; and 14% red. One isolate formed brown colonies.

Investigations of Baltic cultures showed that, unlike Bering Sea cultures, most isolates (60.6%) formed colorless colonies. Among these colonies, only 4 isolates were distinguished: 25.7% white, 9.1% beige.

Most of Bering Sea isolates (67.2%) dissolved gelatine, decomposed peptone (9%), and formed ammonia. Others (12.6%) induced a change in protein molecules and formed hydrogen sulphide. Indole was also formed by 36.6% of the

TABLE I

Morphologic traits of the isolates of heterotrophic bacteria from the Bering and Baltic Seas in 1981 & 1982, respectively.

Morphologic trait	Bering Sea, 1981			Baltic Sea, 1982		
	Number of isolates	Number of isolates with determined morphologic traits	%	Number of isolates	Number of isolates with determined morphologic traits	%
Cocci	432	81	18.6	66	3	4.5
Rods	432	351	81.4	66	63	95.5
Presence of sporification	297	82	27.6	66	9	13.6
Motile forms	432	377	87.4	66	63	95.5
Immotile forms	432	55	12.6	66	3	4.5
Gram-positive	297	210	70.8	66	26	39.5
Gram-negative	297	87	29.2	66	40	60.5
Pigmentation of colonies						
Absence of pigment	432	176	40.8	66	40	60.6
Pigments:						
pink	432	73	16.9	66	-	-
creamy	432	51	11.8	66	4	6.1
yellow	432	41	9.4	66	3	4.5
white	432	39	9.0	66	17	25.7
beige	432	24	5.6	66	6	9.1
brown	432	1	0.2	66	-	-
black	432	-	-	66	2	3.1

197 isolates studied. Nitrates were reduced to nitrites by 37.9% of cultures. Half of the isolates fermented glucose, and 13.5 and 23.2% of the isolates produced acid and gas, respectively. Only 3% of the isolates produced a significant amount of gas.

In addition, of all the strains studied in the Bering Sea, 80.7% possessed catalase activity, 54.8% oxidase, and 29% lecithinase activity. The presence of lipase was found in 40.9% of 332 isolates (see Tables 2,3).

It is noteworthy that while studying the physiological properties of bacteria isolated from an impact region of the World Ocean—the Baltic Sea—significant distinctions were found as compared with the bacterial populations of the Bering Sea, a background region of the World Ocean.

For example, unlike Bering Sea isolates, 25.7% of Baltic microorganisms formed ammonia in the decomposition of peptone (see Table 2). In addition, Baltic isolates (on a percentage basis) possessed a greater ability to ferment glucose,

lactose, and mannitol than that of Bering Sea isolates, and to produce gases (15.0%).

Specific enzyme assays show that 80.7% of Bering Sea isolates possess the catalase activity (80.7%) slightly more than Baltic isolates (59.0%). On the other hand, oxidase (83%) and lecithinase (42.3%) activity proved to be typical of a greater percentage of Baltic isolates as compared to the Bering Sea.

Similar results were found in 1984 for bacteria isolates from different localities in the Bering Sea.

Taxonomic characteristics of 200 isolates from 1981, and 320 isolates from different sites of the Bering Sea were also determined on the basis of morphology and physiology. The results are presented in Table 4. The genera most prevalent were *Bacillus* (27.5%), *Bacterium* (22.5%), *Pseudomonas* (18%) and *Planococcus* (13.5%). These genera accounted for 81.5% of the number isolated from the sea.

TABLE 2

Physiological properties of the isolates of heterotrophic bacteria from the Bering and Baltic Seas in 1981 & 1982, respectively.

Physiological properties	Bering Sea, 1981			Baltic Sea, 1982		
	Number of isolates	Number of isolates with determined traits	%	Number of isolates	Number of isolates with determined traits	%
Break down of gelatine	332	224	67.2			
Formation of ammonia						
glucose	432	225	52.2	66	54	81.5
lactose	432	58	13.5	66	21	31.7
mannitol	432	100	23.2	66	35	53.0
Formation of catalase	432	348	80.7	66	39	59.0
oxidase	432	236	54.8	66	55	83.0
lecithinase	432	125	29.0	66	28	42.3
lipase	332	136	40.9	-	-	-

TABLE 3

Distribution isolates from the Bering and Baltic Seas in 1981 and 1982 according to the basic enzymatic traits.

Groups of bacteria	Isolates possessing the above traits, %	
	Bering Sea, 1981	Baltic Sea, 1982
Lactose positive	13.5	31.7
Oxidase positive	54.8	83.0
Catalase active	80.7	59.0

TABLE 4

Taxonomic position of the isolates from the Bering Sea in 1981 and 1984.

Genus	Isolated strains			
	in 1981		in 1984	
	Number	%	Number	%
<i>Pseudomonas</i>	36	18	86	26.8
<i>Xantomonas</i>	-	-	5	1.7
<i>Bacillus</i>	55	27.5	75	23.4
<i>Bacterium</i>	45	22.5	54	16.9
<i>Planococcus</i>	27	13.5	57	17.8
<i>Aerococcus</i>	2	1	3	0.9
<i>Alcaligenes</i>	2	1	7	2.2
<i>Halobacterium</i>	-	-	2	0.6

These genera also dominated in 1984, accounting for 84.9% of the total number. However, the relative number of the genera *Bacillus* and *Bacterium* was somewhat less, while the numbers of the genera *Planococcus* and especially *Pseudomonas* increased. Generally, pigmented forms dominated (93.3%) of all isolates.

For the Chukchi Sea, isolates fell between bacterial populations of the Bering and Baltic Seas (Table 5). Here, isolates from the Chukchi Sea occurred over 11 genera: *Pseudomonas*, *Xantomonas*, *Alcaligenes*, *Klebsiella*, *Aeromonas*, and others (Fig.1). Taxonomic diversity of the dominating genera in the Chukchi Sea was somewhat less than in the Bering Sea (13 genera) but greater than in the Baltic Sea (9 genera).

TABLE 5

Some morphological traits of isolates of heterotrophic bacteria from the Bering, Chukchi and Baltic Seas in % of the total number of the investigated strains.

Morphologic traits	Bering Sea	Chukchi Sea	Baltic Sea
Cocci	18.6	13.0	4.5
Gram-positive	70.8	29.9	39.5
Gram-negative	29.2	70.1	60.5

Thus, this comparative analysis suggests that a distinction occurs between the morphological, physiological, and taxonomic characteristics of bacterial isolates from the Chukchi Sea relative to the Baltic (an impact region) and Bering (a background region) Seas. Only the index of relation between pigmented and nonpigmented forms does not comply with this assessment. Based on this analysis (i.e., the number of bacillary and Gram-negative bacteria, taxonomic diversity, and number of *Pseudomonas* sp.) the Chukchi Sea is specified as a region with a higher level of anthropogenic pollution.

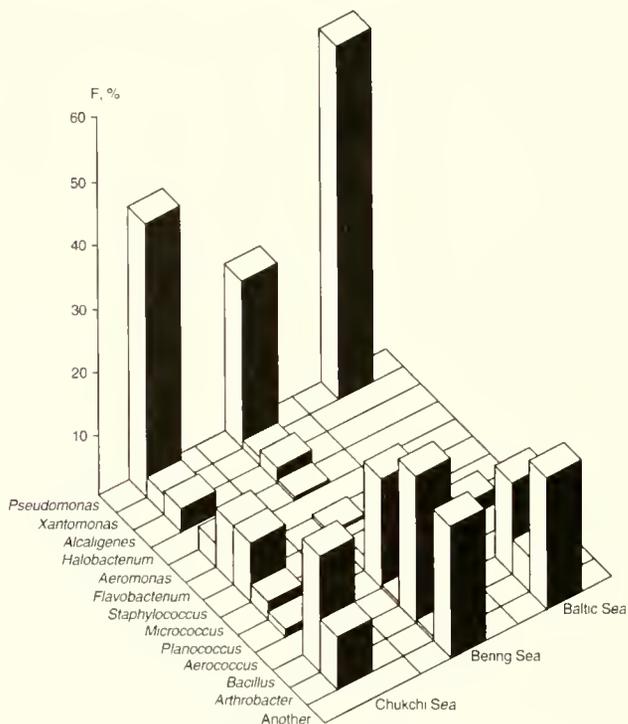


Fig. 1. Taxonomic position of the strains of heterotrophic microorganisms of the Chukchi, Bering, and Baltic Seas.

Subchapter 4.3:

Microbiological Transformation of Organic Matter

4.3.1 Transformation of Benzo(a)pyrene

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Introduction

Microorganisms, distributed in the World Ocean, play a leading role in the functioning of these ecological systems and in biogeochemical cycles. Microflora is the most active component in these ecological systems (Izrael & Tsyban, 1982). Its biomass in the upper 100 m layer of the World Ocean reaches 25×10^4 GC/m², which is similar to plankton biomass. While possessing functional enzyme systems and high biochemical activity, the microbial communities influence oceanic biogeochemical cycles of carbon. Many polycyclic aromatic hydrocarbons (PAH's) that are distributed in sea and ocean ecological systems possess toxic, mutagenic, and carcinogenic properties, which can manifest a clear threat to biotic components and possibly to human health.

Microbial transformation of aromatic hydrocarbons and heterocyclic compounds has been well studied (Rodoff, 1961; Treccan, 1963; Bumpus, 1989). However, the rates of benzo(a)pyrene (BaP) transformation in seawater as well as the significance of this process in local and regional systems have not yet been studied. This paper reports on BaP transformation as a process that eliminates this dangerous compound from the sea. The investigations were conducted in the Bering and Chukchi Seas as part of an all-round investigation of PAH's that started in 1981 (Tsyban *et al.*, 1987d).

Methods and Materials

Studies on the transformation of PAH's were conducted at nine stations in the Bering Sea and in the southern part of the Chukchi Sea in August 1988. This cruise was the Third Joint US-USSR Bering & Chukchi Seas Expedition on board the research vessel *Academik Korolev*.

Seawater was collected in sterile samplers. Surface microlayers was sampled with metal screens (0.02 mm). Water column was sampled with Niskin (depths: 0.5, 2 and, 10 m). Water samples with natural microbial communities were transferred in sterile glass bottles for microbiological studies on board ship.

The rates of BaP transformation by natural bacterioplankton was conducted under *in situ* conditions. Water samples of 250- ml volume was transferred into 500 ml dark glass bottles along with BaP dissolved in acetone. Four BaP concentrations were used: 100 and 20 µg/l (10 days) and, 1.0 and 10 µg/l (21 days). Abiotic factors were followed in sterile water from each depth with respective BaP concentrations. These experiments and controls were repeated 2-3 times.

To simulate *in situ* conditions, samples were incubated on the ship's deck in running water for 10-21 days. To terminate the microflora activity, a few milliliters of concentrated HCl were used. Residual concentrations of BaP were extracted in 250 ml of benzol and stored until analyzed.

The BaP benzol extracts were elated and evaporated. The evaporated part of the benzol extract was eluted by 2 ml of solution of 1,12 benzapareline in octane (concentration 0.1 mg/ml) and also used as an inner standard.

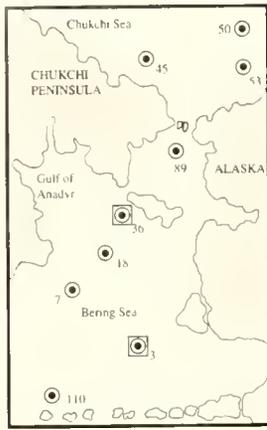
The concentration of BaP in non-octane solution was determined by spectral and fluorescent analysis with the use of Shpolsky at 196°C on spectrographer C-12 (Shpolsky *et al.*, 1952; Fedoseeva *et al.*, 1986). Sensitivity of the method was determined at 1×10^{-10} g/ml \pm 10%. The rate was determined as the difference between the initial (artificially introduced) and final mass of BaP. Rates are expressed in percent of BaP transformed.

Results and Discussion

One consequence of PAH's circulation in the sea is its distribution relative to specific microflora that are adapted to new hydrochemical conditions and capable of transforming these dangerous compounds. Our results show that BaP transformation occurs in Bering Sea waters (Tsyban *et al.*, 1987c). During the 1988 cruise in the subarctic region of the Chukchi Sea, BaP transformation was again confirmed. The distribution of BaP transformers was patchy with numbers in the 0.5 m surface layer ranging from 10 to 1,000 cells/ml. The maximum density occurred in the Chirikov basin at Station 89 where more than 10^3 cells/ml were found.

The potential activity of the microflora to transform BaP was studied in 10 *in situ* simulation experiments. The results show that bacterioplankton from the Bering and Chukchi Seas possess the ability to transform BaP (Fig. 1). Microbial transformation of BaP varied from 8 to 51% (Table 1) with little variation between replicates. The lowest transformation (2-3%), which is within experimental error, was found in the central part of the Chirikov basin.

Comparison of 1984 and 1988 data (Fig. 1; Tsyban *et al.*, 1986; Izrael *et al.*, 1987) shows that BaP transformation is relatively stable in the Bering Sea. At North Polygon, BaP transformations (10-day incubation) were about 45-55% during these years. Considering the differences in experimental conditions, the results show that maximum biodegradation occurred in the 0.5 m level of the Gulf of Anadyr waters. The rate was 39 mg of BaP/l over a period of 10 days. In the



BaP transformation in percent from the original concentration

— surface layer 1984
 — surface layer 1988
 — 0.5 m 1988

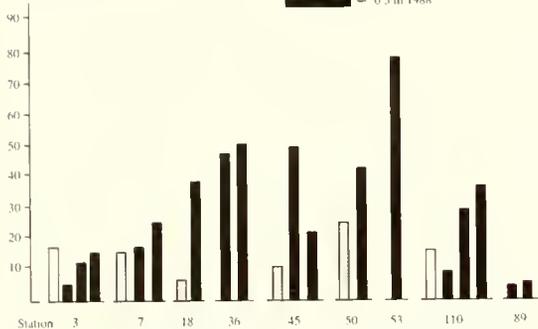


Fig. 1. BaP microbial transformation in experiments *in situ* in the Bering and Chukchi Seas water (August, 1988).

Chukchi Sea, maximum activity of microbial populations was found at Stations 45 and 50, where 25–45% of the BaP was transformed.

The experiments showed little differences in the amount of PAH's degraded by bacterioplankton in the surface microlayer and 0.5 m level (Table 1). In certain areas of the World Ocean, these processes are more pronounced in the surface microlayer, the zone of air–sea interaction (Tsyban, 1985). However, there is no direct correlation between the BaP content in sea waters and amount transformed. For example, low rates of BaP transformation occurred in waters with the highest concentration of BaP, 63 $\mu\text{g/l}$ at Station 29.

To study the degradation of PAH's at *in situ* concentrations (1 and 10 $\mu\text{g/l}$), long *in situ* experiments were conducted up to 21 days. The results show that 54–57% of the initial BaP mass was transformed with the first 5–7 days (Table 2); after 21 days the process declined considerably. Maximum degradation was 67–85% of the initial concentrations. Similar results were found for concentrations of 1 and 10 $\mu\text{g/l}$. The results from Stations 36 and 50 showed that despite local features of the BaP transformation (Table 1), bacterioplankton of the Bering and Chukchi Seas possess similar biodegradation potential. Transformation and removal of BaP in the surface layer occurred at a rate of 7 $\mu\text{g/l}$ over a period of 3 weeks.

In summary, from the investigations performed in 1981, 1984, and 1988 in the Bering and Chukchi Seas, heterotrophic microflora exist in the waters, and the heterotrophic microflora show a pronounced biodegradation potential in relation to

TABLE 1

Microflora transformation of BaP in the Bering and Chukchi Seas Water in *in situ* experiments of 10 days, August 1988.

Region of the works	Station No., date	Level of sampling	BaP concentration, $\mu\text{g/l}$		BaP Microbial transformation, % C_1
			Initial C_1	Final Control Exper.	
East Polygon	3,	0.5	100	99.8	14.7
	28.07	0.5	100	85.3	8.5
The Gulf of Anadyr	7,	Surface microlayer	100	99.7	
	01.08	Surface microlayer	100	81.5	18.5
		0.5	100	76.0	24.0
		0.5	100	80.5	19.5
The Gulf of Anadyr	18,	Surface microlayer	100	99.7	
	03.08	Surface microlayer	100	93.9	6.1
		0.5	100	60.7	39.3
The Chukchi Sea	45	Surface microlayer	20	19.9	
	09.08	Surface microlayer	20	17.9	10.5
		0.5	20	9.7	51.5
		0.5	20	15.8	21.0
The Chukchi Sea	50	Surface microlayer	20	20.0	
	10.08	Surface microlayer	20	15.1	24.5
		0.5	20	10.9	45.5
The Chirikov basin	89	0.5	20	20.0	
	11.08	0.5	20	19.2	3.8
		0.5	20	19.5	2.6
The Bering Sea	110	0.5	20	20.0	
	10.08	0.5	20	17.8	11.0
		0.5	20	13.8	31.0
		0.5	20	12.1	39.5

PAH's (Izrael *et al.*, 1987). In addition, the rate of BaP transformation in the Bering Sea microflora is sufficiently high and similar to rates measured in the Baltic Sea (Tsyban *et al.*, 1985). Thus, the metabolism of PAH's by microflora should be considered as an essentially important process in the detoxication and removal of pollutants from the ecosystems of the World Ocean.

TABLE 2

Dynamics of BaP transformation caused by the Bering and Chukchi Sea waters microflora in long *in situ* experiments (August 1988).

Region, Station No.	Length of exposition, days	BP transformation			
		Original concentration BaP = 1.0 $\mu\text{g}/1/C_1$		Original concentration BaP = 10.0 $\mu\text{g}/1/C_{10}$	
		μg	% from C_1	mg	% from C_{10}
The Bering Sea, North Polygon, Station No. 36	0 7 10 14	0 0.31 0.59 0.85	0 31 40 85	0 4.21 5.47 6.68	0 42.1 54.7 66.8
South-East part of the Chukchi Sea, Station No. 53	0 3 5 7 10 14 21	0 0.29 0.52 0.80 0.81 0.83	0 29 52 80 81 83	0 1.53 3.91 5.70 7.12 7.64 7.81	0 15.3 39.1 57.0 71.2 76.4 79.1

4.3.2 Transformation of Polychlorinated Biphenyls by Marine Bacterioplankton

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Introduction

Pollution of biosphere, the World Ocean, by xenobiotics has become not only an ecological problem but a social problem. In the postwar years, production of synthetic organic compounds increased worldwide. In 1950, 7 million tons were produced—by 1970, 63 million tons, and by 1985, 250 million tons (Geiss & Bourdeaux, 1986). At present, 5 million different xenobiotics are produced by chemical manufacturers, with fifty thousand being sold on the world market every year. No more than 10% of synthetic compounds (of the total amount produced) are reportedly toxic and only twenty thousand xenobiotics have been studied for genotoxic activity (Loprieno, 1981; Tanabe, 1985).

Most investigated chlorinated hydrocarbons are PCB's (Tanabe, 1985). This is due to wide application in industrial and domestic materials, resistance to biodegradation and bioaccumulation capability, acute toxicity, and unfavorable effect upon reproductive processes in pelagic organisms. Also, analytical techniques allow for reliable PCB determination in most environmental samples.

Current predictions (Bletchly, 1984) on the dynamics of chlorinated hydrocarbons in the marine environment indicate that chlorinated hydrocarbon concentration in the World Ocean will increase 1.5–1.7 times by the year 2000. Because of the production of new synthetic substances and accumulation in the environment, scientists are interested in knowing the sources and fates of xenobiotics. At present, the elimination of PCB's from the environment occurs through photochemical oxidation and microbial degradation.

Aspects of PCB biotransformation need further study. In recent years, a great body of information has been collected, transformation of PCB's by individual strains of microorganisms, relating to different systematic groups (Ahmed & Focht, 1973; Sayler *et al.*, 1977; Furukawa *et al.*, 1978; Furukawa *et al.*, 1979, 1983; Liu, 1980; Furukawa & Chakrabarty, 1982; Furukawa, 1982; Brunner *et al.*, 1985; Unterman *et al.*, 1985; Bedard *et al.*, 1986; Bopp, 1986; Bedard *et al.*, 1987a, 1987b; Kohler *et al.*, 1988). Many bacteria have been shown to utilize PCB's as a source of carbon and energy (Karasevich, 1982; Shields *et al.*, 1985). However, not all PCB congeners are subject to microbial attack, which is

associated with the structure of PCB components. Thus, results from laboratory assays indicate that different PCB congeners are subject to different degrees of microbial attack and that each strain is capable of transforming a different spectrum of congeners (Kohler *et al.*, 1988).

Because the World Ocean can be regarded as a reservoir of anthropogenic compounds, the assessment of PCB transformation in the marine environment is important. Our investigations of PCB microbial transformation under natural marine conditions were conducted during the Third Joint US-USSR Bering & Chukchi Seas Expedition. This work assesses biodegradation potential of PCB's by isolated bacterial strains and natural marine bacterioplankton communities.

Materials & Methods

Experimental assessment of marine microflora biodegradation potential of PCB's was made on board the research vessel *Akademik Korolev* in July–August 1988. Overall, 12 assays (Table 1) were conducted in the eastern, northern, and southern parts of the Bering Sea, including the Gulf of Anadyr, the Chirikov basin, and the southern Chukchi Sea.

TABLE 1

Characteristics of the regions of sampling when conducting experiments (see Frontispiece for location of Stations).

Sea, Sampling Region	Stations	Experiment Number	Water Temperature °C	Salinity (%)
Bering Sea, East Polygon	3	1	8.8	32.60
Bering Sea, Gulf of Anadyr	7 18 22	2 3 4	7.2 7.3 6.5	32.60 31.16 31.46
Bering Sea, North Polygon	35	5	7.4	30.91
Chukchi Sea	45 50 53 55 69	6 7 8 9 10	2.3 6.1 4.4 5.3 2.2	24.04 31.66 31.09 31.56 32.26
Bering Sea, Chirikov basin	89	11	6.1	31.70
Bering Sea, South Polygon	110	12	9.6	32.94

Niskin bottles (5–10 l) sterilized with 96° ethanol were used to collect samples from the upper 0.5-m surface layer. Subsamples (200 ml) were drained into 500 ml dark glass bottles. These bottles were washed thoroughly, rinsed with acetone and hexane, and sterilized with dry heat at 200°C for

2 hours. For assay control, seawater from the same samples were sterilized by autoclaving at 1 atm (1.01×10^5 Pa) for 30 minutes.

Gas-liquid chromatography (Tuistra & Traag, 1983; Kohler *et al.*, 1988) was used to determine background PCB concentrations in 200-ml samples, which were always below detection. To determine the most probable number (MPN) of saprophytic (SB) and PCB-transforming (PCBB) bacteria, a dilution method was used (Tsyban *et al.*, 1988).

To determine the MPN of SB, a broth based on seawater from the various regions was used as the culture medium (see Subchapter 4.3). The medium was distributed into test tubes and sterilized by autoclaving. After inoculation, PCB solution was added into each test tube.

Considering the distribution of PCB in the Bering Sea conducted in 1984 (Izrael & Tsyban, 1990), experiments were based on the use of PCB Aroclor 1232 mixture, a composition similar to the PCB mixture found in the region. Each experiment was conducted with two series of test bottles; the first series with PCB concentration of 100 ng/l and the second series of 10 ng/l. Each test was duplicated.

Polychlorinated biphenyls solution in ethanol was added to control and test bottles and thoroughly shaken for 1–2 min and then incubated in the dark to prevent photochemical processes. The experiment was incubated under *in situ* conditions (range 2–10°C) over the period of investigations.

At 1, 3, 5, 10, 14, and 21 days, water (1 ml) was taken from each test and control bottle to determine the MPN of SB and PCBB. Concentrated H_2SO_4 (10 ml) was added into each bottle to stop microbial metabolism. The amount of PCB remaining was determined by gas-liquid chromatography.

Results and Discussion

From the Aroclor 1232 experiment, 19 out of 70 congeners were transformed and those (Table 2) became the focus of the study.

In the East Polygon in the Bering Sea, the percentage of individual Aroclor 1232 consumption, with an initial concentration of 100 ng/l, varied from 7% for hexachlorobiphenyls (Table 2) to 95–100% for dichlorobiphenyls (Figs. 1, 2). Trichlorobiphenyls were also transformed, ranging from 64 to 90%. Degradation of pentachlorobiphenyls varied little, ranging 36–44% (Fig. 1, Table 3). For tetrachlorobiphenyls, this group of Aroclor 1232 congeners can be divided into those that were readily labile over the 10–21 days, a biotransformation rate of 49–58% of the initial content, and those that were relatively stable, a rate of 10–18% of the initial content.

Similar observations were revealed with an initial PCB concentration of 10 ng/l. Transformation of congeners, however, was more rapid, especially during the first 3 days (Table 3).

Figure 1a shows the change in number of saprophytic and PCB-transforming microorganisms with an initial PCB concentration of 100 ng/l. After the first day, the MPN of the bacteria did not increase over the initial numbers, but bacterial break down of PCB's continued. For dichlorobiphenyls, 40 to 52% of these congeners (nos. 5,8,15; Fig. 1b) were transformed

TABLE 2

Systematic numbering of Aroclor 1232 congeners (Ballschmitter and Zell, 1980), and congeners subjected to transformation by bacterioplankton of the Bering and the Chukchi Seas.

Congeners Numbers	Structure
Dichlorobiphenyls	
5	2,3
8	2,4/
15	4,4/
Trichlorobiphenyls	
18	2,2/5
22	2,3,4/
28	2,4,4/
31	2,4/5
Tetrachlorobiphenyls	
40	2,3/3,3/
44	2,2/3,5/
47	2,2/4,4/
52	2,2/5,5/
60	2,3/4,4/
66	2,3/4,4/
70	2,3/4/5
77	3,3/4,4/
Pentachlorobiphenyls	
87	2,2/3,4,5/
97	2,2/3/4,5
101	2,2/4,5,5/
Hexachlorobiphenyls	
153	2,2/4,4/5,5/

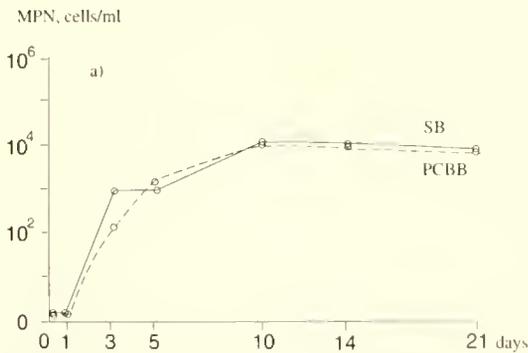


Fig. 1a. Most probable number of saprophytic bacteria (SB, cells/ml) and PCB transforming bacteria (PCBB, cells/ml)

in the first day. The same trend also occurred with an initial PCB concentration of 10 ng/l. In the first day, 70–73% of dichlorobiphenyls were transformed (Table 3).

Over the next 10 days bacterial numbers increased exponentially with both bacterial groups of SB and PCB reaching 1.8×10^4 cells/ml (confidence interval, 2.7×10^3 to 1.2×10^5 cells/ml). The percentage of transformation of PCB

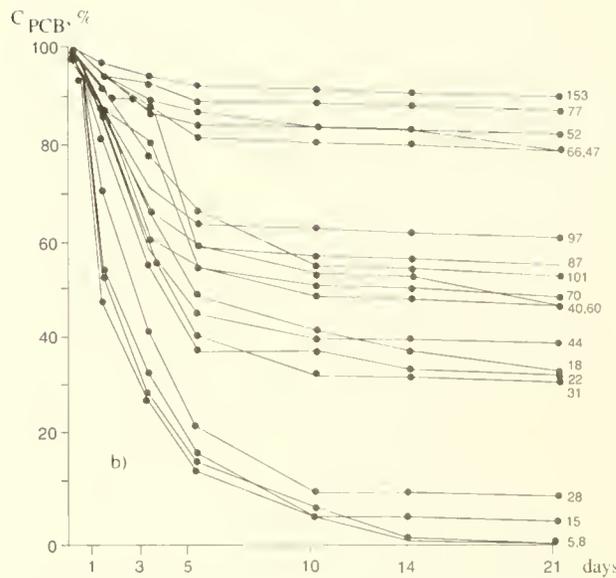


Fig. 1b. Microbial transformation of individual Aroclor 1232 congeners (%) in the experiments. In Experiment No. 1, PCB initial concentration was at 100 ng/l. Numbers are coherent numbers, see Table 2. Samples collected from the Bering Sea, East Polygon (Station 3).

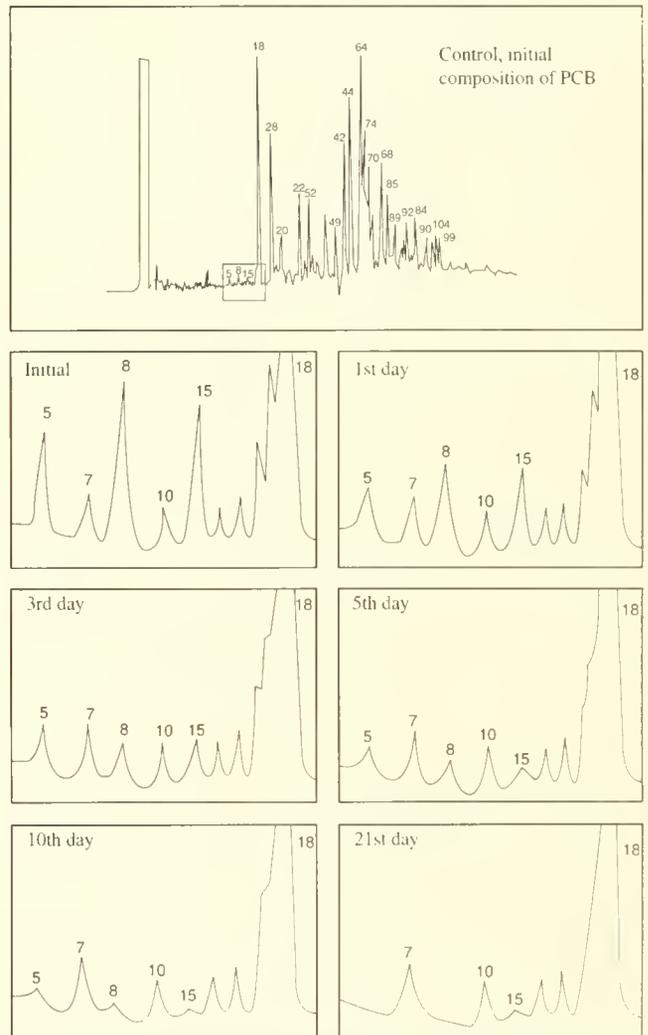


Fig. 2. Microbial transformation of Aroclor 1232 (congeners numbers 5, 8, 15; see Table 2) in the central Bering Sea, Station 3 (East Polygon) in July 1988.

also followed the increase in all numbers (Fig. 1a,b). However, after 10 days biotransformation decreased as most of PCB congeners remained practically unchanged.

Figure 2 shows Aroclor 1232 chromatograms that reflect the change in concentrations of individual PCB congeners over the experiment period. The concentration of congeners varied from 0 to 10%.

Experimental data (Table 3; Figs. 3,4,5) indicate a great similarity in the rates of PCB transformation in various regions of the Bering and the Chukchi Seas. In the Chukchi Sea, with a thawing ice flow and a low salinity of 24.04%, the change in the MPN of bacteria under study and the rate of Aroclor 1232 transformation were similar to those found in the Bering Sea (Figs. 1,5; Table 3). Control bottles with sterile water and PCB concentrations at 100 ng/l or 10 ng/l remained unchanged.

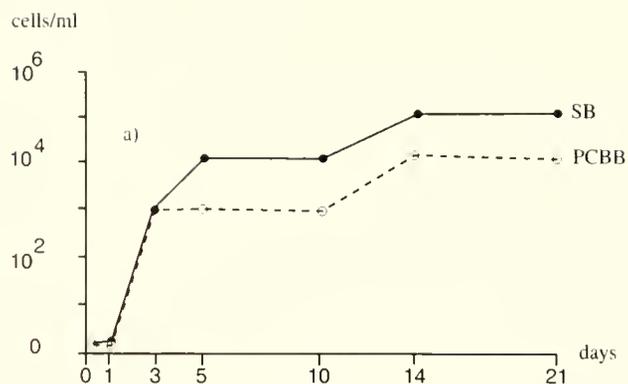


Fig. 3a. Most probable number (MPN) of saprophytic bacteria (SB, cells/ml) and PCB transforming bacteria (PCBB, cells/ml).

TABLE 3

Transformation rate (degradation percentage) of individual Aroclor 1232 congeners by bacterioplankton of the Bering and the Chukchi Seas.

Experiment Numbers	Congeners Numbers	Initial concentration of PCB 100 ng/l						Initial concentration of PCB 10 ng/l					
		1 day	3 days	5 days	10 days	14 days	21 days	1 day	3 days	5 days	10 days	14 days	21 days
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	5	52	71	87	94	100	100	70	86	92	98	100	100
	8	46	72	86	95	100	100	73	87	95	100	100	100
	15	40	67	84	95	95	95	70	81	94	100	100	100
	18	14	34	50	57	61	64	33	57	58	61	63	63
	22	14	44	61	61	65	65	31	54	57	62	62	62
	28	29	58	78	90	90	90	54	82	89	90	90	90
	31	12	38	59	66	66	66	30	52	55	59	61	67
	40	10	10	40	45	45	50	30	50	52	55	55	55
	44	18	40	54	58	58	58	38	48	55	58	58	60
	47	5	12	15	15	15	18	6	13	17	20	20	20
	52	5	10	12	15	15	15	10	12	13	14	15	15
	60	13	38	44	50	50	50	32	48	54	56	58	58
	66	5	11	18	18	18	18	6	13	17	19	20	20
	70	12	19	45	48	48	49	32	44	51	52	52	52
	77	5	7	10	10	10	10	6	8	10	10	10	10
87	10	33	40	42	42	42	20	40	43	45	45	45	
97	9	29	35	36	36	36	20	28	36	37	38	38	
101	8	22	33	44	44	44	21	25	36	47	48	48	
153	3	5	7	7	7	7	2	6	8	8	8	8	
2	5	53	72	88	95	100	100	71	87	93	99	100	100
	8	46	72	87	94	100	100	72	86	95	100	100	100
	15	41	66	85	96	96	96	69	82	95	100	100	100
	18	13	35	51	57	61	65	32	56	57	62	64	65
	22	14	43	62	64	67	67	30	55	58	62	62	62
	28	30	57	77	90	90	90	50	80	86	90	90	90
	31	12	40	60	66	66	66	31	52	54	60	60	65
	40	10	10	39	44	44	49	29	51	53	54	56	56
	44	17	41	55	57	58	58	37	49	54	59	60	60
	47	6	12	15	15	17	18	7	14	18	21	21	22
	52	5	10	12	15	15	15	10	12	13	14	15	15
	60	12	40	44	50	50	50	27	51	55	59	59	59
66	6	12	19	19	19	19	6	13	17	19	20	20	

TABLE 3 - continued

Transformation rate (degradation percentage) of individual Aroclor 1232 congeners by bacterioplankton of the Bering and the Chukchi Seas.

Experiment Numbers	Congeners Numbers	Initial concentration of PCB 100 ng/l						Initial concentration of PCB 10 ng/l					
		1 day	3 days	5 days	10 days	14 days	21 days	1 day	3 days	5 days	10 days	14 days	21 days
1	2	3	4	5	6	7	8	9	10	11	12	13	14
	70	10	20	44	48	48	48	33	46	52	52	52	52
	77	5	7	10	10	10	10	6	8	10	10	10	10
	87	9	32	41	42	42	42	21	41	43	45	45	45
	97	21	29	36	37	38	39	20	28	36	37	38	38
	101	8	22	33	44	44	44	20	26	38	48	48	48
	153	3	5	7	7	7	7	2	6	8	8	8	8
5	5	52	72	88	95	100	100	72	86	92	100	100	100
	8	47	71	85	95	100	100	70	87	94	100	100	100
	15	40	65	84	95	100	100	72	85	94	100	100	100
	18	14	35	52	55	62	64	31	57	59	61	65	65
	22	13	44	61	64	68	68	29	54	59	63	63	63
	28	30	57	77	90	90	90	51	81	87	90	90	92
	31	12	39	59	66	66	66	31	55	55	59	64	66
	44	17	41	55	58	58	58	36	50	56	60	61	61
	47	6	12	15	15	17	18	6	14	19	22	22	22
	52	4	11	12	14	15	15	10	12	13	14	15	15
	60	40	41	45	51	51	51	33	50	55	57	59	62
	66	5	12	18	18	18	18	6	13	17	19	20	20
	70	11	19	45	48	48	49	27	47	55	56	56	56
	77	5	7	10	10	10	10	6	8	10	10	10	10
	87	10	32	41	42	42	43	20	42	44	46	47	48
	97	10	28	37	38	38	38	20	23	36	37	38	38
	101	8	22	33	44	44	44	20	25	37	47	48	50
	153	2	5	7	7	7	7	2	6	8	8	8	8
11	5	50	72	86	94	100	100	70	88	95	98	100	100
	8	45	72	85	96	100	100	71	87	92	100	100	100
	15	40	65	86	95	95	95	69	87	92	100	100	100
	18	14	35	55	55	63	65	28	55	62	64	65	65
	22	14	44	61	66	68	68	24	56	68	64	64	64
	28	29	59	77	89	90	90	53	81	87	90	92	92
	31	11	39	59	66	66	66	30	52	54	58	62	66
	40	10	10	39	45	45	50	22	50	53	58	58	58
	44	16	41	55	58	58	58	33	55	59	62	62	63
	47	5	12	15	15	15	18	6	18	21	22	22	23
	52	5	11	15	15	16	16	10	12	13	14	15	15
	60	12	42	44	50	50	50	23	55	60	65	69	70
	66	5	12	18	18	18	18	6	13	17	19	20	20
	70	12	19	47	48	48	48	29	47	50	59	59	60
	77	5	7	10	10	10	10	6	8	10	10	10	10
	87	10	32	42	42	42	42	20	40	45	45	45	45
	97	9	29	38	38	38	39	20	28	36	37	38	38
	101	8	22	33	44	44	44	20	25	42	50	50	50
	153	3	5	7	7	7	7	2	6	8	8	8	8

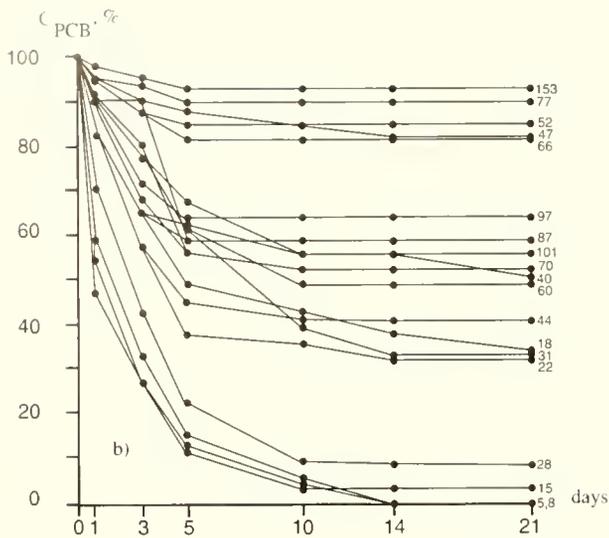


Fig. 3b. Microbial transformation of individual Aroclor 1232 congeners (%) in Experiment No. 2. PCB initial concentration was at 100 ng/l. Samples collected from the Gulf of Anadyr of the Bering Sea, Station 7. Numbers are coherent numbers, see Table 2.

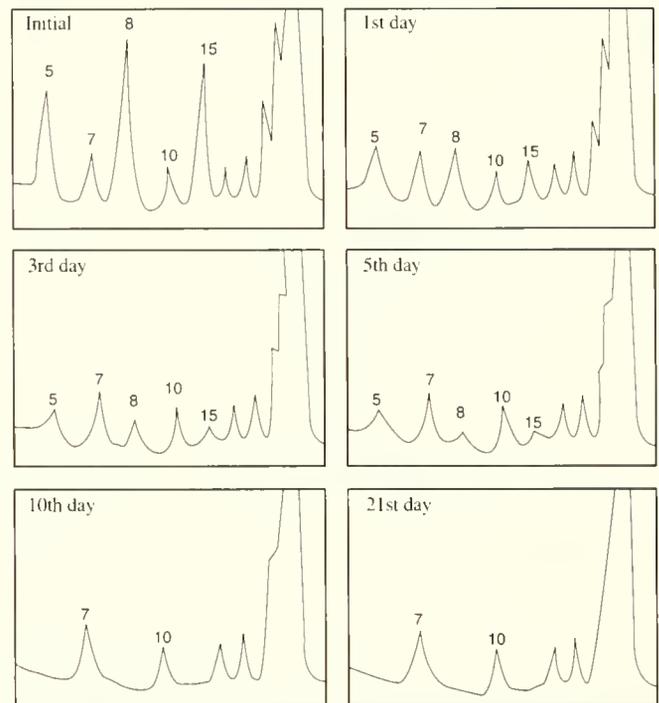
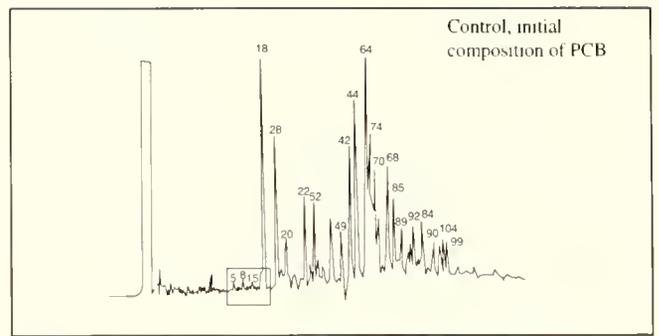


Fig. 5. Microbial transformation of low chlorinated Aroclor 1232 congeners (coherent numbers 5, 8, 15) at Station 4 in the southern Chukchi Sea in August 1988.

Analysis of PCB congeners, after biological degradation, showed that the decomposition of the chlorinated hydrocarbon is primarily affected by steric configurations and halogen atom substitutions. The stability of PCB congeners is probably influenced by intermolecular bonds. The decomposition of PCB occurs through the production of arene-oxides, which are substituted with biphenyl molecules in positions 2, 2', 5, 5'.

Thus, the results show that only low chlorinated biphenyls are subject to rapid microbial decomposition in the arctic and subarctic waters. Many such compounds, however, are only partially transformed, which in turn may be more toxic to marine biota. Highly chlorinated biphenyls, in contrast, are extremely resistant to degradations. Consequently, these compounds may accumulate in the ecosystem and circulate in the marine environment for many decades (Izrael & Tsyban, 1989).

In summary, the results clearly show the ecological toxicity of chlorinated hydrocarbon pollution in the arctic regions. Because of low arctic temperatures, chemical degradation of xenobiotics is practically absent due to slow rates of microbial transformation.

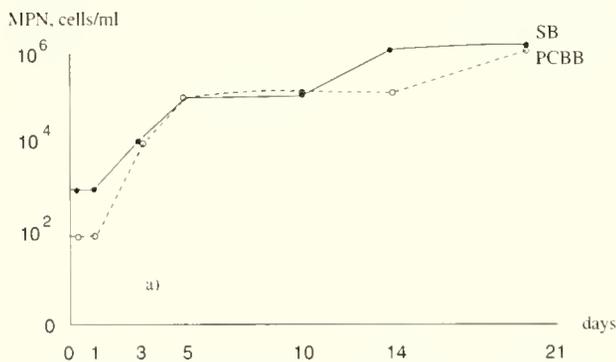


Fig. 4a. Most probable numbers of SB and PCBB.

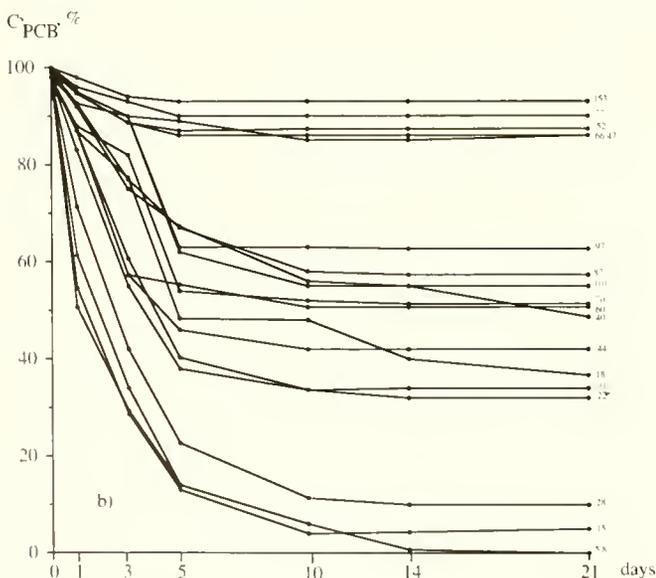


Fig. 4b. Microbial transformation of individual Aroclor 1232 congeners in Experiment No. 6. PCB initial concentration at 100 ng/l, water from the Chukchi Sea, Station 45. Numbers are coherent numbers, see Table 2.

Subchapter 4.4:

Biologic Characteristics of Marine Microorganisms

4.4.1 Biological Features and Genotoxic Properties of Microorganisms

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Introduction

Local or regional increase in the concentration of some natural components, such as heavy metals, oil, and nonnatural components up to toxic levels, is a characteristic feature of the present ecological situation in the World Ocean (Izrael *et al.*, 1987). Therefore, a serious problem has arisen, concerning a change in the metabolism of microorganisms as well as their adaptation to new chemical conditions of the environment.

It has been determined that adaptation of microorganisms plays an important role in biodegradation of toxic organic compounds. Adaptation can be defined as a change in the microbial population which increases the rate of transformation of toxic substances as a result of the preliminary contact with these compounds. It is quite obvious that to predict the biodegradation rate of organic pollutants in the marine environment, it is necessary to gain an understanding of the mechanisms of microbial transformation, such as genetic transfer or mutation, enzyme induction, and changes in the level of populations. It is also obvious that these mechanisms play an important role in the process of adaptation of microbial populations to new substances.

Although mechanisms of microbial degradation may differ, the process is under the genetic control of chromosome or extra chromosomal (plasmid) material. Numerous forms of genetic transmission with plasmids can occur and can offer strong possibilities for genetic engineering in nature, including the World Ocean. Evidence in support of this can be seen in the distribution of benzo(a)pyrene- and PCB-transforming bacteria in estuaries, the Baltic, Bering, and Chukchi Seas (see preceding Subchapters).

While studying the mechanisms of biodegradation, controlled by plasmids, the traits providing selective advantages to marine organisms become of primary importance. Such traits are the resistance to bactericidal toxic compounds (for instance, heavy metals) and the ability to utilize a number of substances of a biogenic origin (Karasevich, 1982; Izrael *et al.*, 1987). Thus, protective functions determined by plasmid genes can be acquired by a microbial cell under changing environmental conditions. Although other traits should not be disregarded, they are not related to direct selection. These traits provide a cell with some advantages in the habitat and possibility of transferring traits inside a bacterial population (Izrael & Tsyban, 1989).

The above account outlines the importance of studying the signs of plasmid transmission in marine microorganisms. The purpose was to assess and forecast the ecological state of the environment, including protective properties of marine

ecosystems. In addition, change in the genotypes of marine microorganisms can be determined (Izrael & Tsyban, 1990). New data on the biological properties of heterotrophic microorganisms of the Bering Sea were recently obtained. Investigations of the physiological, biochemical, and genetic features of strains isolated from various components of marine ecosystems were conducted by microbiologists of the Natural Environment and Climate Monitoring Laboratory (Institute for Global Climate and Ecology from 1991) of the USSR State Committee for Hydrometeorology and USSR Academy of Sciences. These materials have already been published in part by Izrael *et al.* (1987) and Izrael & Tsyban (1989, 1990). The present paper describes research on the biological, biochemical, and genetic features of strains isolated from the Bering and Chukchi Seas in 1984 and 1988.

Methods and Materials

Investigations were conducted on 320 strains of heterotrophic bacteria isolated from the Bering Sea in 1984, and on 77 strains of bacteria isolated from the Chukchi Sea water in summer 1988. Selection of traits was determined by plasmids, and methods of data processing were determined by experimental procedures.

The specific character of genetic investigations of a large collection of microorganisms isolated from the marine environment has necessitated the choice of the mass screening method. The collection of the cultures was subdivided into homogeneous groups based on traits that are easily identified in mass screening (Izrael & Tsyban, 1990). Resistance of cultures to antibiotics, organic pollutants, and heavy metals (Hg, Cd, Co, Cu, Pb, and Ni) were investigated as signs of the presence of plasmids.

Ability to degrade petroleum hydrocarbons and paraffin was determined from the presence of the zone where bacteria grew on the compact nutritious medium prepared on seawater (Tsyban, 1980) around sterile disks soaked with relevant hydrocarbons. Minimum inhibiting concentrations (MIC) were serially diluted in a solid medium. Eleven antibiotics of the basic groups: ampicillin (Amp), benzylpenicillin (Ben), and methicillin (Mtt) from the penicillin group; gentamicin (Gen), kanamycin (Kan), monomycin (Mon), and streptomycin (Str) from the group of aminoglycosides; chloramphenicol (Clm) and tetracycline (Tet), broad-spectrum antibiotics; polymyxin (Pol) from the group of polypeptide antibiotics; and nalidixic acid (Nal) in the range of concentrations from 0.06 to 4,000 µg/ml. Due to high sensitivity of microorganisms to gentamicin, the range of its concentration was 0.06 to 8 µg/ml.

Resistance of the strains to each antibiotic taken separately, frequency of mono-, di-, and polyresistant strains, as well as resistance spectra (R-spectra) were recorded.

To determine the resistance of heavy metals, the following salts were used: $\text{Hg}(\text{NO}_3)_2 \cdot 2\text{H}_2\text{O}$, $\text{Pb}(\text{NO}_3)_2$, CdCl_2 , CuSO_4 (waterless), and NiSO_4 in the range of 0.5 to 1,024 $\mu\text{g}/\text{ml}$. In terms of the number of ions, this amounted to 0.4–882 for Hg^{2+} ; 0.35–670 for Pb^{2+} ; 0.3–627 for Cd^{2+} ; 0.2–464 for Co^{2+} ; and 0.15–331 for Cu^{2+} .

Choice of the concentrations of antibiotics and heavy metals and assessment of the bioresistance level of marine microorganisms were based on literature data. Kulskyi *et al.* (1986), working on the problems of natural sensitivity of different representatives of microflora from aquatic and soil biocenoses, published information on maximum permissible concentrations (MPC) of these pollutants.

The genotoxic effects of cultured microorganisms were studied using a biological model including three indicator strains of *Escherichia coli*: *E. coli* WP-2 (a wild strain that retains its unchanged complete gene pool), *E. coli* Pol A- (a strain that is unable to synthesize one of the enzymes responsible for DNA repair [DNA polymerase I]), and *E. coli* Rec- (a strain that lacks a recombination system, specified by conjugation [Slater *et al.*, 1971]).

Growth suppression of genetically altered strains *E. coli* Pol A- and *E. coli* Rec- to a genotoxic effect of the substrate under study was accepted as proof of its carcinogenic activity.

The pathogenic properties of bacteria strains were assessed using white mice as well the cultures of human embryo kidney cells (RH) and fish skin cells (EPC) (Tsyban, 1988).

Results and Discussion

In the process of experimental investigations, data were obtained that characterize the following biological properties of marine microorganisms: the relation to organic pollutants (e.g., resistance and degradation ability), resistance to heavy metals, genotoxic and DNA-damaging properties, and pathogenicity.

Growth of cultures on media containing organic pollutants is defined not only by the cultures' ability to degrade these compounds, but also by their resistance to high concentrations of pollutants. The screening test made it possible to divide the strains of the dominant taxons into three groups: 1. resistant to a pollutant and capable of degradation; 2. resistant but not capable of degradation; and 3. sensitive to a pollutant (Table 1). The results show that microorganisms isolated from the Bering Sea are rather resistant to the impact of oil and paraffins. The greatest activity for oil degradation was exhibited by bacteria of the genus *Pseudomonas*; 72.6% of active cultures occurred among them, and only 6.0% of the strains proved sensitive to oil. In the study of effects of paraffin on the tested strains, it was observed that Bering Sea microorganisms were sensitive and that 28.7% of the investigated strains failed to grow in the presence of paraffin.

TABLE 1

Decomposition of petroleum hydrocarbons and paraffin by microorganisms of different taxonomic groups isolated from the Bering Sea.

Genus	Number of strains	Percent of positively tested strains					
		Oil			Paraffin		
		DR	R	S	DR	R	S
<i>Pseudomonas</i>	84	72.6	21.4	6.0	65.5	10.7	23.8
<i>Bacterium</i>	52	69.2	25.0	5.8	67.3	17.3	15.4
<i>Planococcus</i>	58	65.5	27.6	6.9	62.1	5.2	32.7
<i>Bacillus</i>	76	69.7	23.7	6.6	53.9	7.9	38.2
Other genera	47	66.0	23.4	10.6	46.8	21.3	31.9
TOTAL	317	69.1	24.0	6.9	59.6	11.7	28.7

Note: D = decomposition; R = resistance; S = sensitivity.

One of the processes occurring in natural microbial populations is microevolution of bacteria, proceeding under the selective pressure of anthropogenic factors. Thus, a variety of microorganisms may develop in their bioresistance to a number of pollutants.

The mechanism of acquired polyresistance to unfavorable environmental factors is based on the intensive intra- and interspecific exchange of extrachromosomal elements of nuclear material (i.e., plasmids). The level of this exchange is highest in sewage and may be the same in water bodies having high pollution levels (Baya *et al.*, 1986; Kulskyi *et al.*, 1986; Day *et al.*, 1987; Boominathan *et al.*, 1988; Gealt, 1988; Linton, 1988; Schmidt & Schlegel, 1989).

The character and level of antibiotic resistance were studied in representatives of the genera *Pseudomonas* and *Bacillus* that dominate in the microbial communities of the Bering and Chukchi Seas. MIC of antibiotics, the proportion of sensitive and stable strains, the number of resistance determinants, and the most widespread R-spectra were determined. In the study of R-strain distribution, the strains for which the MIC of an antibiotic exceeded 31.2 $\mu\text{g}/\text{ml}$ (2 $\mu\text{g}/\text{ml}$ for gentamicin), were considered R-strains.

A common feature of all represented taxonomic groups of Bering Sea microorganisms was the small percentage of strains sensitive to all the antibiotics (0 to 6.3% in different taxonomic groups). The percentage of strains resistant to one antibiotic averaged 24.6%, with a maximum value for the representatives of *Bacillus* genus (37.5%). Strains resistant to two antibiotics occurred on average 12.0%, with small variations among different taxonomic groups, a range of 8.3–15.6%. Strains resistant to methicillin were most frequent and dominated among the representatives of the genera *Pseudomonas* and *Planococcus* (54.2 and 46.5%, respectively). They averaged 43.5% (Table 2).

TABLE 2

Resistance of Bering Sea microorganisms of different taxonomic groups to antibiotics
(the proportion of resistant strains - R-strains, %).

Genus of micro-organisms	Total number of the strains	Antibiotics									
		Penicillins				Oxc	Aminoglycosides				
		Amp	Ben	Krb	Mtt		Gen	Kan	Mon	Ris	Str
<i>Pseudomonas</i>	48	45.8	37.5	20.8	54.2	56.3	16.7	14.6	16.7	37.5	12.5
<i>Planococcus</i>	43	27.9	23.3	9.3	46.5	39.5	2.3	32.6	27.9	20.9	23.3
<i>Bacillus</i>	64	21.9	18.8	9.4	32.8	25.0	6.3	4.7	1.6	10.9	7.8
Other genera	36	38.9	31.0	8.3	44.4	52.8	11.1	8.3	13.9	22.2	16.7
TOTAL	191	32.5	26.7	12.0	43.5	41.4	8.9	14.1	13.6	22.0	14.1

Multiple resistance to antibiotics was typical of the majority of the heterotrophic microorganisms, isolated in the Bering Sea basin, irrespective of their taxonomic position. The percentage of such strains was 60.8%. The highest percentage found in the genera *Pseudomonas* and *Planococcus* was 70.8 and 67.5%, respectively (Table 3).

TABLE 3

Number of determinants of resistance to antibiotics with microorganisms of different taxonomic groups.

Genus	Total number of the strains	Percent			
		Sensitive	Monoresistant	Diresistant	Polyresistant
<i>Pseudomonas</i>	48	2.1	14.6	12.5	70.8
<i>Planococcus</i>	43	2.3	18.6	11.6	67.5
<i>Bacillus</i>	64	6.3	37.5	15.6	40.6
Other 10 genera	36	0	27.8	8.3	63.9
TOTAL	191	2.6	24.6	12.0	60.8

The percentage of microorganisms resistant to natural and semisynthetic penicillins ranged from 12.0% for carbenicillin to 26.7–41.4% for benzylpenicillin, ampicillin, and oxacillin. The tendency was typical of all taxonomic groups. However, most strains were among the genus *Pseudomonas* (above 50% in some cases). Resistance to antibiotics is characteristic of *Pseudomonades* (Palleroni, 1975).

Resistance of Bering Sea heterotrophic microorganisms to aminoglycosides occurred much less frequently. Maximum resistance to hentamycin, kanamycin, monomycin, and streptomycin varied from 8.9 to 14.1%. Resistance to ristomycin was somewhat higher (22.2%). Among the different taxonomic groups, the greatest number of strains resistant to aminoglycosides occurred in the genus *Planococcus*.

Analysis of resistance spectra of Bering Sea strains of the main taxonomic groups revealed great diversity (42, 37, and 33 spectra in the genera *Pseudomonas*, *Planococcus*, and *Bacillus*, respectively) as well as the absence of the dominating

R-spectra. Diversity of R-spectra can probably be considered as an indication of an extraordinary genetic plasticity of the studied Bering Sea microorganisms.

The study of antibiotic resistance of the strains isolated from Chukchi Sea water was conducted and compared with antibiotic resistance of the strains isolated from the Baltic Sea—an impact region of the World Ocean (Table 4).

TABLE 4

Resistance of the microorganisms of the Chukchi and Baltic Seas (the proportion of R-strains, %).

Antibiotics	Genera of microorganisms			
	<i>Pseudomonades</i>		Others	
	Chukchi Sea	Baltic Sea	Chukchi Sea	Baltic Sea
Amp	14.8	77.8	8.8	68.2
Ben	70.3	93.3	64.7	90.9
Mtt	100.0	86.7	79.4	95.5
Gen	11.1	6.7	14.7	13.6
Kan	77.7	17.8	58.8	50.0
Mon	92.6	28.9	67.6	68.2
Str	33.3	35.6	23.5	36.4
Clm	33.3	86.7	17.6	86.4
Nal	63.0	95.6	61.8	95.5

In Table 2, *Pseudomonades* of the Chukchi Sea were characterized by resistance to benzylpenicillin and methicillin, kanamycin and monomycin (77.7 and 92.6%, respectively), and nevirammon-nalidixic acid (63.0%). The majority of the Chukchi Sea strains showed a low resistance to gentamicin (11.1%) like those of the Baltic Sea. Only one-third of the strains proved resistant to streptomycin (33.3 %).

Pseudomonades from the Chukchi and Baltic Seas were distinguished by the number of strains resistant to ampicillin, levomycetin, kanamycin, and monomycin. The proportion of the strains from the Chukchi Sea, which were resistant to the first two antibiotics, were considerably less than of Baltic *Pseudomonades* (14.8 and 33.3% versus 77.8 and 86.7%, respectively). As far as resistance to kanamycin is concerned,

the contrary situation was observed. The percentage of the strains resistant to kanamycin and other aminoglycosides in the Chukchi Sea were considerably higher (77.7 and 92.6% versus 17.9 and 28.9% in the Baltic Sea).

The similar irregularities were found for other genera, isolated from the Chukchi Sea (Table 4). It should be noted that the modal values of MIC of antibiotics for *Pseudomonades* from the Chukchi Sea did not exceed (except for methicillin) 125 µg/ml, while in similar representatives of Baltic microflora, the modal MIC values of all antibiotics of the groups of penicillins, chloramphenicol, polymyxin, and nevigramon were 1,000 µg/ml (Table 5).

TABLE 5

Modal values of the MIC of antibiotics for marine bacteria, percent.

Antibiotics	Genera of microorganisms			
	<i>Pseudomonades</i>		Others	
	Chukchi Sea	Baltic Sea	Chukchi Sea	Baltic Sea
Amp	7.8/40.7	>1,000.0/60.0	7.8/32.4	>1,000.0/36.4
Ben	31-125.0/18.5	>1,000.0/73.3	250.0/26.5	>1,000.0/77.3
Mtt	>1,000.0/62.9	>1,000.0/84.4	>1,000.0/50.0	>1,000.0/90.9
Gen	0.5/55.6	0.3/31.1	0.5/38.2	1.0/36.4
Kan	62.5/37.0	15.6/31.1	31.2/20.6	125.0/27.3
Mon	125.0/40.7	15.6/37.7	250.0/23.5	62.5/27.3
Str	31.2/33.3	7.8/31.1	15.6/38.2	>1,000.0/27.3
Clm	15.6/29.6	>1,000.0/46.6	7.8/47.1	>1,000.0/31.8
Nal	250.0/25.9	>1,000.0/40.0	15.6/23.5	>1,000.0/68.2

Note: Modal values of the MIC (µg/ml) are in the numerator; the proportion of strains with the given modal values (%) in the denominator.

A similar situation was revealed in the analysis of the modal MIC values for other heterotrophic microorganisms of the Chukchi Sea. Among the *Pseudomonades* of both the Chukchi and Baltic Seas, the percentage of those that are shown to be polyresistant to antibiotics is high (92.5%).

Combination of resistance determinants are presented by 18 R-spectra. In contrast to Baltic strains, no dominating R-spectrum was revealed in Chukchi strains (Table 6).

To determine if it is appropriate to relate the diversity of R-spectra and polyresistance to the antibiotics of the dominating taxonomic groups of heterotrophic microorganisms as criteria of the pollution level of the region under investigation, a comparison of data was obtained for *Pseudomonas* bacteria, isolated from the Bering, Chukchi, and Baltic Seas (Fig. 1, Table 4).

In Fig. 1, antibiotics were grouped according to the resistance to them by marine microorganisms. Resistance to the first group, comprising ampicillin, kanamycin, and streptomycin, is determined by plasmid genes. Resistance to the second group, comprising benzylpenicillin, methicillin, and monomycin, is determined by chromosomal genes. Figure 1 shows that in the Baltic and Chukchi Seas, among bacteria in the genus *Pseudomonas*, the number of strains resistant to the antibiotics is much higher than that in the Bering Sea. In the Baltic Sea, microorganisms of other taxonomic groups were

TABLE 6

Antibioticogram of strains of marine *Pseudomonades* from the Chukchi Sea.

R-spectra	Distribution among the spectra	
	Abs. number	percent
Amp Ben Mtt Kan Mon Str Clm Nal	2	7.4
Amp Ben Mtt Mon Str Clm Nal	1	3.7
Ben Mtt Kan Mon Str Clm Nal	2	7.4
Ben Mtt Gen Kan Mon Str Clm	1	3.7
Ben Mtt Kan Mon Clm Nal	1	3.7
Ben Mtt Gen Kan Mon Str	1	3.7
Amp Ben Mtt Kan Nal	1	3.7
Ben Mtt Kan Mon Nal	3	11.1
Mtt Kan Mon Str Nal	1	3.7
Mtt Gen Kan Mon Str	1	3.7
Ben Mtt Kan Mon	4	14.8
Ben Mtt Mon Nal	2	7.4
Ben Mtt Kan Nal	1	3.7
Mtt Kan Mon Nal	2	7.4
Mtt Mon Clm	1	3.7
Mtt Mon Nal	1	3.7
Mtt Mon	1	3.7
Mtt	1	3.7

more resistant to antibiotics than those in the Chukchi Sea. In the Bering Sea, they were the most sensitive to antibiotics. Of special interest, in the Chukchi Sea, the *Pseudomonades* and other microorganisms showed more resistance to those antibiotics, which was determined by chromosomal genes.

Bacteria of the genus *Pseudomonas* from the impact region of the Baltic Sea possessed a rather high sensitivity to aminoglycosides, especially to gentamicin and kanamycin. Resistance to penicillins was also found in 77.8–93.3% of the cases. In this case, the number of polyresistant strains, having three and more determinants of polyresistance, accounted for 95.6%. However, the Baltic strains also possessed the dominating R-spectrum in 42.2% of the strains.

This information suggests that among the dominant heterotrophic microflora in the Chukchi and Bering Seas, the formation of strains resistant to antibiotics exists. However, their abundance as a whole is less than in the impact region of the World Ocean, such as the Baltic Sea. Thus, it is possible to state that the percentage of resistance spectra and the level of polyresistant strains in bacterial cenoses reflect the level of pollution in the region.

Based on toxicological estimates of "stress indices," heavy metals ranks second among pollutants behind pesticides (Izrael & Tsyban, 1989). Therefore, the abundance of dominant marine bacteria that are resistant to heavy metals, may also characterize the degree of marine pollution. To examine this hypothesis the resistance of Chukchi Sea microflora to Cd, Co, Cu, Ni, Hg, and Pb ions was investigated. Similar responses of the strains from the Baltic Sea were studied for comparison (Tables 7,8).

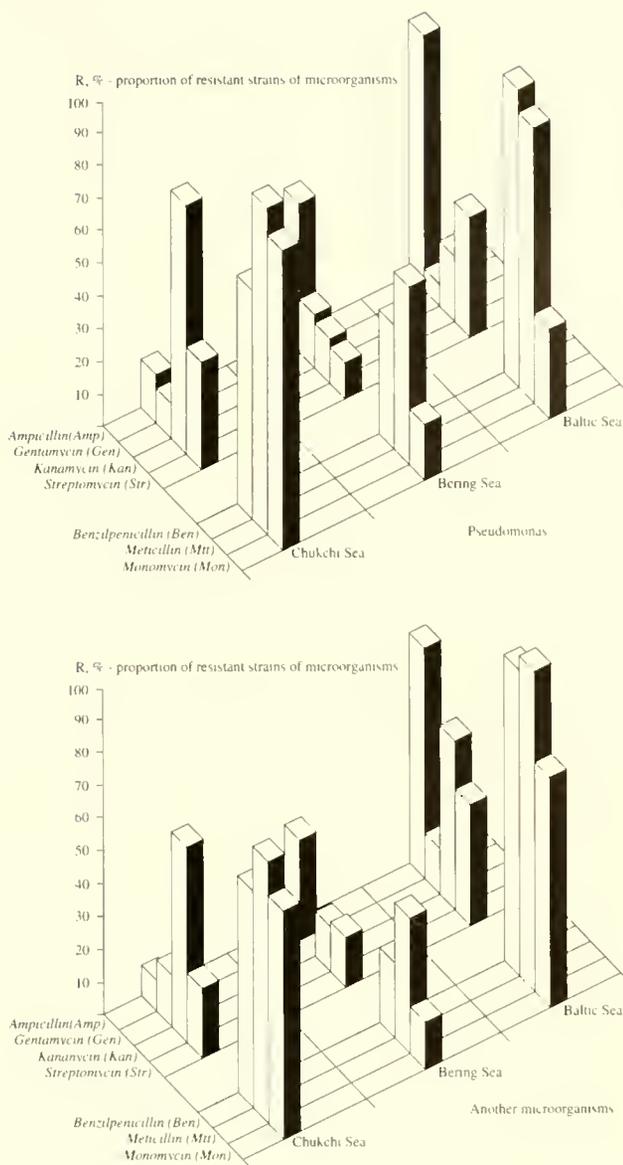


Fig. 1. Resistance of marine microorganisms to antibiotics.

Thirty-three strains of *Pseudomonades*, 17 strains of other bacillary bacteria (including 7 strains from the group *Flavobacterium-Cytophaga*, 5 from the genus *Arthrobacter*, 2 from the genus *Bacillus*), and 12 strains of coccid forms (including 8 strains from the genus *Staphylococcus*, 2 from the genus *Planococcus*, and 2 from the genus *Micrococcus*) were studied for resistance to heavy metals. Results show that strains from the Chukchi Sea respond to heavy metals as those from the Baltic Sea; that is, a wide MIC range and high modal MIC values were found.

These results suggest that bacteria from the Chukchi Sea have adapted to high concentrations of heavy metals. Because all groups of bacteria did not differ in the mode and MIC range of cadmium and lead, natural stability of the strains is one explanation. However, modal values for Co, Cu, Hg, and, partially, Ni, are substantially lower in Chukchi Sea strains relative to those from the Baltic Sea. For instance, the mode of cobalt MIC was 1.024 mg/l for Chukchi Sea strains and 128 mg/l for Baltic strains, while that for Cu was 256 and 128 mg/l and Hg was 32 and 16 mg/l, respectively.

However, for Chukchi Sea strains, the lower and upper values of the MIC range were somewhat lower for most metals. Although specific strains from the Chukchi Sea are resistant to heavy metals, their resistance was considerably lower than in strains from the Baltic Sea.

Anthropogenic pollution of marine waters with chemical substances produces a considerable negative effect on the genetic apparatus of microbes. This effect is due to mutagenic and genotoxic material of certain pollutants. Microorganisms are not only targets for the genotoxicants or mutagens, but in some cases they themselves enhance the effect and strengthen it. Thus, microorganisms can, in the process of decomposition, activate transforming pollutants into more toxic forms. Similarly, it is acknowledged that microorganisms produce different biologically active substances that elicit a broad antibiotic effect. The chemical composition and structure of these compounds suggest that they can also possess mutagenic and genotoxic effects and, under environmental pressures, the mutagenic and genotoxic activity of microorganisms themselves can be strengthened. Thus, the development of marine microorganisms, conditioned by chemical pollution, can serve as an extra factor that strengthens the mutagenic stress upon microbial communities. If ecological conditions continue to deteriorate as in some regions of the World Ocean, the frequency of induced mutations may increase, resulting in an artificial evolution of bacterial strains.

The problem of mutagenic, genotoxic, and carcinogenic effect of marine pollution, and the role of the microorganisms are not yet investigated.

To detect genotoxic and DNA-damaging effects of chemical compounds, bacteria that are most sensitive are widely used. The disturbance of bacteria genotype is immediately expressed in its phenotype because of the gaploid chromosomes. In addition, a high level of correlation is observed between mutagenic activity found in microorganisms and their carcinogenic properties in animals.

Therefore, three strains of *Escherichia coli* were used for the genetic screening: *E. coli* WP-2, *E. coli* Rec-, and *E. coli* Pol A-. Sixty-two strains of bacteria capable of decomposing hydrocarbons and cyclic organic compounds of the Bering Sea were studied. This work involved: 1. heat-killed marine bacteria; 2. exometabolites—metabolic products released by bacteria into the culture medium; and 3. endometabolites—metabolites contained in bacterial cells and released by ultrasound disintegration.

The investigations showed that the ability to synthesize metabolites with general toxic activity and DNA-damaging effect was common to the different taxonomic groups of *Pseudomonas*, *Bacterium*, *Alcaligenes*, *Planococcus*, *Flavobacterium-Cytophaga*, *Xantomonas*, *Arthrobacter*, and *Bacillus*. The general toxic effect of *Pseudomonades* was noted for exo- and endometabolites and killed cells at 75, 50, and 60% of the 32 strains, respectively (Table 9). The DNA-damaging effect was found in 83% of all Bering Sea strains. The results suggest that the genotoxic effect of the genus *Pseudomonas* is not a specific feature of this genus. On *E. coli* Pol A- model this effect was typical of exometabolites found in 69% of the strains, endometabolites in 54% of the strains, heat-

TABLE 7

Range of heavy metal MIC values for microorganisms of the Chukchi and Baltic Seas.

Metallions	Seas	Range of heavy metal MIC values, mg/l			
		<i>Pseudomonades</i>	Other non-spore forming rods	<i>Bacilli</i>	<i>Micrococci</i>
Cd ²⁺	Chukchi	156.7	19.6-313.4	19.6-156.7	39.2-156.7
	Baltic	78.3-313.4	78.3-313.4	39.2-156.7	not investigated
Co ²⁺	Chukchi	14.5-116.2	29.0-116.2	29.0-116.2	29.0-116.2
	Baltic	29.0-464.7	232.3-464.7	29.2-4	not investigated
Cu ²⁺	Chukchi	10.0-39.9	10.0-39.9	2.5-39.9	10.0-39.9
	Baltic	20.0-39.9	20.0-39.9	20.0-39.9	not investigated
Ni ²⁺	Chukchi	96.5-386.0	96.5-386.0	96.5-386.0	96.5-386.0
	Baltic	48.0-386.0	96.5-386.0	96.5-386.0	not investigated
Hg ²⁺	Chukchi	2.4-19.3	4.8-19.3	4.8-19.3	4.8-19.3
	Baltic	4.8-38.5	4.8-38.5	4.8-19.3	not investigated
Pb ²⁺	Chukchi	160.1-640.4	80.0-320.2	40.0-320.2	160.1-320.2
	Baltic	80.0-320.2	160.1-320.2	160.1-640.1	not investigated

TABLE 8

Modal MIC values of heavy metal salts for marine bacteria from the Chukchi and Baltic Seas.

Metallions	Seas	Mode of MIC of strains (mg/l)/percent			
		<i>Pseudomonades</i>	Other non-spore forming rods	<i>Bacilli</i>	<i>Micrococci</i>
CdCl ₂	Chukchi	256/90.9	256/76.4	256/50.0	256/58.3
	Baltic	256/40.6	128-256/35.7	256/42.9	not investigated
CoCl ₂	Chukchi	128/48.5	128/58.8	128/58.4	128/58.4
	Baltic	1,024/59.5	512-1,024/42.9	1,024/42.9	not investigated
CuSO ₄	Chukchi	128/45.4	128/58.8	64/41.7	128/58.4
	Baltic	256/67.6	256/71.4	256/64.3	not investigated
NiSO ₄	Chukchi	1,024/42.4	256-512/35.3	256/50.0	512/50.0
	Baltic	1,024/62.2	512-1,024/35.7	512/50.0	not investigated
Hg(NO ₃) ₂ ·2H ₂ O	Chukchi	16/51.5	16/58.8	16/41.716/50.0	not investigated
	Baltic	32/35.1	32/35.7	32/42.9	not investigated
Pb(NO ₃) ₂	Chukchi	256/51.5	256/82.3	256/66.7	256/75.0
	Baltic	256/81.1	256/85.8	256/85.8	not investigated

Note: Modal values (mode) of MIC is in the numerator; proportion of the strains resistant to the given concentration of the metal ions is in the denominator.

killed cells in 38% of the strains. On the *E. coli* Rec- model, the above figures were 50, 50, and 67%, respectively (Table 9). Twenty-eight percent of the strains of Bering Sea *Pseudomonades* produce compounds possessing DNA-damaging effect upon both mutant strains. This suggests carcinogenic activity.

TABLE 9

Toxic and DNA-damaging effects of metabolites of *Pseudomonades* from the Bering Sea.

Test-object	Number of strains (%) with positive effect		Killed cells
	Exometabolites	Endometabolites	
<i>E. coli</i> WP-2	75	50	60
<i>E. coli</i> Pol A-	69	54	38
<i>E. coli</i> Rec-	50	50	67

In representatives of the *Flavobacterium-Cytophaga* group, DNA-damaging effect appears considerably lower than the *Pseudomonas*. Only one of the seven strains gave a positive effect in the model *E. coli* Pol A-.

From the comparison of the results on toxic and genotoxic properties of the metabolites of the genus *Pseudomonas* isolated from the Bering and Chukchi Seas, it was found that the Chukchi Sea occupies an intermediate position between the Baltic and Bering Seas. With respect to an increase in the number of strains possessing the genotoxic activity, the seas are listed in the order of the Bering Sea, the Chukchi Sea, and the Baltic Sea.

Thus, investigations showed that an ability to produce metabolites with a genotoxic effect is a marginal characteristic of marine bacteria, such as *Pseudomonas*, *Alcaligenes*, *Xantomonas*, *Arthrobacter*, *Bacillus*, and *Flavobacterium-Cytophaga*. However, the ability of marine bacteria to produce substances possessing genotoxic activity, which was determined under laboratory conditions, does not affirm if these properties are dangerous under natural conditions. It remains unknown whether bacteria produce a genotoxic effect in the marine environment.

To determine the minimum concentrations of bacteria, sufficient to elicit DNA-damaging effect, three strains of the *Flavobacterium-Cytophaga* group, which manifested a genotoxic effect, were used. It was determined that the maximum dilution of exometabolites, at which the DNA-damaging action was preserved, was 1:125. This corresponds to a bacterial density in seawater on the order of 1×10^5 cells/ml under experimental conditions. The active dilution for two other strains ranged from 1:25 to 1:5. This corresponds to a bacterial density to 1×10^7 to 1×10^9 cells/ml.

Exo- and endometabolites of four strains (including the above strains) with genotoxic and DNA-damaging effects were analyzed by means of the standard Ames test. The purpose is to elucidate questions about mutagenic activity.

As test strains, the specialized strains *Salmonella typhimurium* TA-98 and TA-100, when used, revert to prototrophicity with respect to histidine due to mutation of a reading frame shift and replacement of base pairs.

The results from this test suggest that one of the four strains produced metabolites with mutagenic activity. Exometabolites of this strain, in a volume of 0.1 ml per Petri cap, induced genetic mutations of the frame shift type. The frequency of occurrence was more than 40 times higher than spontaneous mutation ($82.6 \times 10^{-6}\%$ as compared to the control value of $2.0 \times 10^{-6}\%$).

Of great importance seems to be the DNA-damaging effect clearly marked in the genus *Pseudomonas*. This genus has gained an advantage in conditions of marine pollution and develop in waters subjected to heavy anthropogenic inputs. So we speculate that the development of indicator microflora, which includes bacterial decomposers in impact regions of the World Ocean, is secondary pollution of the marine environment (i.e., intensifying the potential response of chemical pollution and threatening the genotype of marine ecosystems).

The ability of certain forms of microorganisms to change under the effect of chemical pollution can be far from safe for other marine organisms and man. There is a risk of possible genetic transformation of harmless bacteria under the pressure of the environmental mutagens and selection towards aggressive pathogenic forms of microorganisms. The risk increases if the protective mechanisms of animals and man have not yet adapted. In this case, transformation of the microorganisms can mutate from the nonpathogenic to quasi-pathogenic group and from the latter into the pathogenic group.

Two main models are used to determine pathogenicity of microorganisms. One is classical and is based on the reproduction of an infection process in laboratory animals. The other examines the effect of bacteria on man and animal cell cultures as a model. Cell cultures provide a less expensive, rapid answer, with a more stable assay with higher sensitivity and reliability than results with experimental animals.

Pathogenic properties of 14 strains from the Bering Sea, 18 strains from the Chukchi Sea, and 27 strains from the Baltic Sea were studied with the use of white mice and the reinoculated kidney cells of a human embryo (RH) and fish skin cells (EPC) (Tsyban *et al.*, 1988).

The study included 26 strains of two groups of bacterial populations. These groups were *Pseudomonas* and *Flavobacterium-Cytophaga*, isolated from the Bering Sea and other regions of the World Ocean. With the use of the model of intraperitoneal infection, white mice did not reveal pathogenic properties. However, the use of cell cultures revealed a differentiation of strains by the level of potential pathogenic activity of bacteria cells.

The cytopathic effects cause morphological changes of cells and disruption of the monolayer. For pathogenic strains, cytopathic response occurred in 50–100% of the tests, quasi-pathogenic (potentially pathogenic) strains—25–50%, and nonpathogenic strains—less than 25%. Changes observed included vacuolization of cytoplasm, rounding-off of some cells, and acidification of the medium. For controls, two species were used: *Pseudomonas fluorescence* BKM-894(H)

as nonpathogenic, and *Pseudomonas aeruginosa* 2-9 as pathogenic. Cytopathic effect of these strains on RH cells suggested that *P. fluorescence* BKM-894(H) did not produce an appreciable effect on the cell culture, while the aggressive strain *P. aeruginosa* 2-9 killed laboratory animals, destroyed the cell culture monolayer by 75–100% after 48 hours and completely suppressed the mitotic activity of the cells.

Analysis of cytopathic data (Table 10) showed that 44.5, 44.4, and 11.1% of the bacterial strains of the genus *Pseudomonas*, isolated from the Baltic Sea, were pathogenic, quasi-pathogenic (potentially pathogenic), and nonpathogenic strains, respectively. Thus, both the quantitative and qualitative assessment of cytopathic data suggests a high pathogenicity of Baltic strains, and much higher than those of Bering strains. These results support the related level of anthropogenic pollution in the Baltic Sea (an impact region) and the Bering Sea (a background region). In the Chukchi Sea, the proportions of pathogenic, quasi-pathogenic, and nonpathogenic strains made up 66.7, 11.2, and 22.2% of the total number of the investigated strains, respectively.

TABLE 10

Cytopathic effect of the strains of *Pseudomonades* on the culture of RH cells from the Bering, Chukchi and Baltic Seas.

Region	The proportion of strains with cytopathic effect, %		
	Nonpathogenic	Potentially pathogenic	Pathogenic
Bering Sea 1984	42.9	50.0	7.1
Chukchi Sea 1988	22.2	11.1	66.7
Baltic Sea 1987	11.1	44.4	44.5

The discovery of pathogenic microorganisms in the Chukchi Sea is of much interest and requires a thorough study. The limited information available restricts an interpretation about the cause of this phenomenon. The results of parallel investigations of the cytopathic effect and invasive properties of 18 strains of *Pseudomonas* and *Flavobacterium-Cytophaga* using the culture of kidney cells of a human embryo (RH) and fish skin cells (EPC) are shown in Table 11. The study of Baltic and Chukchi Seas strains, using the model of fish skin cells

(EPC) made it possible to determine their pathogenic properties against fish. The comparison showed that 64.2% of the studied strains possessed cytopathic action. The results also showed that a number of strains that did not manifest pathogenic properties on human cells produced cytopathic effects on fish cells. This confirms the different degree of pathogenicity of the same strains of marine bacteria for man and fish.

TABLE 11

Cytopathic effect of the strains of *Pseudomonades* from the Chukchi and Baltic Seas on the culture of RH and EPC cells.

Region	Number of the investigated strains	Proportion of strains, %					
		Pathogenic		Potentially pathogenic		Nonpathogenic	
		RH	EPC	RH	EPC	RH	EPC
Chukchi Sea, 1988	18	66.7	77.8	11.1	22.2	22.2	0
Baltic Sea, 1987	14	50.0	71.4	50.0	28.6	0	0

Thus, these investigations suggest that under the pressure of chemical pollutants, pathogenic properties of microorganisms can change as a result of transformation and selection. Besides an ability to decompose complex organic compounds and resist the action of antibiotics, heavy metals, and xenobiotics, marine microflora can acquire pathogenic properties.

The discovered tendencies for increasing the aggressiveness of marine bacteria are based on the adaptation of the bacterial community to new chemical substrates, conditioned by transfer of genetic determinants. The process is accompanied by the selection and accumulation of strains in the polluted environment. These strains contain plasmids for decomposition of and resistance to xenobiotics. Based on the premise (Rochelle *et al.*, 1989) of conjugation in one plasmid of genes responsible for decomposition and resistance to xenobiotics, with genes of antibiotics resistance and pathogenic properties, we hypothesize that the processes of adaptation of microorganisms to chemical pollution are accompanied by selection and accumulation of strains pathogenic for fish and man. This transition of microorganisms from saprophytes to quasi-pathogenic (potentially pathogenic) and eventually pathogenic poses serious concerns for marine mammals and man.

Chapter 4 References

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Chapter 5:
PLANKTON

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Subchapter 5.1:

Phytoplankton

5.1.1 Certain Characteristics of Phytoplankton

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Introduction

This report presents results of the preliminary analysis of phytoplankton samples collected during the Third Joint US-USSR Bering & Chukchi Seas Expedition. The specimens were observed by the "living droplet" method using a light microscope. We determined the species composition of the microalgae, their size, and the number of cells. As a result, we have quantitative estimates of the total number and biomass of phytoplankton per unit volume. In addition, dominant species have been identified, since their development in the plant community strongly influences the value of the quantitative indices mentioned before. These results are shown in Table 1.

Distribution of phytoplankton was determined in the following regions: the Chirikov basin (Stations 87-107), the Gulf of Anadyr (Stations 9-41), the central Bering Sea region (Stations 1-7), and the southern Bering Sea region (Stations 108-113).

An intensive development of phytoplankton was observed in the Chirikov basin. The number and biomass of microalgae were high at all stations. The total number in the surface layer varied in the range of $500-1,700 \times 10^3$ cells/l, and the highest value was observed at Station 86. Total numbers of phytoplankton were dominated by diatoms: *Leptocylindrus danicus*, *Chaetoceros socialis*, *Chaetoceros debilis*, and *Rhizosolenia alata*. Biomass at the surface varied in the range of 300-3,000 mg/l. The largest contribution to the total biomass was also due to diatoms: *Leptocylindrus danicus*, *Rhizosolenia alata*, and *Chaetoceros concavicornis*. At all stations in the Chirikov basin, the quantitative indices decreased with the depth. The only exception was Station 106, where the number and biomass were high at a depth of 45 m as well. In general at 40-45 m, the numbers varied in the range of $80-1,000 \times 10^3$ cells/l, and biomass — 120-850 mg/l.

Thus, in the Chirikov basin an intensive development of phytoplankton was observed, with diatoms occupying a leading position in the plant community.

In the Gulf of Anadyr, phytoplankton were not as abundant as in the Chirikov basin and their numbers varied in a smaller range, from 100 to 700×10^3 cells/l. At many stations, the number of phytoplankton increased with the depth (Stations 15, 19, 32, 36). This was probably connected with the presence of the pycnocline at these depths. The most numerous species in the plant community of the Gulf of Anadyr were algae of various classes:

Class Bacillariophyceae — *Fragilaria oceanica*,
Fragilaria striatula,
Chaetoceros compressus,
Chaetoceros socialis,
Leptocylindrus danicus.

Class Dinophyceae — *Gymnodinium wulffii*,
Goniaulax orientalis.
Class Chrysophyceae — *Chromulina* sp.

Biomass of phytoplankton in this region varied over a wide range from 6 to 3,600 mg/l. High values of biomass were caused by the presence of large diatoms like *Rhizosolenia alata*, *Amphiprora hyperborea*, and *Coscinodiscus oculus iridis* in the plant community.

In general, it may be noted that during the period of the expedition, the phytoplankton composition of the Gulf of Anadyr was very diverse. While the number of microalgae was evenly distributed throughout area, there was a wide range in the biomass values. This was connected with the presence of large forms of phytoplankton in the samples.

There was an uneven distribution of phytoplankton in the central area of the Bering Sea. The phytoplankton numbers in the surface waters varied in the range of $100-2,400 \times 10^3$ cells/l and biomass in the range of 40-1,800 mg/l. Quantitative indices decreased with depth, which was characteristic for all the central area stations, except for Station 7. At this station, the number and biomass of phytoplankton were roughly uniform with depth.

Most abundant vegetation in this region consisted of small forms. The taxonomic composition of phytoplankton is characteristically depauperate in diatoms as compared with the northern part of the sea. The following species were numerically dominant:

Class Chrysophyceae — *Chromulina* sp.
Class Haptophyceae — *Calyptrosphaera insignis*.
Class Xanthophyceae — *Meringosphaera mediterranea*.
Class Cyanophyceae — *Synechococcus* sp.
Class Loxophyceae — *Pedimonas mikron*.
Class Bacillariophyceae — *Fragilaria striatula*,
Chaetoceros debilis,
Nitzschia delicatissima.

In the southern part of the Bering Sea, phytoplankton was characterized by the following: their numbers at the sea surface varying in the range of $700-1,700 \times 10^3$ cells/l. Among numerically dominant species there were no diatoms or peridinians. Instead, representatives of the following classes of algae were most abundant in this region:

Class Cyanophyceae — *Synechococcus* sp.
Class Loxophyceae — *Pedimonas mikron*.

Their biomass ranged from 3 to 1,300 mg/l. As for biomass, the following species of microalgae were dominant:

Class Bacillariophyceae — *Fragilaria striatula*,
Chaetoceros concavicornis.

TABLE 1

The number, biomass, and dominant species of phytoplankton.

Sta. No.	Depth	Number cells/l	Biomass mg/l	Dominant Species	
				Numerically	Biomass
1	0	184,600	264.6	<i>Fragilaria striatula</i>	<i>Amphiprora hyperborea</i>
	10	87,414	5.3	<i>Chromulinales</i> sp.	<i>Chromulinales</i> sp.
	20	132,600	266.3	<i>Synechococcus</i> sp.	<i>Amphiprora hyperborea</i>
	25	60,452	6.2	<i>Meringosphaera mediterranea</i>	<i>Meringosphaera mediterranea</i>
	45	51,435	4.0	<i>Synechococcus</i> sp.	<i>Meringosphaera mediterranea</i>
2	0	2,440,800	1,824.8	<i>Chaetoceros debilis</i>	<i>Chaetoceros debilis</i>
	45	39,000	19.9	<i>Synechococcus</i> sp.	<i>Chaetoceros debilis</i>
3	0	106,600	208.3	<i>Fragilaria striatula</i>	<i>Amphiprora hyperborea</i>
	10	648,960	130.6	<i>Synechococcus</i> sp.	<i>Calyptrosphaera insignis</i>
	45	23,400	5.1	<i>Synechococcus</i> sp.	<i>Chaetoceros debilis</i>
4	0	590,200	1,458.3	<i>Chaetoceros debilis</i>	<i>Chaetoceros concavicornis</i>
	15	477,100	484.7	<i>Nitzschia delicatissima</i>	<i>Chaetoceros concavicornis</i>
	45	68,900	127.7	<i>Chaetoceros debilis</i>	<i>Rhizosolenia alata</i>
5	0	285,243	333.5	<i>Fragilaria striatula</i>	<i>Coretron criophyllum</i>
	15	38,592	14.2	<i>Chromulina</i> sp.	<i>Calyptrosphaera insignis</i>
	45	146,523	102.6	<i>Fragilaria striatula</i>	<i>Leptocylindrus danicus</i>
6	15	469,300	215.5	<i>Fragilaria striatula</i>	<i>Fragilaria striatula</i>
7	0	183,300	43.5	<i>Fragilaria striatula</i>	<i>Fragilaria striatula</i>
	45	104,907	45.5	<i>Fragilaria striatula</i>	<i>Denticulopsis seminea</i>
	128	267,800	71.7	<i>Fragilaria striatula</i>	<i>Fragilaria striatula</i>
9	0	678,000	106.4	<i>Chromulinales</i> sp.	<i>Goniaulax orientalis</i>
	32	610,200	54.6	<i>Chromulinales</i> sp.	<i>Gymnodinium</i> sp.
	88	16,250	5.8	<i>Chromulinales</i> sp.	<i>Eucampia zoodiacus</i>
11	135	71,961	23.4	<i>Chroomonas</i> sp.	<i>Distephanus speculum</i>
13	0	3,651,596	26.3	<i>Chromulinales</i> sp.	<i>Chromulinales</i> sp.
	130	119,646	73.8	<i>Chroomonas</i> sp.	<i>Amphiroora hyperborea</i>
15	0	96,030	7.4	<i>Synechococcus</i> sp.	<i>Gymnodinium wulffii</i>
	42	185,600	47.1	<i>Chroomonas</i> sp.	<i>Leptocylindrus danicus</i>
19	0	153,600	211.9	<i>Prymnesiales</i> sp.	<i>Rhizosolenia alata</i>
	55	374,400	56.3	<i>Synechococcus</i> sp.	<i>Leptocylindrus danicus</i>
24	0	363,200	32.1	<i>Thalassiosira nordenskiöldii</i>	<i>Thalassiosira nordenskiöldii</i>
	45	214,400	13.6	<i>Phaeocystis pouchettii</i>	<i>Gymnodinium wulffii</i>
27	0	316,800	3,640.1	<i>Phaeocystis pouchettii</i>	<i>Coscinodiscus oculus-iridis</i>
	45	374,400	334.8	<i>Fragilaria oceanica</i>	<i>Fragilaria oceanica</i>
	32	463,078	56.6	<i>Phaeocystis pouchettii</i>	<i>Dinobryon balticum</i>
32	45	610,324	71.3	<i>Phaeocystis pouchettii</i>	<i>Gymnodinium wulffii</i>
	35	0	224,070	23.9	<i>Prymnesiales</i> sp.
35	45	277,420	171.0	<i>Chaetoceros compressus</i>	<i>Chaetoceros compressus</i>
	36	0	126,973	18.7	<i>Phaeocystis pouchettii</i>
41	45	313,698	151.2	<i>Chaetoceros socialis</i>	<i>Chaetoceros socialis</i>
	41	0	742,632	2,584.5	<i>Leptocylindrus danicus</i>
83	45	83,226	123.5	<i>Phaeocystis pouchettii</i>	<i>Leptocylindrus danicus</i>
	83	0	496,000	269.0	<i>Chroomonas</i> sp.
86	0	1,740,800	3,158.0	<i>Chaetoceros socialis</i>	<i>Chaetoceros concavicornis</i>
89	0	912,000	2,659.8	<i>Chaetoceros subsecundus</i>	<i>Leptocylindrus danicus</i>
	45	281,600	521.3	<i>Leptocylindrus danicus</i>	<i>Leptocylindrus danicus</i>
96	0	953,600	937.8	<i>Chaetoceros socialis</i>	<i>Leptocylindrus danicus</i>
	40	1,046,400	850.2	<i>Chaetoceros socialis</i>	<i>Leptocylindrus danicus</i>
100	0	1,148,800	2,934.2	<i>Chaetoceros debilis</i>	<i>Leptocylindrus danicus</i>
102	0	486,400	3,109.7	<i>Leptocylindrus danicus</i>	<i>Leptocylindrus danicus</i>
108	0	651,600	2.7	<i>Pedimonas mikron</i>	<i>Hemisehnis</i> sp.
	45	1,248,000	54.1	<i>Synechococcus</i> sp.	<i>Distephanus speculum</i>
110	0	1,667,200	1,339.2	<i>Synechococcus</i> sp.	<i>Chaetoceros concavicornis</i>
112	0	1,420,800	131.5	<i>Synechococcus</i> sp.	<i>Fragilaria striatula</i>
	45	358,400	82.2	<i>Synechococcus</i> sp.	<i>Fragilaria striatula</i>
113	0	1,324,800	121.5	<i>Synechococcus</i> sp.	<i>Gymnodinium wulffii</i>
	45	1,244,800	73.2	<i>Synechococcus</i> sp.	<i>Distephanus speculum</i>

Class Dinophyceae — *Gymnodinium wulffii*.
Class Cryptophyceae — *Hemiselmis* sp.
Class Chrysophyceae — *Distephanus speculum*.

Thus, due to large cell sizes, representatives of both diatoms and peridinians dominated the biomass.

In general, the following relationships in distribution of qualitative and quantitative characteristics of phytoplankton in the Bering Sea, in 1988, were noted:

1. Depletion of the diatom and peridinian flora from north to south, which can be attributed to the seasonal succession of phytoplankton.

2. As for quantitative indices, they were subject to sharp variations both from station to station and at different depths, which was characteristic for the region under investigation, being hydrologically complex.

5.1.2 Phytoplankton Biomass Distribution in the Northern Bering Sea and Southern Chukchi Sea

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Introduction

The ecosystem of the northern Bering Sea and southern Chukchi Sea Shelf region is strongly influenced by the advection of cold, nutrient-rich seawater from the edge of the deep Bering Sea basin (Springer, 1988). This conclusion resulted from data collected by Inner Shelf Transfer and Recycling (ISHTAR) Project investigators between 1983 and 1989 (Walsh *et al.*, 1989). The project was the first large-scale scientific study attempting to elucidate the ecological processes of these northern shelf waters, a region of extremely high primary and secondary productivity (McRoy *et al.*, 1972; Motoda & Minoda, 1974; Sambrotto *et al.*, 1984; Springer, 1988) leading to high upper trophic level productivity (Hood & Kelley, 1974). The Third Joint US-USSR Bering & Chukchi Seas Expedition, aboard the *Akademik Korolev*, provided the first opportunity to extend the ISHTAR experimental design across the whole northern shelf area to examine the areal and vertical distribution of phytoplankton biomass.

Historical studies of the Bering Sea region show high productivity associated with the continental shelf area in the southeastern Bering Sea (Banahan & Goering, 1986; Sambrotto *et al.*, 1986; Schneider *et al.*, 1986; Smith & Vidal, 1986; Walsh & McRoy, 1986) and in Bering Strait (McRoy *et al.*, 1972; Motoda & Minoda, 1974; Iverson *et al.*, 1979). Zenkevitch (1963), working with many years of Soviet data, proposed that cold oceanic water from the North Pacific Ocean and warm shelf water from the southeastern Bering Sea create an east-west biogeographical division in the northern shelf region. A Japanese study by Motoda and Minoda (1974) also described zoogeographic associations in the pelagic fauna with cold and warm water masses. Kinder *et al.* (1975) described the Bering Slope Current system as a northwest, subsurface flow of North

Pacific Ocean water entering through the Aleutian Islands and continuing along the continental shelf slope bisecting at Cape Navarin to form the Anadyr Stream.

Takenouti and Ohtani (1974) and Coachman *et al.* (1975) described the northern Bering Sea as consisting of three distinct water masses: Alaskan Coastal, Bering Shelf, and Anadyr water. Productivity and chlorophyll data from McRoy *et al.* (1972), Sambrotto *et al.* (1984), Springer (1988), and Whitledge *et al.* (1988) showed extremely high phytoplankton production in the northern Bering Sea and southern Chukchi Sea. Benthic studies (Zenkevitch, 1963; Alton, 1974; Grebmeier *et al.*, 1988; Grebmeier & McRoy, 1989) revealed rich benthic fauna in this region, also indicating a persistent system of intense primary production in the overlying water. These studies led to the hypothesis that advection of cold, nutrient-rich, oceanic water (Anadyr water) onto the continental shelf of the northern Bering and southern Chukchi Seas fueled the high primary productivity (Walsh *et al.*, 1989). This production regime has been described as a "continuous culture" system analogous to an upwelling regime (Sambrotto *et al.*, 1984).

Prior to 1988, the data set describing the production associated with this flow was confined to the waters east of the US-USSR convention line. The joint US-USSR expedition allowed expansion of the data set across the entire shelf (see Frontispiece) to include the core of the Anadyr Stream.

Study Area

The study area extended from the South Polygon (53°N, 175°E) in the southern Bering Sea to the southeastern Chukchi Sea near Cape Lisburne (69°N, 167°W; Frontispiece). Ecological investigations began at the East Polygon (58°N, 175°W; Stations 1-5) and continued in the Gulf of Anadyr and

the Bering Shelf area southwest of St. Lawrence Island (Stations 6–43). After investigation of Anadyr Strait, the expedition proceeded north into the Chukchi Sea (Stations 44–75). After completing the studies in the Chukchi Sea, Bering Strait was surveyed twice (Stations 76–86). Proceeding south from the Bering Strait, studies were undertaken in the Chirikov basin (Stations 87–107) and the southern Bering Sea (Stations 108–113), including the South Polygon.

Materials and Methods

Phytoplankton biomass was assessed at each station in the Bering and Chukchi Seas as chlorophyll *a* fluorescence (Parsons *et al.*, 1984).

Briefly, water samples (250 ml) were collected at 11 depths from each station using Niskin bottles attached to a rosette sampling apparatus. Samples were filtered through 25 mm Gelman glass fiber filters (pore size: 0.3 μm) in a multiple-sample filtration apparatus using a vacuum pump. Each filter was suctioned dry and then placed in a 20-ml glass test tube with 10 ml of 90% acetone to extract the photosynthetic pigments. To facilitate extraction of all pigments, a tissue grinder was used to homogenize the filter in acetone. The sample was then transferred to a 15-ml centrifuge tube and centrifuged for 10 min. After centrifugation, the supernatant was transferred to a cuvette, where its fluorescence was measured using a Turner Designs fluorometer before and after acidification with two drops of 5% HCl.

For analysis, chlorophyll data from stations on the shelf south of St. Lawrence Island, in the Gulf of Anadyr, and in the polygon stations were integrated from the surface to 50 m to give areal chlorophyll values. In the Chirikov basin and Chukchi Sea where the bottom is less than 50 m deep, chlorophyll values were integrated from surface to bottom.

Results

Chlorophyll concentrations were measured at each of the 113 stations studied during the cruise from 27 July to 2 September 1988. Samples for chlorophyll analysis were obtained at approximately 10 discrete depths at each station. Over 1,000 samples were collected and analyzed in this comprehensive study of the Bering and Chukchi Seas.

Central Bering Sea Polygons

The East and South Polygons each consist of five stations in the deep Bering Sea. The polygon stations are part of a continuing study and were included in the Second Joint US–USSR Bering Sea Expedition in 1984.

East Polygon. Stations 1 to 5 were located in the East Polygon (58°N, 175°W) over the shelf slope area in the eastern Bering Sea (Frontispiece). Bottom depth at these stations ranged from 140 m at Station 5 to 3,190 m at Station 3. Integrated chlorophyll values ranged from 22 mg/m² at Station 5 to 121 mg/m² at Station 2. The average for all stations was 66 mg/m². Deep-water (2,689 m and 3,190 m) Stations 2 and 3 had the highest values, 121 and 90 mg/m², respectively, with

the lowest values 22 and 48 mg/m², being found at the shallower (140 m and 150 m) shelf-slope Stations 5 and 4, respectively.

South Polygon. Stations 108 to 113 were located in the South Polygon (53°N, 175°W) in the deep basin of the Bering Sea over Bowers Ridge (Frontispiece). The minimum depth at these stations is 220 m. Integrated chlorophyll values were less than 30 mg/m² at each station with the exception of Station 112 (67 mg/m²). The average for all stations was 35 mg/m².

Gulf of Anadyr and Western Bering Shelf

Stations 7 to 43 were located in the Gulf of Anadyr and on the adjacent shelf southwest of St. Lawrence Island (Frontispiece). Integrated chlorophyll ranged from 13 mg/m² at Station 12, east of Cape Navarin outside the Gulf of Anadyr, to 797 mg/m² at Station 24 in the central region of the gulf (Fig. 1). Relatively low values (13 to 45 mg/m²) characterized the southern half of the study area, particularly the shelf area south of St. Lawrence Island. High values were measured near the northern coast of the Gulf of Anadyr. Stations 24 and 26 had exceptionally high concentrations of 797 mg/m² and 430 mg/m², respectively. These were some of the highest values measured during the cruise. Station 26 had chlorophyll concentrations greater than 50.0 mg/m³ in the top 10 meters, decreasing to less than 1.0 mg/m³ below 20 meters (Fig. 2b).

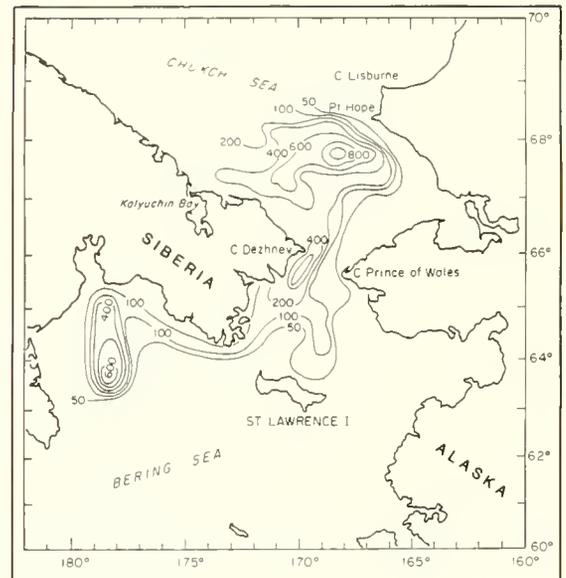


Fig. 1. Depth integrated (0–50 m) chlorophyll (mg chl *a*/m²) for *Akademik Korolev* stations.

The highest chlorophyll values were found in the north and central Gulf of Anadyr with concentrations decreasing to the south and east (Fig. 1). A cross section, from Station 26 in the northwest corner of the gulf to Station 35 on the adjacent shelf area south of Anadyr Strait, shows a subsurface chlorophyll maximum (>15.0 mg/m³) located along the northern coast of

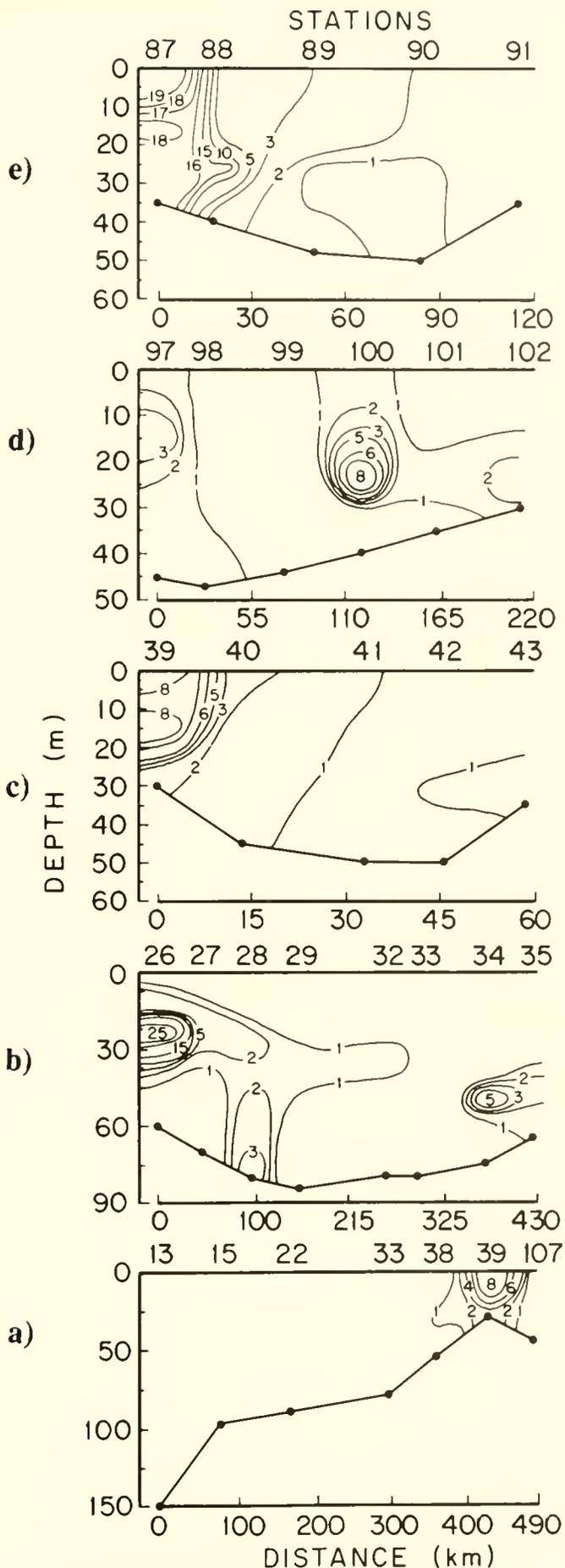


Fig. 2. Vertical cross-sections of chlorophyll (mg/m^3) arranged from South to North (a to e). Transect location given on Frontispiece.

the gulf at a depth of 20 to 30 m (Fig. 2b). A cross section from Station 13 to Station 39, from the outer shelf (150 m) to Anadyr Strait (30 m), reveals high phytoplankton biomass strictly limited to the strait area providing evidence of the influence of nutrient-rich Anadyr water (Fig. 2a).

Anadyr Strait

Data from Anadyr Strait indicate that high integrated chlorophyll values were associated with waters near the Siberian coast at Station 39 ($193 \text{ mg}/\text{m}^2$). Values decreased to the east to $23 \text{ mg}/\text{m}^2$ at Station 43 next to St. Lawrence Island (Fig. 1). A cross-section of Anadyr Strait provides another view of the association between phytoplankton stocks and Anadyr water. Chlorophyll concentrations decrease to less than $1.0 \text{ mg}/\text{m}^3$ across the eastern half of the strait (Fig. 2c).

Chirikov basin

Stations 87 to 107 were in the Chirikov basin (Frontispiece). Data from this area revealed high chlorophyll values on the western side of the basin, suggesting the presence of higher nutrient water (Fig. 1). Integrated chlorophyll values as high as $593 \text{ mg}/\text{m}^2$, at Station 87, were observed close to the Soviet coast. The western side of the basin is characterized by values over $100 \text{ mg}/\text{m}^2$. Chlorophyll values decrease to the east across the basin. Phytoplankton biomass of less than $50 \text{ mg}/\text{m}^2$ was characteristic of the eastern side of the basin in Alaska Coastal water. The maximum eastward extent of high chlorophyll values was observed in the central part of the basin at Station 94 ($307 \text{ mg}/\text{m}^2$). Data from a transect across the central basin, from stations 97 to 102, shows distinct areas of high biomass, one next to the Soviet coast and one in the central part of the basin (Fig. 2d). The western concentration has a subsurface chlorophyll maximum ($>3.0 \text{ mg}/\text{m}^3$) at 10 to 15 m while the eastern area has a maximum ($>8.0 \text{ mg}/\text{m}^3$) at 20 to 25 m. These two areas of high biomass lose their identity and converge with the water masses flowing toward Bering Strait (Fig. 2e). The highest concentration of chlorophyll in the Chirikov basin was measured at Station 87 the closest station to the Soviet coast.

Bering Strait

Bering Strait was surveyed twice. The first transect occupied six stations (76–81) across the strait while the second transect occupied five of the same stations (82–86), omitting only the westernmost station. Integrated values of chlorophyll indicate the same pattern for both transects (Fig. 1). Highest values, up to $619 \text{ mg}/\text{m}^2$ at Station 76, were observed adjacent to the Soviet coast west of Ratmanov Island and the lowest value ($27 \text{ mg}/\text{m}^2$ at Station 81) occurred east of Diomedé Island near the Alaskan coast.

During the first passage, the chlorophyll maximum on the western side of the strait ($>25 \text{ mg}/\text{m}^3$) was at the surface at Station 76 (Fig. 3a). On the eastern side of the strait there were no concentrations higher than $1.7 \text{ mg}/\text{m}^3$. Although the western side of the strait showed high integrated values throughout the water column, most phytoplankton were close to the Soviet coast. In the second transect a similar pattern existed as in the first with the exception of a subsurface maximum ($8.0 \text{ mg}/\text{m}^3$) on the western side at 30 m. Bottom concentrations on the eastern side near Diomedé Island appear to match bottom

concentrations next to the islands on the western side indicating that some of the phytoplankton associated with Bering Shelf–Anadyr water flowed through the eastern portion of the strait.

Chukchi Sea

Stations 44 to 75 were in the southern Chukchi Sea (Frontispiece). The highest values of integrated chlorophyll (625, 696, and 1,167 mg/m^2) found during the cruise were observed at stations 54, 56, and 55, respectively. Values in excess of 300 $\text{mg chl}/\text{m}^2$ characterized the majority of these stations with the highest values found in the center of the region (Fig. 1). Thirteen of the 31 stations, all in the center of the region or near the Soviet coast, had integrated chlorophyll values greater than 300 mg/m^2 . Only the outer regions of the study area to the north and east had values less than 100 mg/m^2 . In the Chukchi, as with the Bering Sea components of the cruise, high chlorophyll values were observed off the Soviet coast at Stations 44, 59, 71, and 72. The lowest values in the area, less than 50 mg/m^2 , were found closer to the Alaskan coast. Cross sections from Stations 72–75 and Stations 71–66 show high phytoplankton biomass on the western side of the basin, presumably as a result of the flow of Bering Shelf–Anadyr water carrying its load of phytoplankton and nutrients (Figs. 3b,c).

Cross sections from Stations 59–65, and Stations 44–50, indicate that the characteristic water masses of this system are no longer recognizable from chlorophyll distribution measurements (Figs. 3d,e). North of approximately 67° latitude, the Bering Shelf–Anadyr water masses appear to spread out as current speed decreases and the flow becomes bathymetrically steered (Coachman & Shigaev, Subchapter 2.1, this volume). High chlorophyll concentrations occurred all across the transect even close to the Alaskan coast at Station 48 (Fig. 3e). High integrated chlorophyll (>300 mg/m^2) is characteristic of Stations 54 and 64 near the eastern side of the study area (Fig. 1). Cross sections from the northern Chukchi Sea (Figs. 3d,e) exhibit a pronounced subsurface chlorophyll maximum similar to those observed in the Chirikov basin and Bering Strait. Concentrations greater than 70.0 mg/m^3 were measured at 15 m at Station 54.

Discussion and Conclusion

Our data support the general model that the advection of the Anadyr water mass over the continental shelf of the northern Bering Sea and into the Chukchi Sea strongly influences the biological regime. In its wake (Coachman *et al.*, 1975) is left a bounty of biological production resulting from its nutrient load and the morphology of the shelf.

Chlorophyll measurements from the Gulf of Anadyr indicate a northward flow of nutrient-rich water around the gulf's perimeter, originating from the bifurcation of the Bering Slope Current in the vicinity of Cape Navarin. The influence of Anadyr water (created by slight modification of Bering Slope water in the Gulf of Anadyr) is not evident until it reaches the euphotic zone as it flows around the Gulf of Anadyr and through Anadyr Strait. The first biological indications of this water mass are present at shallow-water stations in the northwest Gulf of Anadyr where the nutrient-rich water is exposed to the

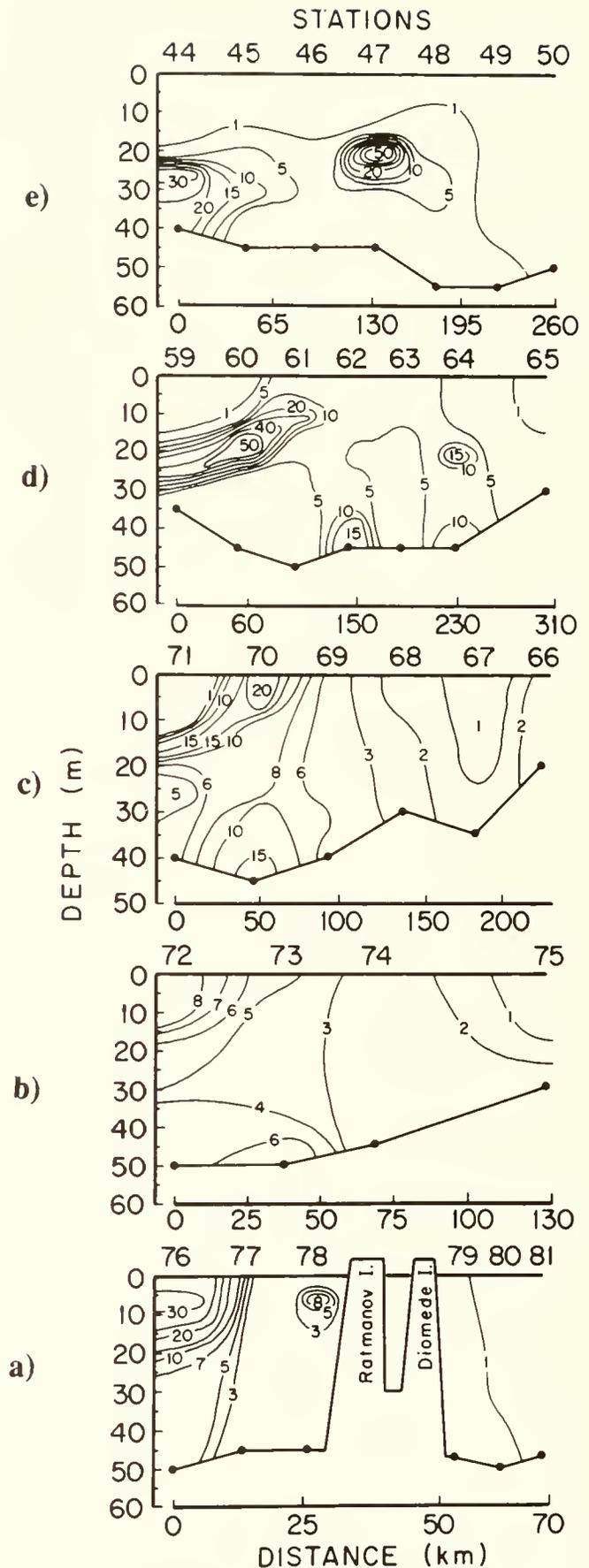


Fig. 3. Vertical cross-sections of chlorophyll (mg/m^3) arranged from South to North (a to e). Transect location given on Frontispiece.

euphotic zone. High phytoplankton biomass at Stations 24 and 26 with lower biomass at surrounding stations indicate that there may be a more complex production system operating in the Gulf of Anadyr than our sampling regime was able to adequately evaluate.

Chlorophyll data indicate that the flow of Anadyr water as the Anadyr Stream is entrained along the Soviet coast as it flows north. High chlorophyll measurements consistently occur near the Soviet coastline in the northern Bering Sea. However, the influence of the Anadyr Stream on phytoplankton biomass further from the coast was evident in a large loop of chlorophyll isopleths in the central Chirikov basin (Fig. 1). This pattern of phytoplankton distribution could result from the flow of Anadyr water through the western end of Shpanberg Strait into Chirikov basin or it could result from eastward advection of high nutrient water flowing through Anadyr Strait. Analysis of cross-sections from Chirikov basin indicate that the loop of phytoplankton biomass, shown as a distinct subsurface chlorophyll maximum, may be a separate entity from the phytoplankton stock closer to the Soviet coast (Fig. 2d). Both phytoplankton concentrations merge as Anadyr and Bering Shelf waters merge and flow through the western side of Bering Strait. The highest phytoplankton biomass in the Chirikov basin can be found near the Soviet coast. Future expeditions should examine the Soviet coastal areas more intensely.

Water masses in the Chirikov basin (Anadyr, Bering Shelf, and Alaska Coastal) appeared well-defined with respect to phytoplankton biomass distribution. An explanation for the "loop" of phytoplankton in the central Chirikov basin is difficult from chlorophyll data alone. The flow of Anadyr and Bering Shelf water into the Chukchi Sea carries not only nutrients but phytoplankton from the productive regions upstream in the Chirikov basin. As opposed to the areas south of Bering Strait, identification of individual water masses by chlorophyll distribution is difficult. The absence of high chlorophyll values

near the Alaskan coast reflects the passage of nutrient-poor Alaska Coastal water. The high nutrient Anadyr and Bering Shelf water masses and their associated phytoplankton stocks mix in Bering Strait and flow into the Chukchi Sea creating the large chlorophyll pool in the center of the basin (Fig. 1).

Chlorophyll distribution in the Chukchi Sea supports the presence of a southeast flowing current, from the north on the Soviet coast (Zenkevitch, 1963; Coachman & Shigaev, Subchapter 2.1, this volume). Areal distribution and depth-sections of data indicate that the high chlorophyll values found in this region have a distinct source near the Soviet coast (Figs. 1,3c-e). Depth-sections from the northernmost (Stations 59-65 and 44-50) transects suggest the existence of two separate chlorophyll stocks, one over Hope Sea Valley in the central Chukchi basin and one along the Soviet coast northeast of Kolyuchin Bay (Figs. 3d,e). Data from the southernmost transects in the Chukchi Sea, below 67° latitude, do not clearly show these stocks (Fig. 3b). It is difficult to distinguish the potential influence of high nutrient Siberian Coastal water from that of Anadyr Stream flowing north through Bering Strait.

The data from the *Akademik Korolev* expedition fill several gaps in the growing data base for the Bering/Chukchi Seas. Since 1983, the ISHTAR Project has studied the ecology of the northern Bering and southern Chukchi Shelf. But it was not until the results of the expedition aboard the *Akademik Korolev* that hypotheses concerning the functioning of this productive marine ecosystem could be confirmed (see Walsh *et al.*, 1989).

This project was part of the Third Joint US-USSR Bering & Chukchi Seas Expedition aboard the Soviet research vessel *Akademik Korolev*. We express appreciation to the US Fish and Wildlife Service and the USSR State Committee for Hydrometeorology, who made our participation possible. Our participation was funded in part by the National Science Foundation, Grant DPP-8405286. Contribution No. 627, Institute of Marine Science, University of Alaska, Fairbanks, AK 99775-1080, USA.

5.1.3 Distributions of Algal Pigments in Near-surface Waters

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Introduction

The Bering Sea is a productive, high-latitude oceanic environment whose expansive shelf supports large standing stocks of zooplankton and marine vertebrates. In contrast to most oceanic regions, the Bering Sea has high levels of phytoplankton biomass and production associated with waters

overlying its shelf domain, as well as its open-ocean domain (Holmes, 1958; Kawamura, 1963; Taniguchi, 1969; McRoy *et al.*, 1972; Koike *et al.*, 1982; Sambrotto *et al.*, 1984, 1986; Hansell *et al.*, 1989). Walsh *et al.* (1985) proposed that a significant proportion of the shelf-based production is transported to the Bering Sea Slope, which serves as a major storage site for atmospheric carbon dioxide. The fact that the

zooplankton-to-phytoplankton biomass ratio calculated for the Bering Sea is higher than most oceanic areas (Motoda & Minoda, 1974) suggests that there is an efficient transfer of phytoplankton carbon to higher trophic levels. However, recent work by Springer *et al.* (1989) indicates that on average the zooplankton of the northern Bering Sea are unable to control the large blooms of diatoms that occur during springtime in this region.

Sambrotto *et al.* (1986) have shown that there is a significant degree of seasonal variability in both phytoplankton biomass and production on the southeastern Bering Sea Shelf. The shallowing of the mixed layer was the most important process responsible for bloom initiation, which occurs annually during early May. The investigators also concluded that vertical mixing forced by atmospheric events is important in controlling the magnitude of the spring bloom. Innerannual variations in zooplankton biomass have also been documented for the Bering Sea, which may reflect variations in meteorological conditions (Motoda & Minoda, 1974).

During early to midsummer, boreal-oceanic diatoms dominate the phytoplankton community of the open western/central Bering Sea and the eastern Bering Sea Shelf, while temperate-neritic diatoms are characteristically found in the vicinity of the Aleutian Island chain (Motoda & Minoda, 1974; Whitedge *et al.*, 1988). The dominant offshore diatoms include representatives from the following genera: *Chaetoceros* sp., *Rhizosolenia* sp., *Denticula* sp., *Thalassiosira* sp., *Nitzschia* sp., *Fragilaria* sp., and *Thalassiothrix* sp. On the southeastern Bering Sea Shelf, diatoms are dominated by *Thalassiosira aestivalis* and *T. nordenskioldii* during prebloom conditions (April) and *Chaetoceros* spp. (especially *C. debilis*) during bloom conditions that occur during May (Sambrotto *et al.*, 1986). Kisselev (1937) also reported the presence of dinoflagellates and green algae in the northern Bering Sea.

To further investigate the distributions of phytoplankton in the Bering and Chukchi Seas, near-surface water samples were analyzed for pigment content by high-performance liquid chromatography (HPLC). This study was part of the Third Joint US-USSR Bering & Chukchi Seas Expedition, designed to examine biological-chemical-physical interactions in the Bering Sea.

Materials and Methods

A series of stations were occupied during July-August 1988 aboard the R/V *Akademik Korolev* in the Bering and Chukchi Seas. Near-surface samples were collected at 112 of these stations for the determination of photosynthetic pigment concentrations (Figs. 1-12). One-liter water samples were filtered through 47 mm GF/F glass fiber filters and transported to Texas A&M University for HPLC pigment analysis. Filters were extracted in 6 ml 100% acetone (final acetone concentration = ~90%) for 24-48 h (-20°C). Following extraction, pigment samples were centrifuged for 5 min to remove cellular debris. Pigment extracts were analyzed for pigment content by HPLC

(Bidigare, 1989). Briefly, chlorophylls and carotenoids were separated using a Spectra-Physics Model SP8700 liquid chromatograph equipped with a Radial-PAK C₁₈ column (0.8 × 10 cm, 5 μ particle size; Waters Chrom. Div.) at a flow rate of 6 ml/min⁻¹. Prior to injection, 1 ml aliquots of the standards and algal extracts were mixed separately with 300 μl of ion pairing solution (Mantoura & Llewellyn, 1983). A two-step solvent program was used to separate the algal pigments. After injection (500 μl sample), mobile phase A (80:15:5; methanol:water:ion-pairing solution) was ramped to mobile phase B (methanol) over a 12-min period. Mobile phase B was then pumped for 18 min for a total analysis time of 30 min. Individual peaks were detected and quantified (by area) with a Waters Model 440 Fixed Wavelength Detector (436 nm) and a Spectra-Physics Model SP4400 integrator, respectively. The identities of the peaks were determined by comparing their retention times with those of pure standards and extracts prepared from "standard" plant materials of known pigment composition. On-line diode array spectroscopy (HPLC/DAS; 350-550 nm for carotenoids and 400-700 nm for chlorophylls) using a Hewlett-Packard Model HP8451 Diode Array Spectrophotometer was performed to confirm the identities of the major chlorophylls and carotenoids. The HPLC system was calibrated with pure standards whose concentrations were determined spectrophotometrically in 1-cm cuvettes (Bidigare, 1989). Known pigment quantities were injected and resultant peak areas were used to calculate individual standard response factors (ng area⁻¹). Pigment concentrations (ng pigment l⁻¹) of the samples were calculated with these response factors and knowledge of the extraction and sample volumes. The HPLC method employed is not capable of separating chlorophyll c₁ from chlorophyll c₂, nor zeaxanthin from lutein.

Results

The quantitatively important algal pigments measured in suspended particulate samples collected from near-surface waters of the Bering and Chukchi Seas were chlorophyll *a*; chlorophyllide *a*; chlorophyll *b*; chlorophylls c₁ + c₂; chlorophyll c₃; 19'-hexanoyloxyfucoxanthin; 19'-butanoyloxyfucoxanthin; fucoxanthin; peridinin; diadinoxanthin; diatoxanthin; and β,β-carotene (Table 2). Concentrations of zeaxanthin plus lutein, prasinoxanthin, and alloxanthin were near or below the limit of HPLC quantification. Phytoplankton pigments in the study area were not uniformly distributed. Chlorophyll *a* concentrations ranged from 12 to 26,618 ng l⁻¹, with highest concentrations measured in the Gulf of Anadyr and the Chukchi Sea (Fig. 1). Distributions of chlorophyllide *a*, chlorophyll *c*, fucoxanthin, diadinoxanthin, diatoxanthin, and β,β-carotene all displayed patterns similar to that of chlorophyll *a* (Figs. 2,4,7,10,11,12). In contrast, elevated concentrations of chlorophyll *b* and peridinin were measured in a narrow zone extending from the Chirikov basin to just north of the Bering Strait (Figs. 3,6). Chlorophyll c₃, 19'-hexanoyloxyfucoxanthin, and 19'-butanoyloxyfucoxanthin

levels were highest at stations occupied in the Chirikov basin and the south-central Bering Sea (Figs. 5,8,9). A tabular listing of stations, positions, and algal pigment concentrations is given in the Table 1.

Discussion

The concentrations of photosynthetic pigments in the marine environment are primarily dependent on the quantity, species composition, and photoadaptive state of the phytoplankton present. For these reasons, accessory chlorophyll and carotenoid pigments have been used as diagnostic "tags" for investigating algal distributions and their physiological processes. In coastal waters off Australia, Jeffrey (1974) documented the usefulness of accessory pigments for examining phytoplankton distributions in the water column. The thin-layer chromatographic method employed identified the major pigments as chlorophylls *a*, *b*, and *c*; carotene; astaxanthin; fucoxanthin; peridinin; diadinoxanthin; and neoxanthin. Chromatographic data were used to "fingerprint" vertical and temporal variations in the phytoplankton community structure.

Several recent investigations have demonstrated the utility of HPLC as a "chemotaxonomical" tool for identifying marine algal groups. For example, high concentrations of zeaxanthin were used to infer the presence of cyanobacteria in the North Sea and tropical Atlantic Ocean (Gieskes & Kraay, 1983a). In another study, the dominance of a symbiotic cryptomonad was established for a spring bloom in the central North Sea by HPLC identification of alloxanthin, a carotenoid characteristic of this marine algal group (Gieskes & Kraay, 1983b). HPLC pigment analysis has also been shown to be useful for characterizing phytoplankton biomass and compositional changes across frontal systems located at the northern wall of

the Gulf Stream (Arnone *et al.*, 1986; Trees *et al.*, 1986) and in the Santa Barbara Channel (Smith *et al.*, 1987).

In this study, the criteria presented in Table 3 were used to infer distributions for the major algal groups (diatoms, green algae, dinoflagellates, chrysophytes, and prymnesiophytes). The most abundant accessory pigments detected in this study were chlorophyll *c*, diadinoxanthin, and fucoxanthin (Table 2), which reflect the dominance of diatoms in the Gulf of Anadyr and the Chukchi Sea during midsummer. In addition, the suite of pigments also common to the diatoms (chlorophyllide *a*, diatoxanthin, and β,β -carotene) all displayed elevated concentrations in these regions. Distributions of chlorophyll *b* and peridinin indicate that green algae and dinoflagellate abundances were highest in a band extending from just north of St. Lawrence Island, through the Bering Strait, and into the Chukchi Sea. These distributional patterns are consistent with those described by Kisselev (1937), who found that these algal groups were abundant in the northern Bering Sea. 19'-Hexanoyloxyfucoxanthin and 19'-butanoyloxyfucoxanthin concentrations were highest in waters overlying the Chirikov basin (located just north of St. Lawrence Island) and the central and southern regions of the Bering Sea, reflecting the presence of prymnesiophytes and chrysophytes, respectively; concentrations of these pigments were near the limit of HPLC detection at stations occupied in the Chukchi Sea.

In summary, pigment concentrations in the Bering and Chukchi Seas were complex and variable and suggest that phytoplankton are not uniformly distributed with respect to both biomass and composition. A comparison of these distribution patterns with concurrently measured physico-chemical parameters (i.e., nutrients and currents) will provide insight into the factors affecting phytoplankton abundance in the Bering and Chukchi Seas.

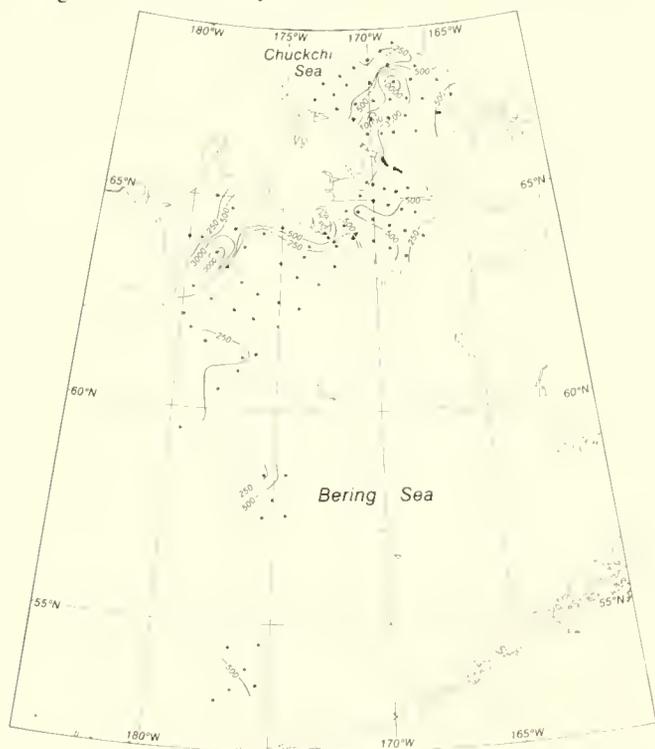


Fig. 1. Contours of chlorophyll *a* (ng·l⁻¹) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

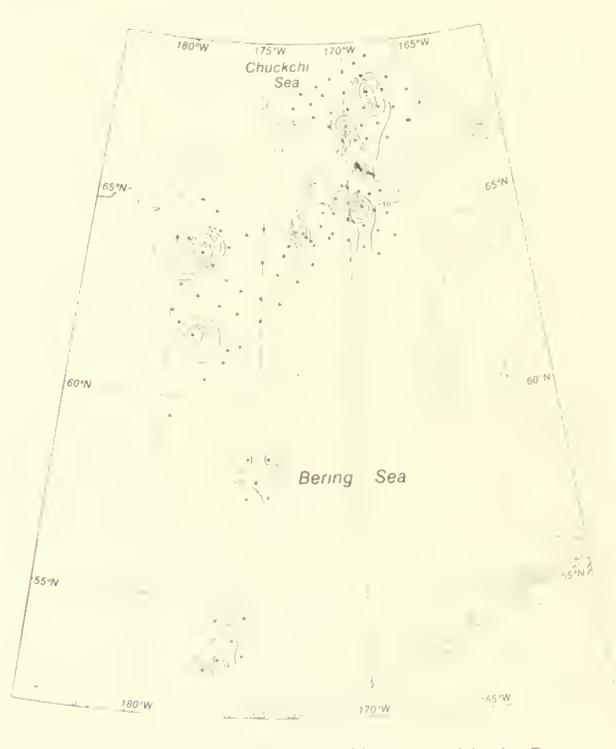


Fig. 2. Contours of chlorophyllide *a* (ng·l⁻¹) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

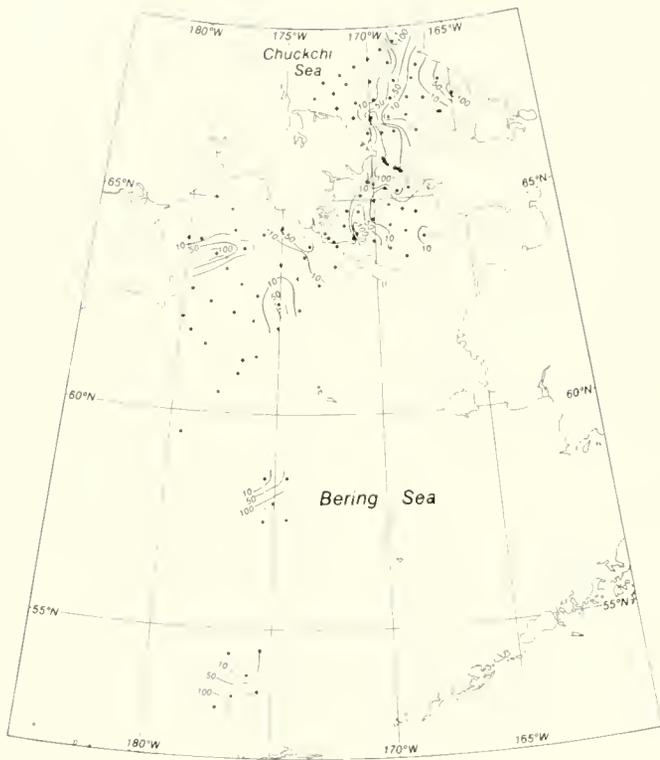


Fig. 3. Contours of chlorophyll *b* ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

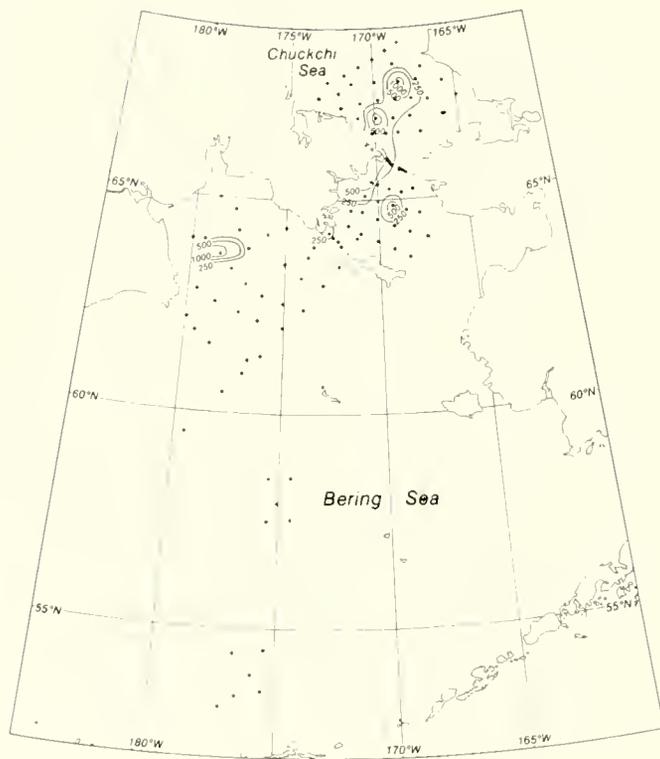


Fig. 4. Contours of chlorophyll *c* ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

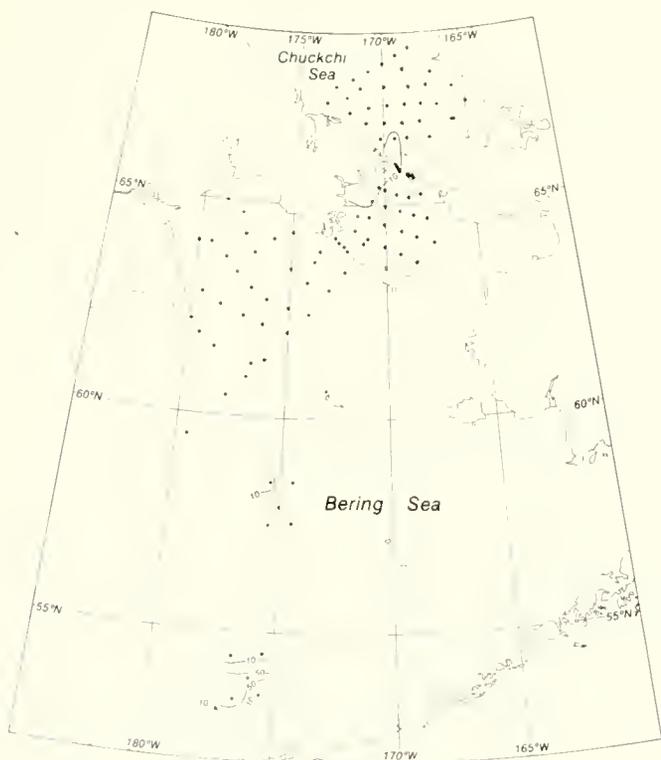


Fig. 5. Contours of chlorophyll *c*₁ ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

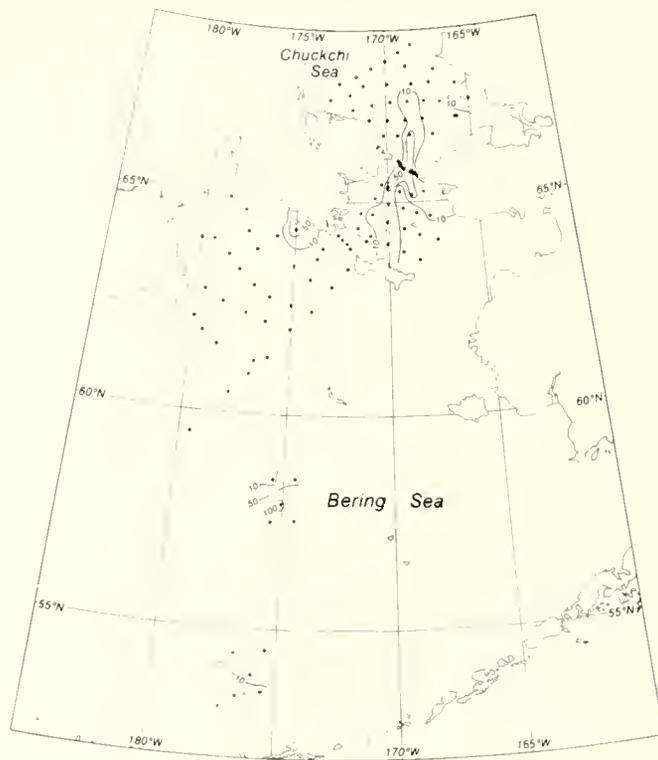


Fig. 6. Contours of peridinin ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

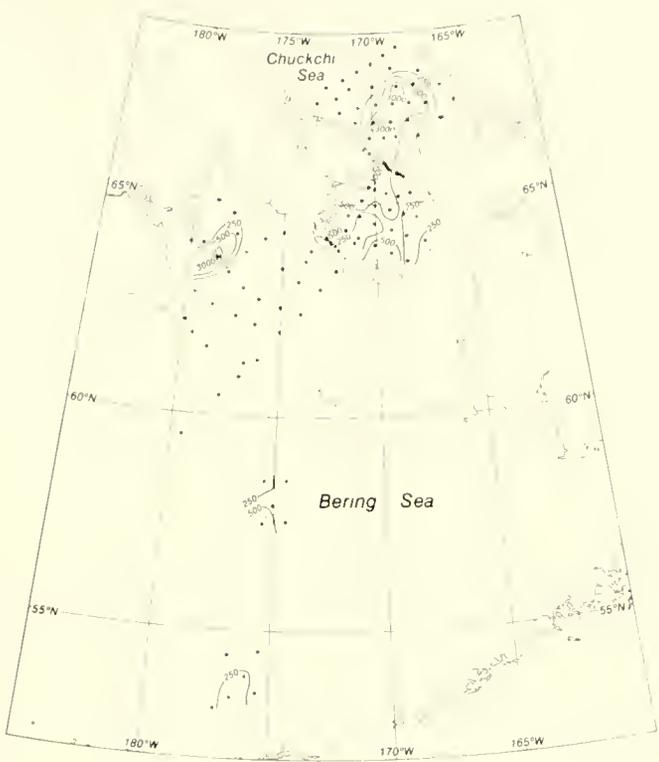


Fig. 7. Contours of fucoxanthin ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

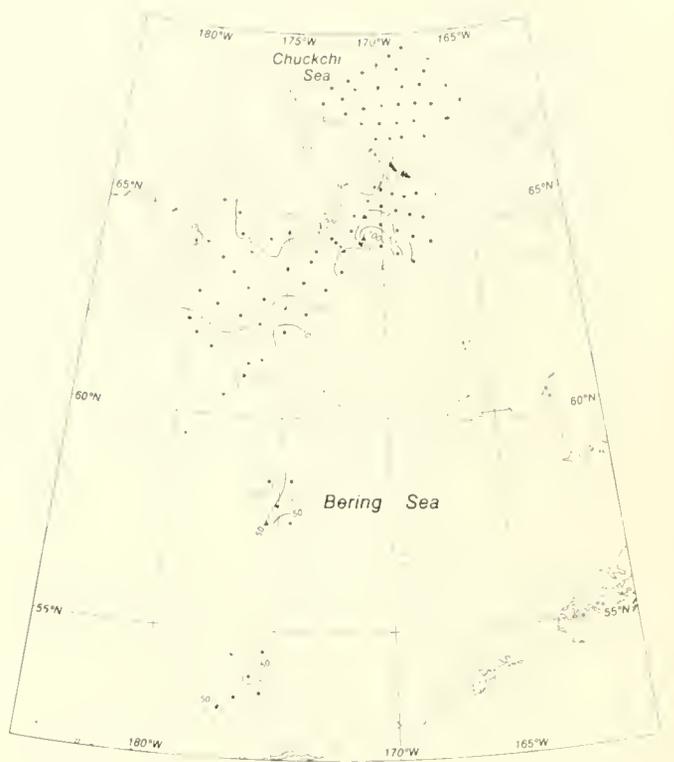


Fig. 8. Contours of 19'-butanoloxyfucoxanthin ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

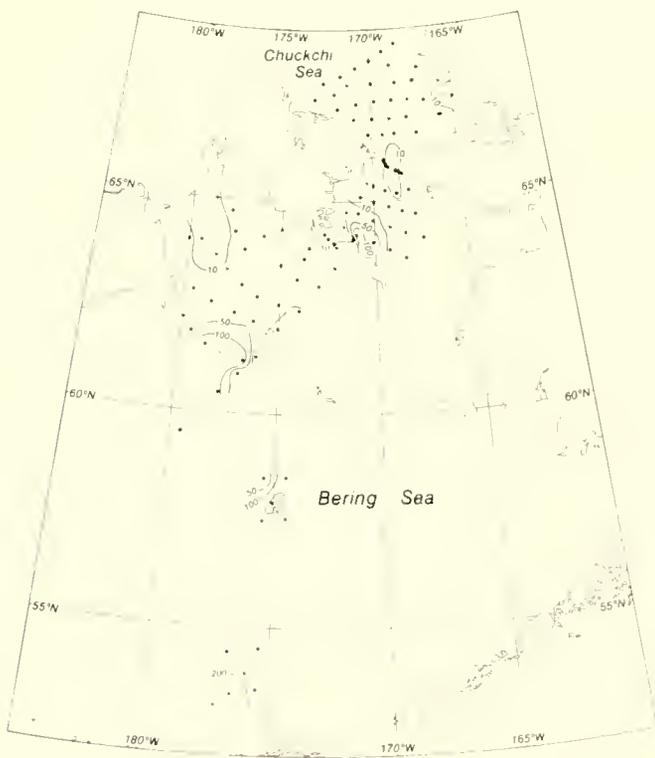


Fig. 9. Contours of 19'-hexanoyloxyfucoxanthin ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

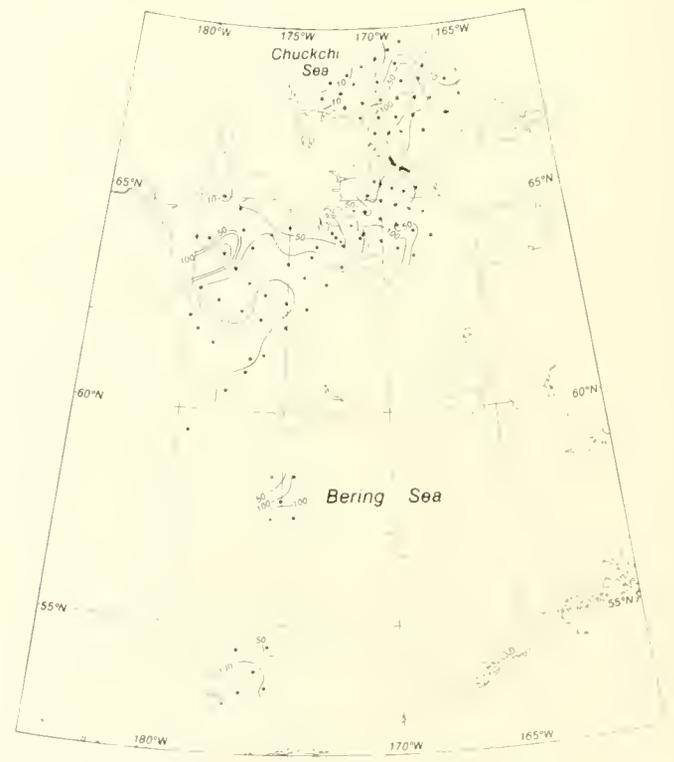


Fig. 10. Contours of diadinoxanthin ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

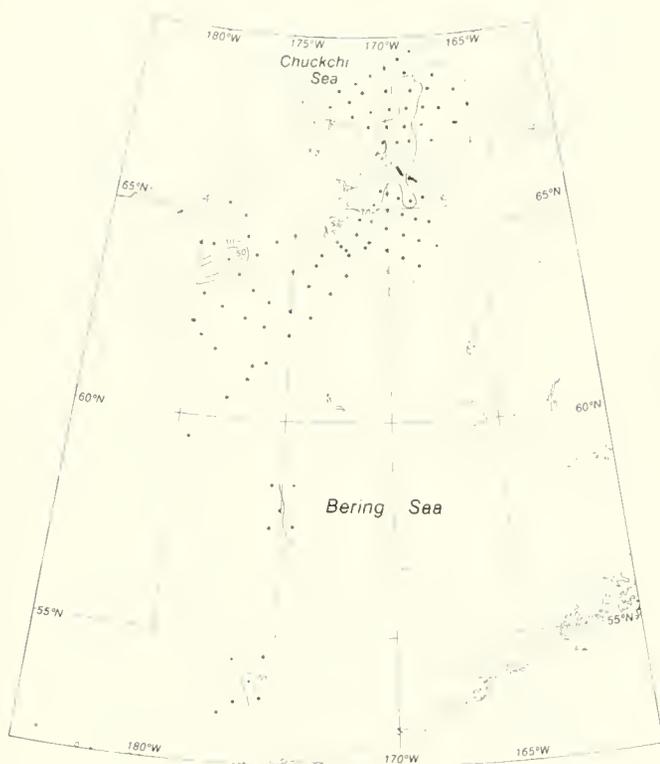


Fig. 11. Contours of diatoxanthin ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

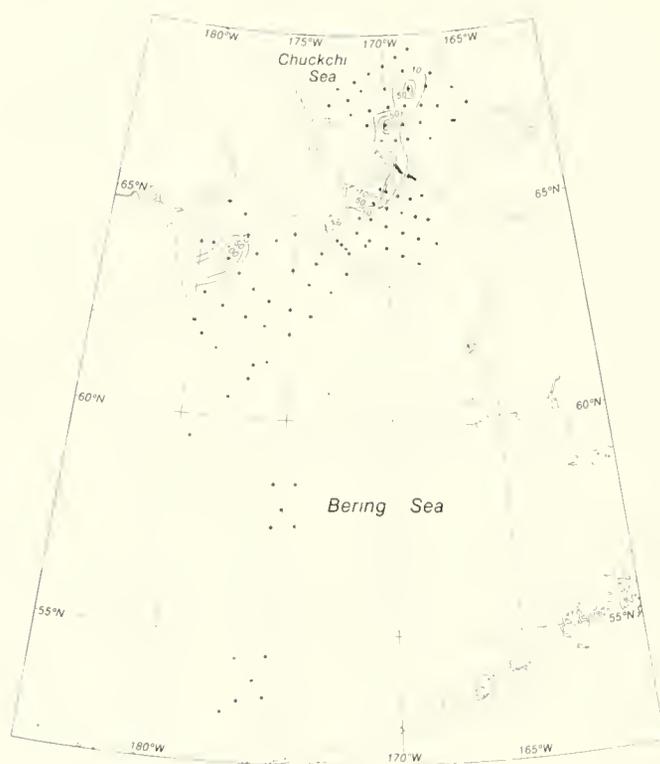


Fig. 12. Contours of β,β -carotene ($\text{ng}\cdot\text{l}^{-1}$) measured in the Bering and Chukchi Seas during July–August 1988, aboard the R/V *Akademik Korolev*.

TABLE 1

Near-surface pigment concentrations (ng l^{-1}) measured in the Bering and Chukchi Seas during July–August 1988.

Station	Lat(N)	Lon(W)	Chl _c ₃	Chl _d	Chl _c	Per	Bfuc	Fuco	Hfuc	Diad	Diat	Chl _b	Chl _a	Car
AKA-1	57.54	174.48	35	42	125	95	35	272	140	60	13	120	717	0
AKA-2	57.50	175.52	26	116	183	66	51	733	181	63	0	112	869	0
AKA-3	57.93	175.08	45	44	186	116	60	476	218	115	9	153	1061	0
AKA-4	58.52	174.49	46	54	171	46	65	466	181	107	29	62	878	0
AKA-5	58.50	175.50	0	0	0	0	0	44	22	14	0	0	194	0
AKA-6	59.50	179.50	0	0	38	20	37	235	124	33	0	74	658	0
AKA-7	60.47	177.83	0	0	46	0	14	57	105	6	0	0	228	0
AKA-8	60.94	176.93	0	0	0	0	8	17	29	0	0	0	175	0
AKA-9	61.34	176.10	0	0	0	0	35	40	9	7	0	0	222	0
AKA-10	61.25	176.76	0	0	42	0	42	70	151	43	9	0	351	0
AKA-11	61.58	178.65	2	76	71	0	21	51	130	42	0	0	280	0
AKA-12	61.88	179.42	0	0	0	0	16	27	41	14	0	0	208	0
AKA-13	62.18	179.85	0	0	0	0	14	47	44	14	0	0	203	0
AKA-14	62.84	179.51	0	0	13	0	1	24	22	10	0	1	292	0
AKA-15	62.58	178.51	0	0	0	0	0	6	10	0	0	0	66	0
AKA-16	62.34	177.33	0	0	0	0	0	24	16	0	0	0	172	0
AKA-17	62.17	176.34	0	0	0	0	12	39	44	23	0	0	190	0
AKA-18	62.01	175.04	0	0	0	0	7	21	7	1	0	14	150	0
AKA-19	62.44	174.01	0	0	0	0	17	17	9	9	0	0	142	0
AKA-20	62.58	175.06	0	0	0	0	24	24	24	13	0	68	195	0
AKA-21	62.75	176.17	0	0	0	0	0	44	10	18	0	0	148	0
AKA-22	63.00	177.03	0	0	0	0	0	0	10	0	0	0	81	0
AKA-23	63.35	177.84	0	0	0	0	3	22	12	12	0	0	162	0

TABLE 1 - continued

Station	Lat(N)	Lon(W)	Chlc ₃	Chida	Chlc	Per	Bfuc	Fuco	Hfuco	Diad	Diat	Chlb	Chla	Car
AKA-24	63.68	178.47	0	186	4,290	0	0	11,666	0	1,074	155	203	26,618	318
AKA-25	64.00	179.33	0	0	0	0	0	55	0	19	0	0	215	0
AKA-26	65.00	178.67	0	0	0	0	0	35	0	4	0	0	89	0
AKA-27	64.74	177.78	0	0	43	0	12	225	42	50	0	0	760	0
AKA-28	64.25	177.50	0	0	61	0	11	278	13	45	0	0	692	0
AKA-29	63.83	176.97	0	0	0	0	2	7	13	4	0	16	99	0
AKA-30	64.17	175.97	0	0	0	0	21	30	44	10	0	0	122	0
AKA-31	64.34	175.01	0	0	15	86	12	155	33	90	0	53	645	0
AKA-32	64.00	180.00	0	0	0	0	26	14	38	13	0	8	143	0
AKA-33	63.49	175.03	0	0	0	0	0	0	10	2	0	0	61	0
AKA-34	63.18	174.14	0	0	0	0	0	0	18	0	0	0	84	0
AKA-35	63.02	173.00	0	0	0	0	0	0	44	5	0	0	119	0
AKA-36	63.45	172.18	0	0	0	0	15	21	13	11	3	34	98	0
AKA-37	63.66	173.82	0	0	0	0	0	6	12	0	0	0	75	0
AKA-38	63.90	173.53	0	0	0	0	0	28	21	17	0	52	392	0
AKA-39	64.23	172.70	0	51	381	0	0	997	0	109	0	0	3,227	0
AKA-40	64.13	172.50	0	37	151	0	0	371	0	69	16	0	697	0
AKA-41	64.03	172.21	0	6	65	0	0	213	0	52	0	0	285	0
AKA-42	63.92	172.07	0	0	0	0	12	38	17	17	0	43	221	0
AKA-43	64.10	171.20	0	0	0	0	9	14	9	14	0	0	164	0
AKA-44	67.37	173.33	0	0	15	0	0	61	0	11	0	0	102	0
AKA-45	67.74	172.80	0	0	0	0	0	39	0	9	0	0	163	0
AKA-46	67.92	171.75	0	0	0	0	0	18	0	8	0	0	104	0
AKA-47	68.10	170.88	0	0	0	0	0	68	0	28	0	0	133	0
AKA-48	68.27	170.00	0	0	21	0	0	158	0	33	0	0	368	0
AKA-49	68.47	169.13	0	0	3	0	0	49	0	5	0	0	250	0
AKA-50	68.66	168.33	0	0	0	0	0	57	9	3	0	113	332	0
AKA-51	68.16	168.74	0	0	0	0	0	75	0	15	0	0	137	0
AKA-52	68.08	167.00	0	0	31	0	0	71	0	6	0	0	266	0
AKA-53	67.70	165.72	0	0	13	0	0	83	0	4	0	67	539	0
AKA-54	67.76	167.32	0	0	69	0	0	419	0	44	0	0	952	0
AKA-55	67.74	168.44	0	193	1,894	0	0	6,723	0	468	45	75	13,198	170
AKA-56	67.74	169.93	0	0	0	0	0	4	0	0	0	0	12	0
AKA-57	67.71	171.35	0	0	0	0	0	78	0	29	0	0	154	0
AKA-58	67.50	172.14	0	0	0	0	0	77	0	26	0	0	165	0
AKA-59	67.15	171.99	0	0	0	0	0	47	0	6	0	0	154	0
AKA-60	67.26	170.83	0	0	13	0	0	89	0	20	0	0	265	0
AKA-61	67.33	169.75	0	17	123	0	0	426	0	44	0	0	938	0
AKA-62	67.34	168.72	0	41	449	32	0	1,361	0	108	13	62	3,265	36
AKA-63	67.34	167.73	0	93	355	0	0	1,517	0	101	0	0	3,135	0
AKA-64	67.30	166.71	0	4	119	0	0	540	0	41	0	0	1,199	0
AKA-65	67.34	164.98	0	0	39	49	0	91	37	17	0	137	485	0
AKA-66	66.93	165.92	0	0	40	0	0	290	0	17	0	0	512	0
AKA-67	66.93	165.83	0	0	0	0	0	89	0	18	0	0	324	0
AKA-68	66.92	167.83	0	19	102	0	0	475	0	45	0	0	834	0
AKA-69	66.91	168.91	0	8	284	0	0	1,283	0	118	23	0	3,147	5
AKA-70	66.91	169.92	0	194	1,329	0	0	4,846	0	257	20	133	10,426	180
AKA-71	66.91	171.01	0	0	9	0	0	118	0	21	0	0	275	0
AKA-72	66.55	170.17	0	11	401	0	0	1,801	0	179	7	0	4,098	21
AKA-73	66.55	169.32	16	84	273	0	0	1,090	6	98	31	119	2,488	12
AKA-74	66.56	168.60	0	38	131	52	0	677	0	67	22	162	1,559	0
AKA-75	66.55	167.29	0	0	20	0	0	242	0	24	0	0	742	0
AKA-76	65.98	169.60	0	184	1,607	0	16	4,521	0	344	28	77	10,713	119
AKA-77	65.93	169.35	0	0	91	0	10	338	8	58	14	67	981	0
AKA-78	65.85	169.22	0	140	422	0	0	1,110	0	80	0	0	2,765	0
AKA-79	65.70	168.68	0	0	55	0	0	399	12	40	0	0	742	0
AKA-80	65.67	168.50	0	0	6	0	0	257	0	7	0	0	485	0
AKA-81	65.63	168.35	0	0	14	0	7	271	0	16	0	0	539	0
AKA-83	65.67	168.50	73	182	196	29	0	341	11	29	0	370	1,039	0
AKA-84	65.71	168.69	0	0	63	95	19	354	48	42	0	190	1,215	0

TABLE 1 - continued

Station	Lat(N)	Lon(W)	Chlc ₃	Chida	Chlc	Per	Bfuc	Fuco	Hfuc	Diad	Diat	Chlb	Chla	Car
AKA-85	65.83	169.17	16	104	288	27	19	887	25	98	23	181	2,357	27
AKA-86	65.94	169.38	27	31	326	0	0	1,577	0	131	21	0	3,835	24
AKA-87	65.41	170.36	41	163	955	0	21	3,231	0	243	31	0	7,813	155
AKA-88	65.36	169.99	0	18	194	58	0	907	0	79	0	65	1,889	14
AKA-89	65.24	169.36	0	47	171	0	0	586	0	53	0	0	825	0
AKA-90	65.18	168.66	0	24	144	54	0	479	15	83	12	53	962	0
AKA-91	65.24	167.98	0	30	64	38	0	360	5	44	0	34	691	0
AKA-92	64.67	167.69	0	0	2	16	0	124	0	27	0	0	329	0
AKA-93	64.75	168.43	0	0	0	0	0	125	0	29	0	0	185	0
AKA-94	64.86	169.19	0	370	794	0	0	906	0	93	0	0	1,729	0
AKA-95	64.97	169.98	0	15	107	19	0	470	0	70	0	0	1,091	0
AKA-96	65.09	170.71	22	32	369	0	0	1,301	0	136	23	43	2,851	65
AKA-97	64.75	171.50	0	0	70	0	0	445	21	68	8	0	944	0
AKA-98	64.72	170.87	0	0	13	25	17	175	15	45	0	62	488	0
AKA-99	64.54	170.04	0	0	12	32	39	158	16	54	0	0	426	0
AKA-100	64.38	169.16	0	22	93	0	0	320	0	42	0	0	421	0
AKA-101	64.23	168.32	0	0	40	0	0	213	0	55	0	0	311	0
AKA-102	64.09	167.39	0	0	21	0	0	273	0	42	0	15	226	0
AKA-103	63.66	168.36	0	0	0	0	0	144	0	39	0	0	251	0
AKA-104	63.85	169.21	0	21	211	0	65	836	0	165	0	0	773	9
AKA-105	64.03	170.09	2	0	112	38	239	583	83	197	7	77	1,315	3
AKA-106	64.22	170.98	2	0	67	0	114	246	122	112	6	127	874	0
AKA-107	64.40	171.62	0	0	36	0	0	295	0	14	0	0	476	0
AKA-108	54.42	176.74	0	0	26	0	66	126	104	59	0	0	483	0
AKA-109	54.51	175.47	0	0	15	0	63	118	104	46	0	10	412	0
AKA-110	53.93	176.01	64	75	114	0	40	267	199	147	14	0	369	0
AKA-111	53.53	175.54	0	0	54	16	61	120	133	85	14	47	396	0
AKA-112	53.43	176.59	99	129	234	30	72	623	308	124	0	75	801	0
AKA-113	53.17	177.22	0	0	103	30	47	108	214	45	0	111	533	0

TABLE 2

Average and range of photosynthetic pigment concentrations (ng l⁻¹)
measured in near-surface waters of the Bering and Chukchi Seas
during July–August 1988 (n = 112).

Parameter	Chlc ₃	Chida	Chlc	Per	BFuco	Fuco	HFuco	Diad	Diat	Chlb	Chla	Car
Average	5	26	167	10	13	567	30	64	5	31	1,301	10
Minimum	ND*	ND	ND	ND	ND	ND	ND	ND	ND	ND	12	ND
Maximum	99	370	4,290	116	239	11,666	308	1,074	155	370	26,618	318

*ND = not detectable

TABLE 3
List of the important phytoplankton pigments used
as diagnostic source markers for interpretation
of HPLC-derived pigment data.

Pigment	Significance
<u>Golden-brown Algae</u>	
Fucoxanthin Chlorophyll c_1+c_2	Diatoms (and some Chrysophytes and Prymnesiophytes
19'-Hexanoyloxyfucoxanthin Fucuxanthin Chlorophyll c_2+c_3	Prymnesiophytes
19'-Butanoyloxyfucoxanthin Fucoxanthin Chlorophyll c_2+c_3	Chrysophytes
Peridinin Chlorophyll c_2	Dinoflagellates
<u>Chlorophyll <i>b</i>-containing Algae</u>	
Lutein Prasincoxanthin Zeaxanthin Divinyl chlorophyll <i>a</i>	Chlorophytes* Prasinophytes* Prochlorophytes
<u>Phycobilin-containing Algae</u>	
Zeaxanthin Alloxanthin	Coccioid Cyanobacteria Cryptophytes

*Also contain minor amounts of zeaxanthin.

5.1.4 Complex Hydrooptic Researches

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Introduction

In the ocean ecological researches of today, the optical methods find practical application alongside of traditional biochemical methods. These new methods have undoubtedly some advantages over the conventional ones. It is possible to make measurements without disturbing the environment; there is high spatial and time resolution and wide diversification of the information received. The interaction of biological and hydrophysical factors gives rise to the formation of conservative optical structures, dependent primarily on phytoplankton and

their metabolites. As waters are carried by currents from regions of formation, the biocenoses living therein undergo gradual transformation, which is reflected in the optical properties. Thus, if we identify those optical features that are typical of water masses of different origin (or characteristic of water mass in one or another stage of transformation), we shall be able to identify ocean waters in terms of productivity and other biological properties. The properties of light scattering are dependent upon phytoplankton, which are extremely susceptible to pollution. By determining the deviation of water optical properties from natural level (in the regions that

potentially can be affected anthropogenically), we can draw conclusions about the extent of pollution and to monitor its dynamics.

The paper presents the results of complex hydrooptical studies in the waters of the Bering and Chukchi Seas. The main objective pursued was to study spatial and time variability of hydrooptical characteristics and their correlation with biological and microphysical parameters of particulates.

Hydrooptical Quantities — Definitions

Distribution of light in the ocean water is a function of its absorption and scattering. These phenomena can (neglecting polarization) be fully described by three primary hydrooptical quantities: 1. indices of absorption κ ; 2. scattering σ ; and 3. the angular dependence of scattering, $\chi(\gamma)$ indicatrix.

If a collimated monochromatic beam of light is incident along an axis (1) traveling through a small volume $dV=dSdl$ in the medium, this beam passes in solid angle, dw and creates illumination $E_n(dS)$ on an area normal to the beam. The amount of flux absorbed by the volume will be proportional to

$$dF_a = \kappa E_n dS dl. \quad (1)$$

Proportionally factor κ is known as the coefficient of absorption, its dimension is $M^{-1} \cdot 0$. The scattering index σ :

$$dF_s = \sigma E_n dS dl, \quad (2)$$

so that the full value of flux, scattered and absorbed on its path dl , will equal equations (1) and (2):

$$dF = dF_a + dF_s = (\kappa + \sigma) E_n dS dl \equiv \epsilon E_n dS dl. \quad (3)$$

The sum of absorption κ and scattering σ indices is known as attenuation index ϵ , and the relationship $\Lambda = \delta/\epsilon$ is the probability of photon survival. The dimension of attenuation index is $\epsilon [M^{-1}]$. $T = e^{-\epsilon}$ defines the transmissivity of a water layer 1-m thick, also referred to as transparency of water.

Expression (3) is a differential form of Bouguer's Law, according to which any flux that has travelled in a scattering and absorbing medium, is attenuated (hereinafter we shall consider the values of relevant indices determined to the ln base):

$$F(l) = F(0) \exp(-\epsilon l). \quad (4)$$

Scattering of light varies with direction. A flux of light, scattered in a single solid angle (or intensity of light dI) in a direction, making up angle γ with axis \vec{l} , will be proportional to the value of volume dV of flux:

$$dI(\gamma) = \alpha(\gamma) E_n dV. \quad (5)$$

Proportionality factor $\alpha(\gamma)$ is termed as the index of directed scattering and has the direction $[M^{-1} \text{ster}^{-1}]$. Scattered (radiation diffused) is known as the indicatrix of scattering:

$$\chi(\gamma) = \frac{\alpha(\gamma)}{\sigma}. \quad (6)$$

Since $\int_{4\pi} \chi(\gamma) dw = 1$, it can be treated as three-dimensional density of probability of photon scattering at some angle (γ) with respect to the direction of light propagation.

Often used in hydrooptics are the so-called integral quantities—indices of scattering in front (δ) and back (β) hemispheres:

$$\delta = 2\pi \int_0^{\pi/2} \alpha(\gamma) \sin \gamma d\gamma, \quad (7)$$

$$\beta = 2\pi \int_{\pi/2}^{\pi} \alpha(\gamma) \sin \gamma d\gamma, \quad (8)$$

and their ratio $K = \delta/\beta$, called the asymmetry factor. The extent of isotropy of scattering is defined by the mean cosine of scattering:

$$\overline{\cos \gamma} = 2\pi \int_0^{\pi} \chi(\gamma) \sin \gamma \cos \gamma d\gamma. \quad (9)$$

Parameters K and $\overline{\cos \gamma}$ characterize indicatrix "stretching," which increases with the increase of particle sizes. The anisotropy of scattering will also be characterized by

$$R(\gamma_0) = 2\pi \int_0^{\gamma_0} \chi(\gamma) \sin(\gamma) d\gamma, \quad (10)$$

determining a part of radiation scattered into solid angle with angular opening from 0 to γ_0 . Let us take 2° for γ_0 .

Hydrooptic Instruments

Critical for making complex hydrooptical measurements *in situ* is their synchronism. The apparatus complex, used by us, made it possible to realize this principle with the help of rather simple technical means. The complex included an immersible transmittance meter with a bathometer and a board meter of angular light scattering indicatrix-meter. First, a vertical profile attenuation index ϵ of water was measured, and second, the angular characteristics of light scattering ($\alpha(\gamma)$) of samples were taken from different horizons.

The photometer/transmittance meter used was a "Kvant-3." The optical-mechanical and electronic units of the instrument are accommodated inside a hermetic case, which, via traction and electric connectors, is connected with a double cable-line, type КГ 7-90-180. The meter measures and compares the intensity of light flux before and after its passing through a layer of certain thicknesses l (defined by the instrument measurement base). This principle of measurement is realized as follows: formed by corresponding elements of the optical-mechanical unit, a probing beam of light is emitted through a

porthole into the seawater; then, after having been reflected from an outboard spherical mirror, it returns. Such a returning beam, attenuated by the seawater, is directed to a photomultiplier where it is compared with a reference beam, passing inside the instrument. Originally, this reference beam has the intensity equal to that of the probing beam. The required spectral range is discriminated with the aid of a suitable light filter, which is installed in front of the photomultiplier. A different signal is transmitted over the cable-line to the board block and registered there as a function of the depth probed. The instrument measurement base is 0.5 m; maximum depth of immersion, 250 m (Kumeisha & Vinokurov, 1984).

The assessment of measurement errors is a very difficult problem because of the lack of "clear water" reference. Usually verification is carried out with the aid of samples that are standardized neutral filters and thin glasses and whose coefficients of transmissivity (or reflection) are measured on a standard spectrophotometric equipment or can readily be calculated. Modeling has shown that the absolute error of measurements made to determine the attenuation index of clear ($\epsilon \leq 0.15 \text{ m}^{-1}$) waters is not in excess of 0.01%; in less clear waters the relative error is nearly 5%.

A bathometer is an attachment to the "Kvant-3" transmittance meter which allows an assessment, on the basis of visual analysis, of a profile of the attenuation index. The bathometer valves are tested for reliable functioning by measuring the transmittance of an assay selected, making use of a special cell in the "Kvant-3" instrument (intended for onboard analysis), and then comparing transmittance values with those measured *in situ* on the horizons of probing. All tests showed satisfactory results.

A board indicatrix meter is constructed as a cylindrical cell with an attached illuminator and scanning device with a photodetector. The illuminator emits a collimated beam of light, which, via portholes in the cell, transilluminates water samples (cell volume is 3 ml). The scanning device receives radiation scattered from the zone at angles from 0.5° to 165° relative to the direction of its propagation. The illuminator and receiver embody aperture and field diaphragms permitting alteration of angular divergence of light fluxes and their cross-sections. The volume, subjected to photometry analysis, is 5–10 ml. Hence, one can safely neglect the contribution of this factor to the scattering of zooplankton.

Received light is directed to the photomultiplier through a glass light filter; an electric signal, proportional to the light flux, is then amplified, filtered, and applied to a digital recorder.

In order to obtain absolute values of scattering indices, the intensity of light that has passed through the instrument is measured (Gabrilovich, 1976). The instrument was verified with the aid of monodisperse polystyrene latex solution. Comparing the results of measurements and calculations, the relative error of angular measurements of light scattering has been found to be 10%.

Results

All primary hydrooptic characteristics were measured at wavelength $\lambda = 530 \text{ nm}$. The obtained vertical profiles of attenuation index were tabulated through 1 m in shallow parts of the seas and through 5 m at depth $H = 100\text{--}250 \text{ m}$. Since, in biology, they often operate with average characteristics (related to water layer or water column), we also calculated average index of attenuation in layer O-H:

$$\langle \epsilon \rangle_H = \frac{\int_0^H \epsilon(H') dH'}{H} .$$

Absolute values $\sigma(\gamma)$ within $0.5\text{--}165^\circ$, full index of scattering and integral characteristics of indices (κ , $\overline{\cos \gamma}$ and $R [\gamma_0 = 2^\circ]$) were calculated from angular relationships of light scattering. Volume concentrations V_c and V_f (in cm^3/m^3) of coarse (particles having radii in excess of $1 \mu\text{m}$) biological and fine mineral (less than $1 \mu\text{m}$) fractions of suspended matter were assessed following Kopelevich (1981). Such calculations are possible using a physical model of scattering. Ocean water particulates is divided into two independent fractions in terms of size and index of refraction. Angles of $\gamma \leq 2^\circ$ for coarse particles, and $\gamma \geq 45^\circ$ for fine, can be calculated; however, the numbers are weakly correlated.

This is, of course, an idealized model of ocean water particulates; yet, on the whole, it allows interpretation of material that has been collected earlier. Its advantage lies in the fact that it permits assessing the content of fine fraction particulates (including submicron particles), which is beyond the capacities of conventional geological methods. It should be noted, however, that the model has not been tried by the author (Kopelevich, 1981) to describe indicatrices of highly productive waters where variation of content of coarse and fine particulates differs from that in open ocean. Fine suspended particles may predominantly be of organic matter. Applicability of generally accepted concepts becomes doubtful when suspended minerals dominate in coarse fraction. This is why the assessments of particulates content, presented in this report, should be regarded only as preliminary, subject to verification through direct biological observations and through appropriate model-based calculations.

Volume content of fine and coarse fractions (V_f and V_c) was inferred from the following relations:

$$V_f = 10.2\sigma_{(45^\circ)} - 1.4 \times 10^{-4} \sigma_{(1^\circ)} - 0.002, \quad (11)$$

$$V_c = 2.2 \times 10^{-2} \sigma_{(1^\circ)} - 1.2 \sigma_{(45^\circ)}, \quad (12)$$

where $\sigma_{(1^\circ)}$ and $\sigma_{(45^\circ)}$ are indices of directed scattering at 1° and 45° angles.

The optical type of water, assessed from measured values of $\sigma_{(45^\circ)}$ and $\sigma_{(1^\circ)}$, will also be helpful when added to the above-mentioned parameters. Since according to (11) and (12) such

values show the content of fine and coarse fractions in particulates, the typification will differentiate waters by their contents of possible volumes of coarse and fine particles. High concentration of a certain fraction will be denoted by the letter "H," medium by "M," low by "L." Combinations of these will be denoted by two-letter codes, of which the first letter specifies volumetric content of fine particles and the second letter that of coarse particles. The numerical equivalent of the letters used has been given in Table 1.

This typification is very helpful. Comparisons of waters in the areas explored by us with typical ocean waters in different stages of development can be made quickly. For instance, from data of the same paper, type MM is typical of open ocean waters; types LM (particularly, LL and ML) are typical of deep-water horizons and types MH, HM, and HH only of higher productivity regions.

TABLE 1

Fraction	Volumetric content, cm ³ /m ³		
	L	M	H
Coarse	<0.1	0.1-0.45	>0.45
Fine	<0.015	0.015-0.055	>0.055

Investigation of Spatial-Temporal Variability of Transmittance Field

It would probably be most reasonable to begin analyzing the hydrooptic characteristics of spatial-temporal variability by considering zonal distribution transmittance in northern waters. The frontispiece shows that route of expedition with numbers of stations. Numeration relates to the period of joint Soviet-American research.

Water transmittance T is dependent upon the attenuation index (ϵ) according to the relation $T = e^{-\epsilon}$. In the literature, data is presented for the attenuation index field. In order to make it possible to compare our results with the data of other researchers, we shall keep to this tradition (i.e., we shall imply, when speaking of "transmittance" and "transmittance field," corresponding values of distribution ϵ).

Figure 1 shows zonal distribution of attenuation index (ϵ) average for a certain layer of water. When interpreting the results, it is useful to bear in mind that, according to Kopelevich (1981), the suspended coarse fraction contributes 40-45% to light attenuation in the green portion of spectrum in oligotrophic and mesotrophic waters and nearly 80% in littoral waters. It seems quite justifiable to apply the latter assessment to productive littoral waters of high latitudes. In this case, the vertical structure $\epsilon_{(H)}$ will depend mainly on the distribution of suspended coarse fraction, while attenuation index (average for the layer) will be dependent on average content of coarse fraction.

Maximum amounts of suspended matter are contained in the Chukchi Sea waters (with absolute maximum found at the area of Stations 55 and 60) and a minimum in the Gulf of

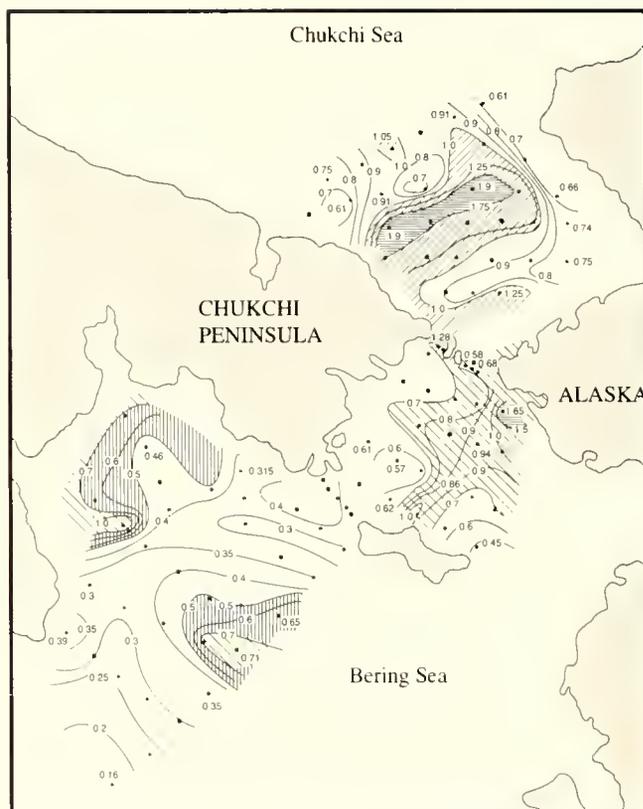


Fig. 1. Zonal distribution of attenuation index (ϵ) average for a certain layer of water.

Anadyr waters (with minimum found in its southeastern periphery) (Fig. 1). When assessed in this way, the Bering Sea waters will be in somewhat medium position.

This zonal distribution reflects the main qualitative transformation that the Pacific waters undergo as they are transported to the Chukchi Sea, with an increase of suspended matter with increasing latitude.

Another parameter that is closely associated with average attenuation, with wide application in oceanology, is transmittancy, or maximum depth at which a reference white disk (Secchi disk) is still seen. Such a depth is determined as follows: the disk is gradually immersed deeper and deeper into water, and the depth is noted at which the disk vanishes from sight and then appears in sight again when being raised. The average value H_s found from the above-mentioned values is termed as Secchi transmittance of water or transmittancy.

These measurements are important because transmittancy (associated with all primary hydrooptic characteristics and illumination conditions), in practice, may accurately be expressed in the form of a single uniparametric relationship derived from average value of attenuation $\langle \epsilon \rangle_{H_s}$ index in layer O-H:

$$H_s = \frac{A}{\langle \epsilon \rangle_{H_s}} \quad (13)$$

Proportionality factor A depends on the rest of primary optic properties of water (and, hence, on ocean region) and on illumination conditions. This allows with known *a priori*

values of A to assess $\langle \epsilon \rangle_{H_0}$ in those regions where no hydrooptic apparatus-assisted measurements have been carried out but a lot of material on white disk observation exists.

The value of A for waters of the World Ocean varies from 3 to 8 (Ivanov, 1975). However, the calculations made by the author (Levin, 1983) show that under certain "standard" conditions of observation, the range of A depends on the actual variability of optical properties so the range should be narrower. Thus, if the Sun's altitude is more than 60° , and if the disk is observed from the solar board side, the coefficient A for waters having transmittancy within 5–20 m and oblong indicatrix of scattering ($1/\kappa \leq 0.02$), will change almost linearly with the change of probability of photon survival Λ from 5.1 (with $\Lambda = 0.06$) up to 6.6 (with $\Lambda = 0.9$). Calculations show that the most scattered ocean indicatrices known lower the A value by 10%. When the Sun's altitude is 30° and Λ is within the same range, the A value must vary from 4 to 5.5 (if observed from the solar side of board) and from 5 to 8.5, when observed from the shadow side. Slight heaving of the sun will lower the A value to 3–5.

From our apparatus-assisted and visual observations, we can assess the value of the proportionality factor for the waters of northern latitudes.

Figure 2 shows an experimentally determined function of H_0 in the waters of the Chukchi Sea (triangles), northern area of the Bering Sea (clear circles), and Gulf of Anadyr (solid circles).

It is obvious that most turbid waters are in the Chukchi Sea ($H_0 = 4\text{--}10$ m), moderately cloudy waters are in the northern area of the Bering Sea ($H_0 = 6\text{--}16$ m), and relatively clear waters are in the Gulf of Anadyr ($H_0 = 10\text{--}24$ m).

Figure 2 illustrates two approximating curves plotted according to (13) for two values of factor A (4.3 and 4.8). It is obvious that clear waters of the Bering Sea are more accurately described by (13) when $A = 4.3$ and turbid waters of the Chukchi Sea at $A = 4.8$. Discrimination, as manifested by the above-given assessments from the paper (Levin, 1983), may possibly be an evidence of different correlation between absorbing and scattering abilities of suspended matter in different areas. However, this fact can more reliably be borne out by numerous apparatus-assisted and visual observations.

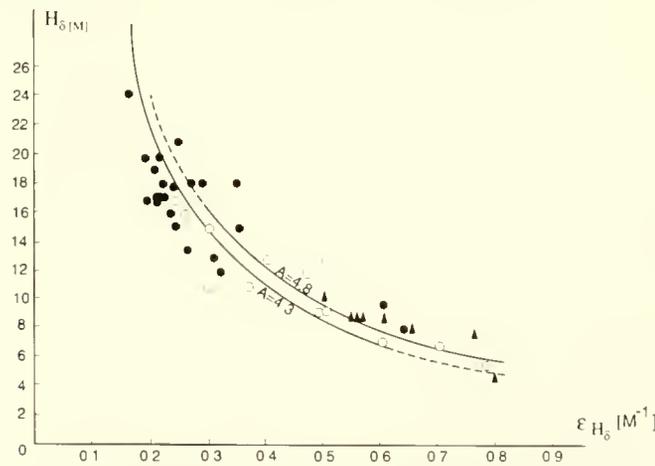


Fig. 2. Experimentally found function of H_0 in the waters of the Chukchi Sea (\blacktriangle), northern area of the Bering Sea (\circ) and Gulf of Anadyr (\bullet).

At this stage, the average value of A for northern areas is equal to 4.5.

As mentioned earlier, the transmittance of water in the blue-green field of spectrum will depend mostly on the amount of particles present in the water. In productive areas of the ocean, the bulk mass of suspended matter is made up of phytoplankton. Optically, the type of algae can be defined by size, shape, and index of refraction. These characteristics directly affect the angular structure scattered radiation. The bigger size of biological particles and the higher their content in the total composition of suspended matter, the more forward-extended is the water scattering indicatrix and the higher the values of its integral characteristics — asymmetry factor K , mean cosine of scattering angle $\cos \gamma$, and portion of light R , scattered in the minor "forward" angle.

As waters are carried over by currents from the regions where they formed, the conditions of suspended matter alter, due to the content changes and composition transformers. It is clear that since the latter of the two processes is more inertial, the angular characteristics of light scattering are more conservative as compared with water transmittance. In this connection, it seems reasonable to determine the totality of angular and integral characteristics that are typical of water in which some species of algae prevail (some peculiar features of such algae being quite typical) and then to employ these characteristics as an indicator for identifying this type of water in the process of its propagation. The transmittance field correlates over lesser areas and can be used to give details in the processes of synoptic nature.

Bearing in mind the aforesaid, let us now turn directly to analyzing the experimental data. We shall begin our review with considering the cross sections of transmittance field in the northern waters moving from to lower to higher latitudes.

Gulf of Anadyr

The crosscurrent flows northwardly through this region (Sukhovoy, 1986). We shall assume that waters at the starting points of the area under consideration are of Pacific origin. The upper layer of water between 60° and 62° north latitude showed clear water in all quasi-latitudinal sections. Such water followed bottom relief and gradually ascended from 100 to 60 m. Beginning approximately from 62°N , the clear water mass was split by a subsurface maximum of cloudiness, propagating northward, to the Gulf of Anadyr.

As proved by the analysis of angular and integral characteristics of light scattering, the waters in the area under investigations have high values of asymmetry factor ($K = 80\text{--}120$) and mean cosine (0.95–0.96), an indication of the presence of coarse biological particles. Their relative volumetric content amounts to 88–92%. A cross section at nearly 63°N (Station 24) has an unusual transmittance structure of water (Fig. 3). In this and other figures, the solid circles show the horizons from which water assays were taken to assess light scattering data. Station numbers and depths from which assays have been taken are given in the figures. In the left-hand column are the asymmetry factor K , relative to volumetric content of suspended matter fine fraction:

$$P = \frac{V_f}{V_t + V_c}; R (\gamma_0=2).$$

and small angle value of indicatrix $\chi(\gamma=1^\circ)$. Given as fractions in the right-hand column are volumetric contents V_c and V_f in (cm^3/m^3) of coarse and fine fractions and also the type of water (Kopelevich, 1983). Here, in the surface 10-m layer of water, there is intense development of diatomic particulates (ocean water was brown). At this station (Station 24), the white disk could be discerned at the depth as small as 3 m. The integral characteristics of light scattering here were also high ($K \geq 90$, $\overline{\cos \gamma} = 0.943$); as for the coarse fraction, its relative content was somewhat lower (84%). For the purpose of comparison, Fig. 4 shows how chlorophyll *a* is distributed throughout that quasi-latitude section (data from Robie *et al.*, subchapter 5.1.2, this volume). Obviously, there is certain correlation between the two presented structures.

It is possible that conditions prevailing at the area of Station 24 were more beneficial for particulates development and that it was just those factors that caused a sharp rise of productivity in originally bioactive Pacific waters. It is noteworthy, however, that these waters give higher values of K and $\overline{\cos \gamma}$. This can be explained as follows: All light-scattering indicatrices measured in northern waters (all in all about 100 angular relationships had been obtained) were analyzed statistically. The analysis showed the volumetric

content of fine fraction increasing with the rise of productivity at a higher rate than that of coarse fraction. In other words, the relative content of the latter drops (which, by the way, was the case at Station 24). Accordingly, the indicatrix becomes less extended and its integral characteristics decrease. Since the water at Station 24 belongs to a very definite type, we shall consider the diatom particulates as having the following characteristics:

$$\begin{aligned} K &= 80-120, \\ \overline{\cos \gamma} &= 0.945-0.960, \\ \chi_{(1^\circ)} &= 50-70, \\ R_{(\gamma_0=2^\circ)} &= 0.17-0.22. \end{aligned} \quad (14)$$

It is understood that the upper and lower boundaries are reached when the volumetric content of coarse fraction equals 88-92% and 84-85%, respectively.

Gulf of Anadyr Littoral Waters

Unusual structure of particulates was observed at Stations 26 and 30 at depths of subsurface maximum (15-30 m). Here, the volumetric content of fine fraction comprised more than

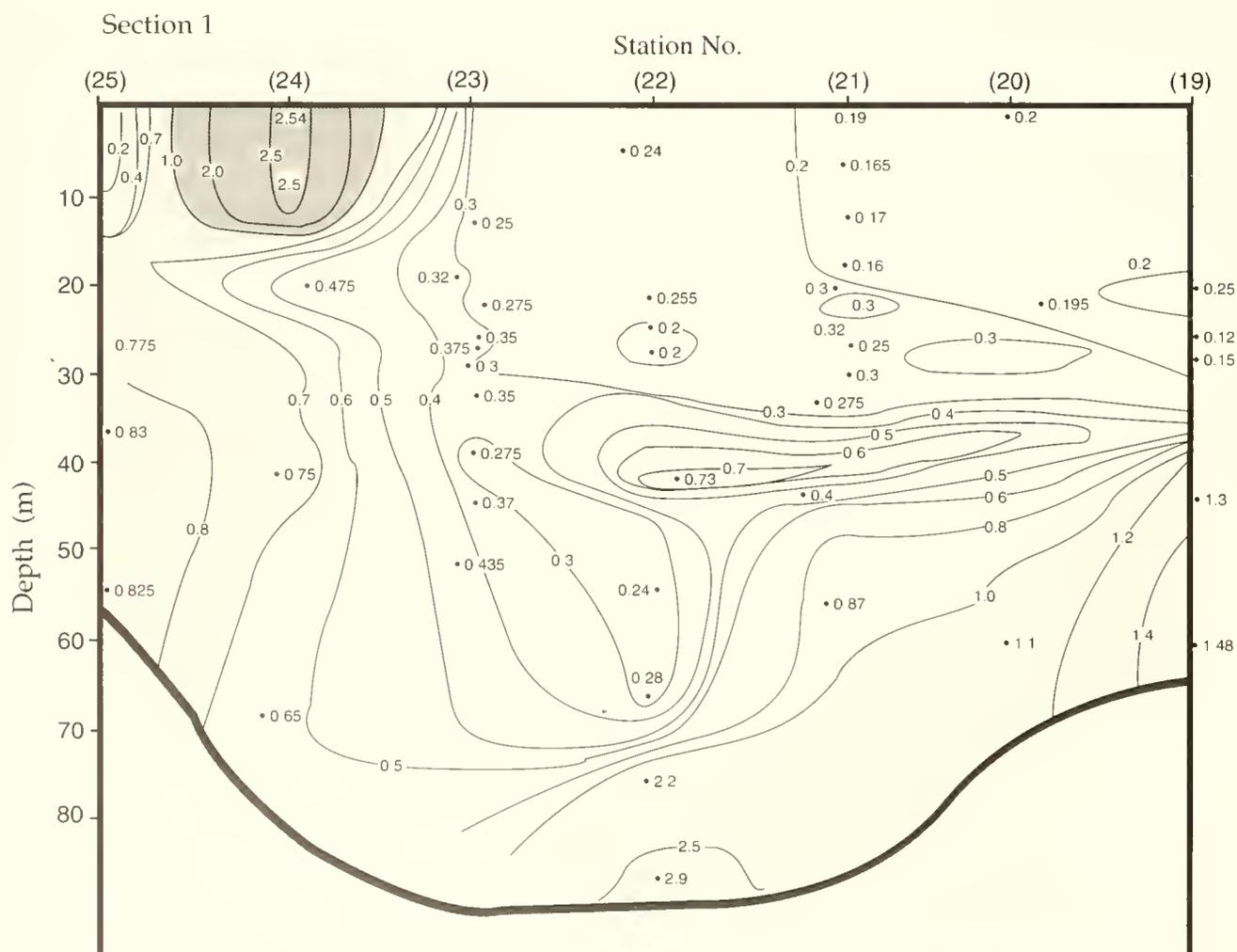


Fig. 3. Section 1. (Stations 25-19) Vertical structure of transmittance.

50%, but integral and angular characteristics were the lowest ($K = 12-13$; $\overline{\cos \gamma} = 0.77-0.78$; $\chi_{(1)} = 44$; $R_{(2)} = 0.135$). Unfortunately, no water assays were taken at intermediate stations. At Station 32, water from the horizon subsurface maximum manifested such integral characteristics of light scattering that are typical of diatomic particulates. This phenomenon can be attributed to the Anadyr River effluence. At Stations 41 and 42 in the Gulf of Anadyr, the transmittance structure was rather primitive; the upper 15–25-m-thick layer was occupied with clear water ($\epsilon \approx 0.2-0.3 \text{ m}^{-1}$), and the lower one was more cloudy ($\epsilon = 0.5-0.7 \text{ m}^{-1}$).

Bering Sea Northern Region

Figures 5–9 illustrate the field of transmittance as seen in the sections of the Bering Sea northern region. Clear water flows through the surface layer at Stations 93, 101, and 103, then runs deeper to 20–25 m (section 5) and flows to the lower part of the right side of the Bering Strait. In the central and western parts of the sections, water turbidity increases up to $0.5-0.7 \text{ m}^{-1}$; the subsurface maximum of particulates, which can be traced on horizons 10–20 m, displaces westward with increasing latitude. The integral and angular characteristics of all assays, taken from subsurface and surface water, have the values that are typical of diatom particulates. Note that in the

Bering Strait, turbid water with similar characteristics flow only on the left side.

Very turbid water was observed in the upper layer of the right side of the strait (section 6), whence it could be traced further to the western part of section 5. This water gradually deepens with decreasing latitude and, in sections 3 and 4, it can be detected only on bed horizons. Its angular and integral characteristics sharply differ ($K = 50-60$; $\overline{\cos \gamma} = 0.91-0.92$; $\chi_{(1)} = 37-45$; $R_{(2)} = 0.11-0.12$) from integral characteristics of light scattering in diatom particulates. Here the relative content of fine fraction comprised 20–30%, with both absolute and relative maximum being on horizon 10 at Station 64.

It is interesting to note that in section 2, cloudy water near the bed (see hatched $\epsilon > 1 \text{ m}^{-1}$) is of another nature. From isolines 0.9–9.9, it appears that cloudy water is associated with overlying productive waters. Moreover, assaying at Station 104 (horizon 26 m) gives a totality of integral characteristics that correlate with such waters. It is quite possible that it is the divergence of flows, flowing around St. Lawrence Island, that caused local features with water transmittance structure typical of zones where waters are rising. Typical of bottom waters in this section is the distribution of chlorophylls (Fig. 10). Note that clear water at the area of Station 103 is also characterized by definitely lower values of Chl *a*.

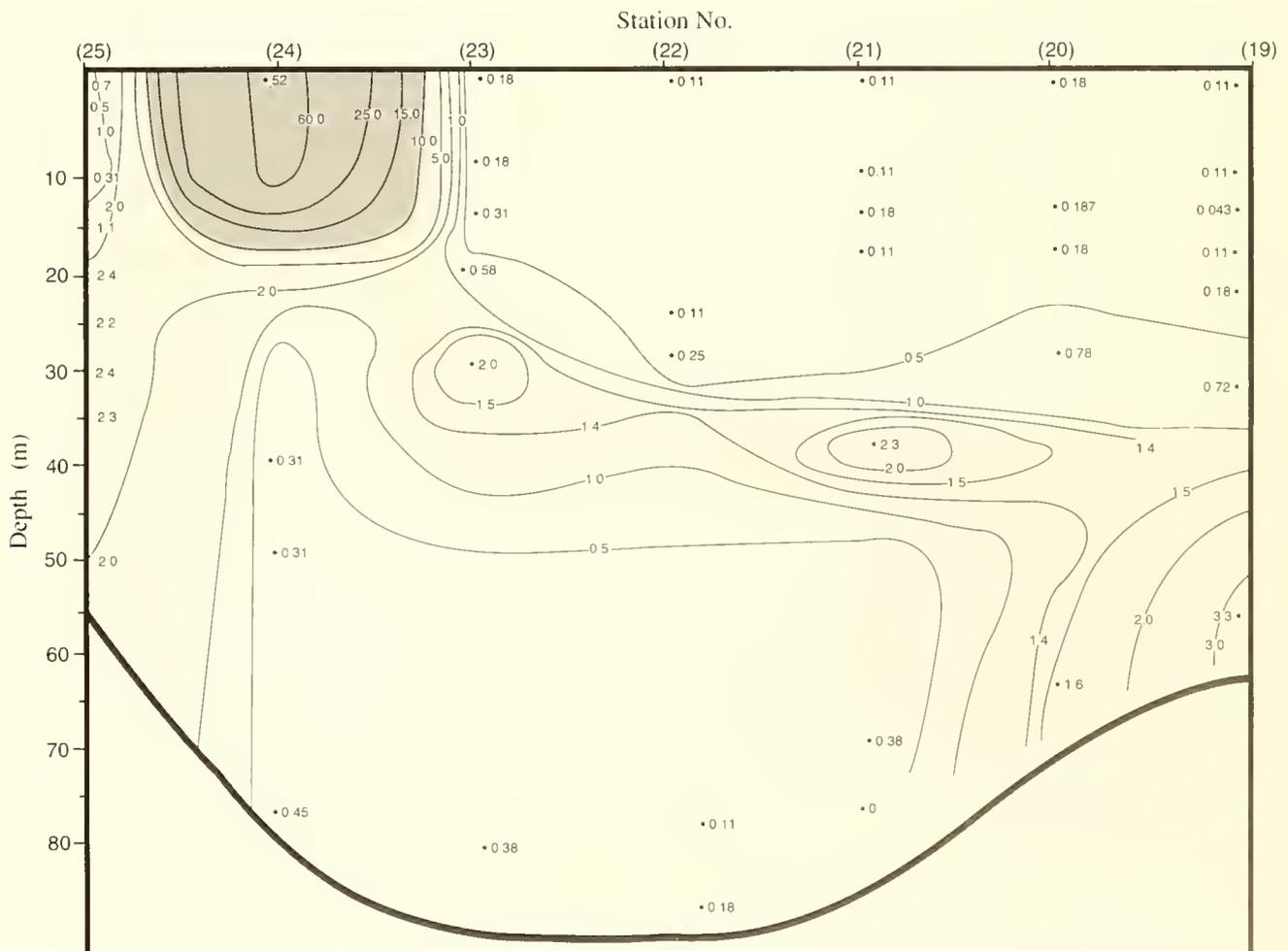


Fig. 4. Section 1, (Stations 25–19) Distribution of chlorophyll *a* (data from Robie *et al.*, Subchapter 5.2.1, this volume).

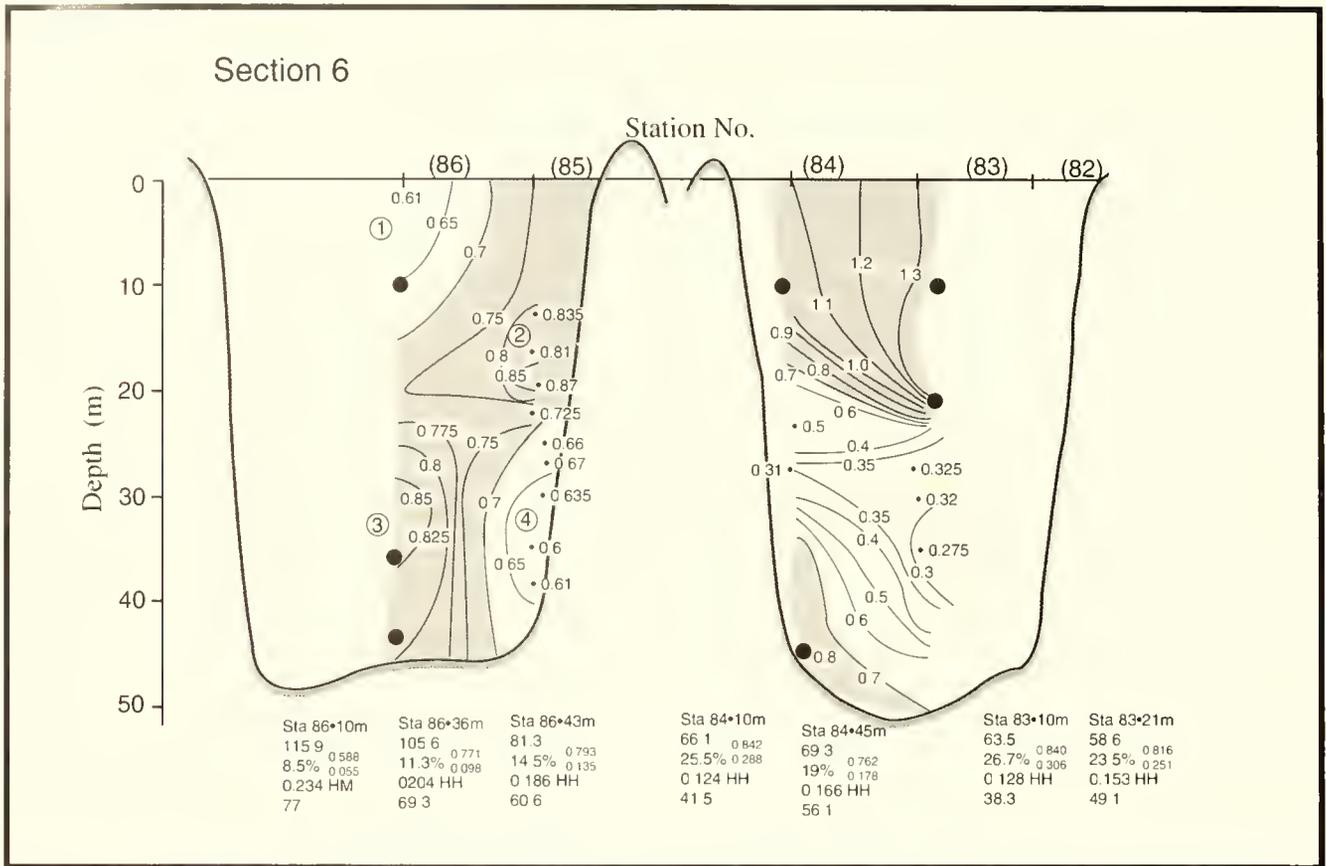


Fig. 5. Section 6. (Stations 82–86) Vertical structure of transmittance. "H" and "M" letter codes above refer to Kopelevich water types; the first letter specifies volumetric content of fine particles and the second letter that of coarse particles. Refer to Table 1 for numerical equivalents.

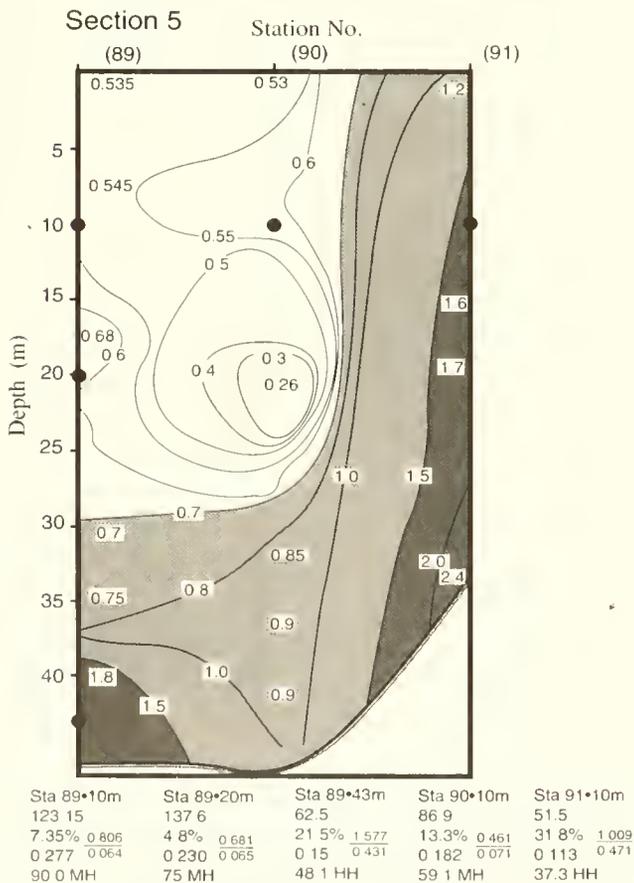


Fig. 6. Section 5. (Stations 89–91) Vertical structure of transmittance. (See Figure 5 legend.)

Chukchi Sea

The attenuation index field for the Chukchi Sea is shown sectionally in Figs. 11–14.

The figures show that clear water ($\epsilon = 0.25\text{--}0.4 \text{ m}^{-1}$) spreads in the surface layer in the northwestern region, and it gradually moves towards the Chukchi coast with decreasing latitude. Areas of clear water can be traced at the northwestern region and at depths of 25–40 m beneath a thick surface layer of particulates (the core of this layer is shown in these sections densely shaded). Occasionally such portions of clear water occur in the lower interlayers. Also, deep clear water is gradually ousted by the rising bottom water and forced to flow towards the Chukchi coast. As a result, the ousted water merges with a cloudy subsurface layer in the central and eastern parts of the region explored. The angular and integral characteristics of assays, taken from surface and deep clear waters at Station 45, horizons 5, 19, and 28, are very close to and generally compatible with those of water containing diatom particulates. The difference lies in higher values of light scattering indicatrices at small angles ($\chi_{(1^\circ)} \cong 95\text{--}105$), which, when studied optically, suggest bigger "effective" size of coarse fraction scatterers. It should be mentioned that the areas of relatively clear surface water have been recorded at Stations 51, 52, 54, 65, and 67. At the areas of its spreading, the average transmittance is somewhat higher, which can be seen in the chart of zonal distribution (Fig. 1, isolines 0.8–0.9 in the eastern part of the region explored).

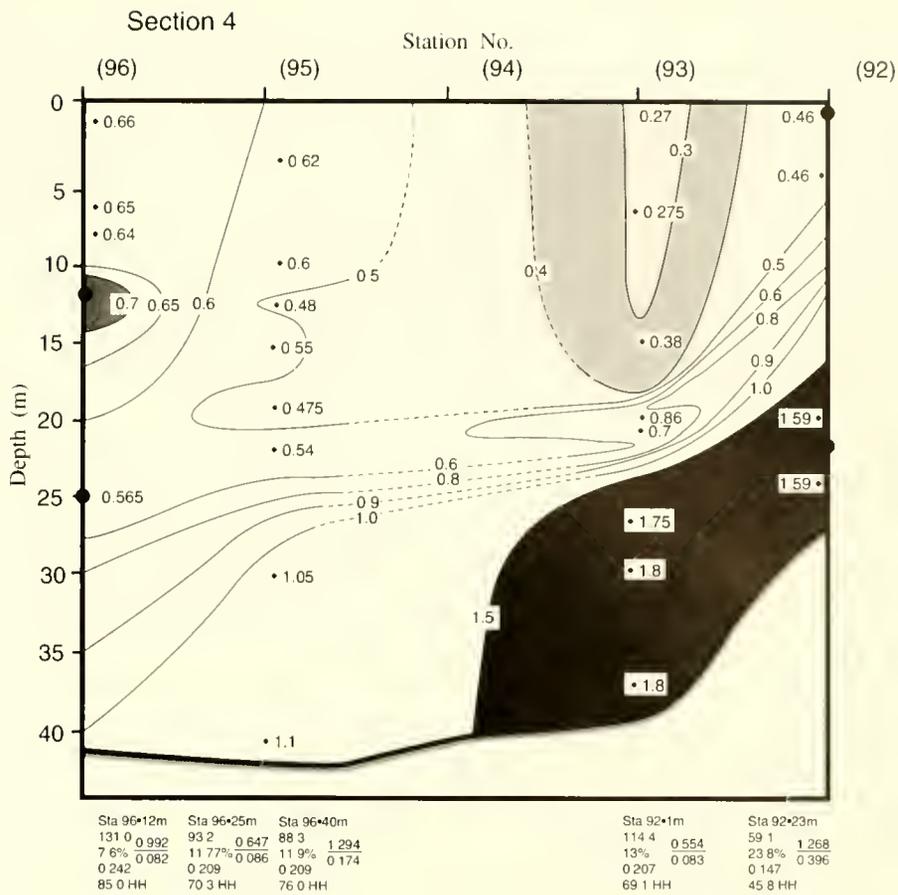


Fig. 7. Section 4. (Stations 96–92) Vertical structure of transmittance. (See Figure 5 legend.)

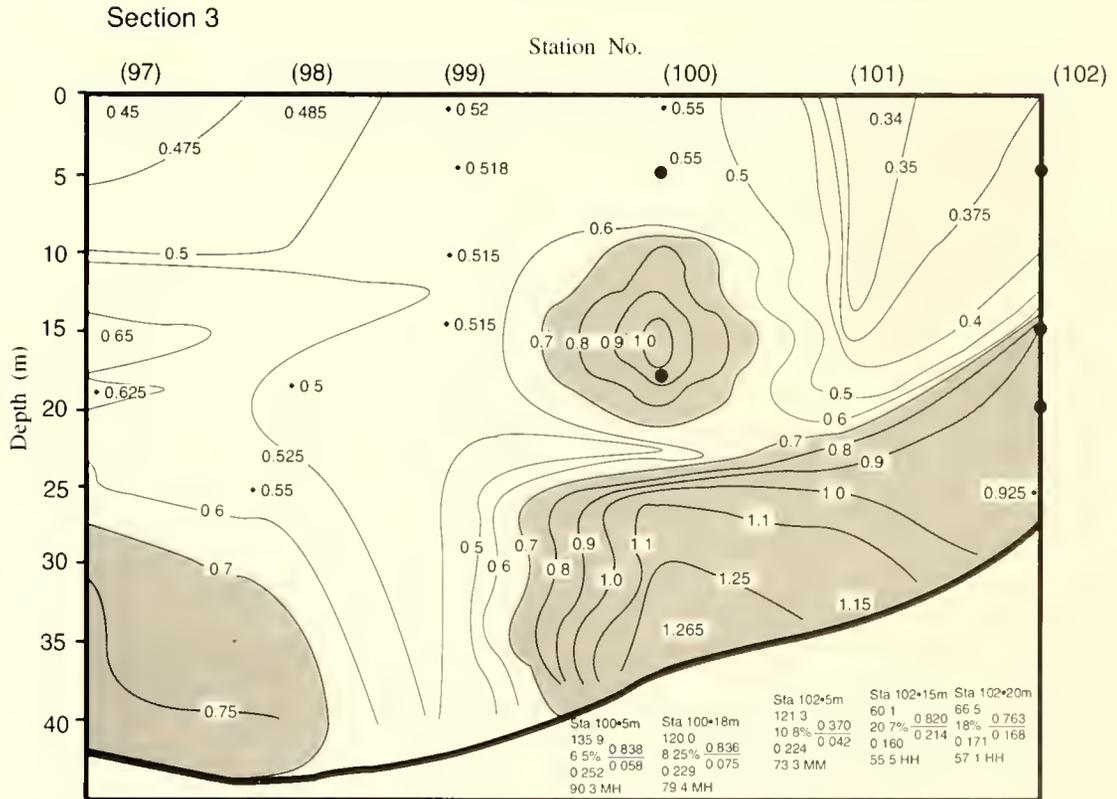


Fig. 8. Section 3. (Stations 97–102) Vertical structure of transmittance. (See Figure 5 legend.)

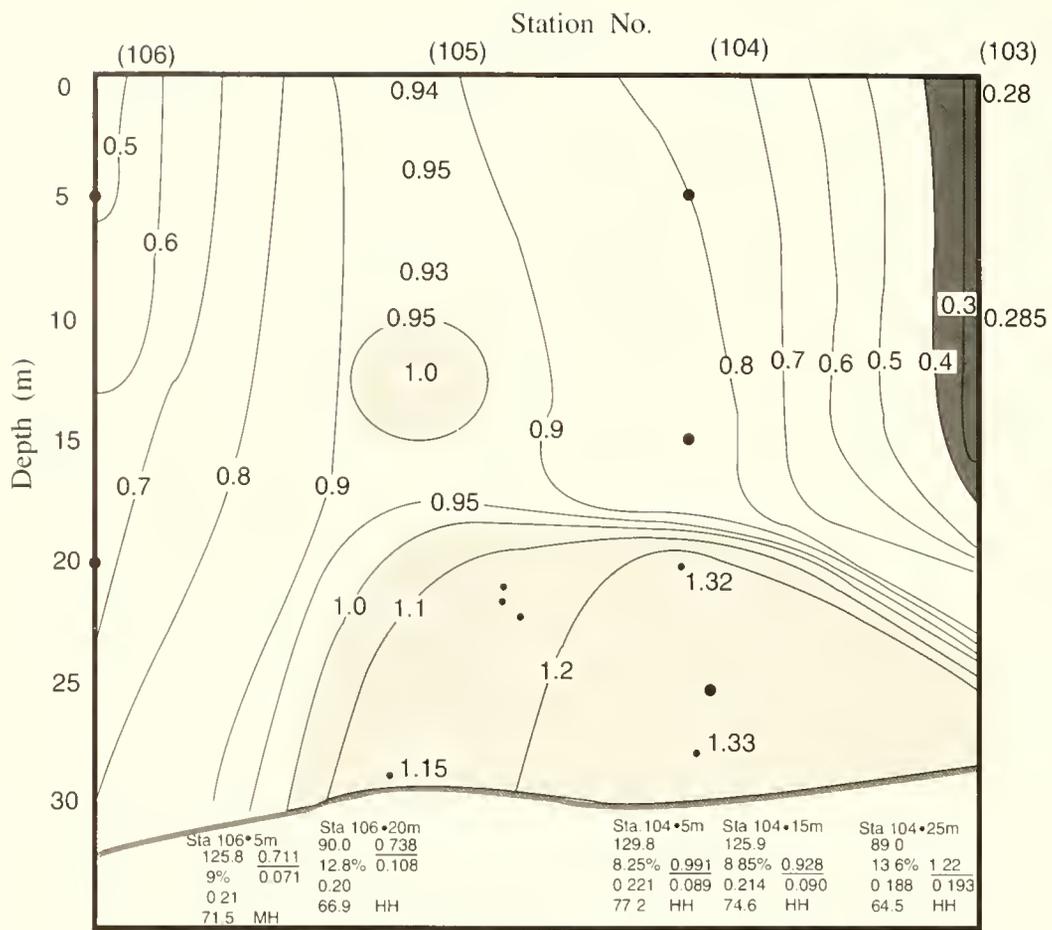


Fig. 9. Section 2. (Stations 106-103) Vertical structure of transmittance. (See Figure 5 legend.)

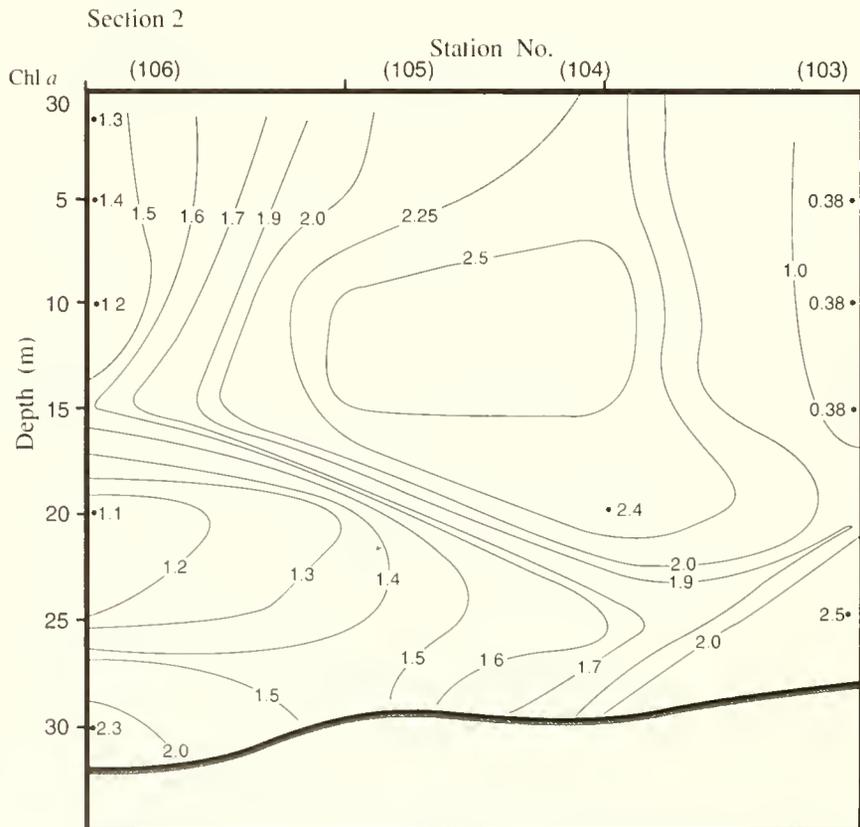


Fig. 10. Section 2. (Stations 106-103) Distribution of chlorophyll *a* (data from Robie *et al.*, Subchapter 5.1.2, this volume).

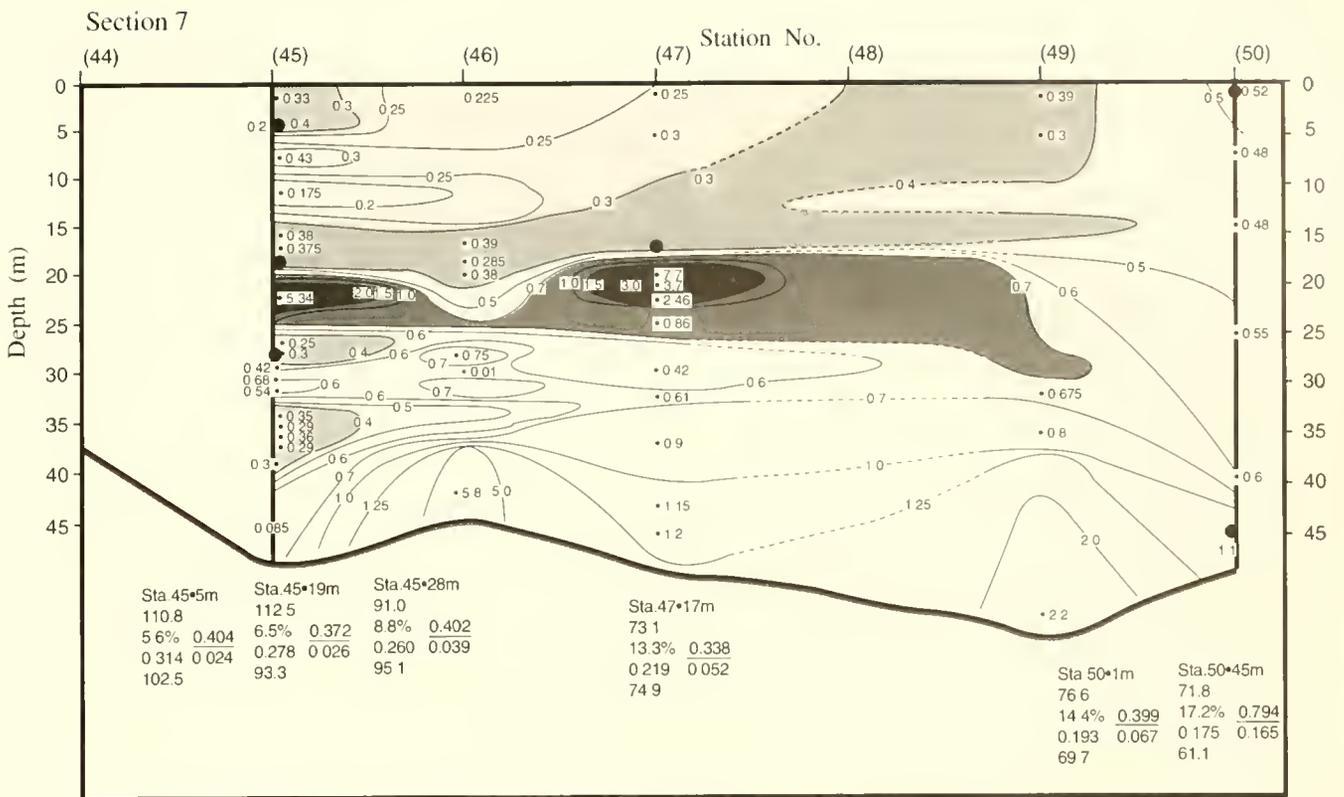


Fig. 11a. Section 7. (Stations 45–50) Vertical structure of transmittance.

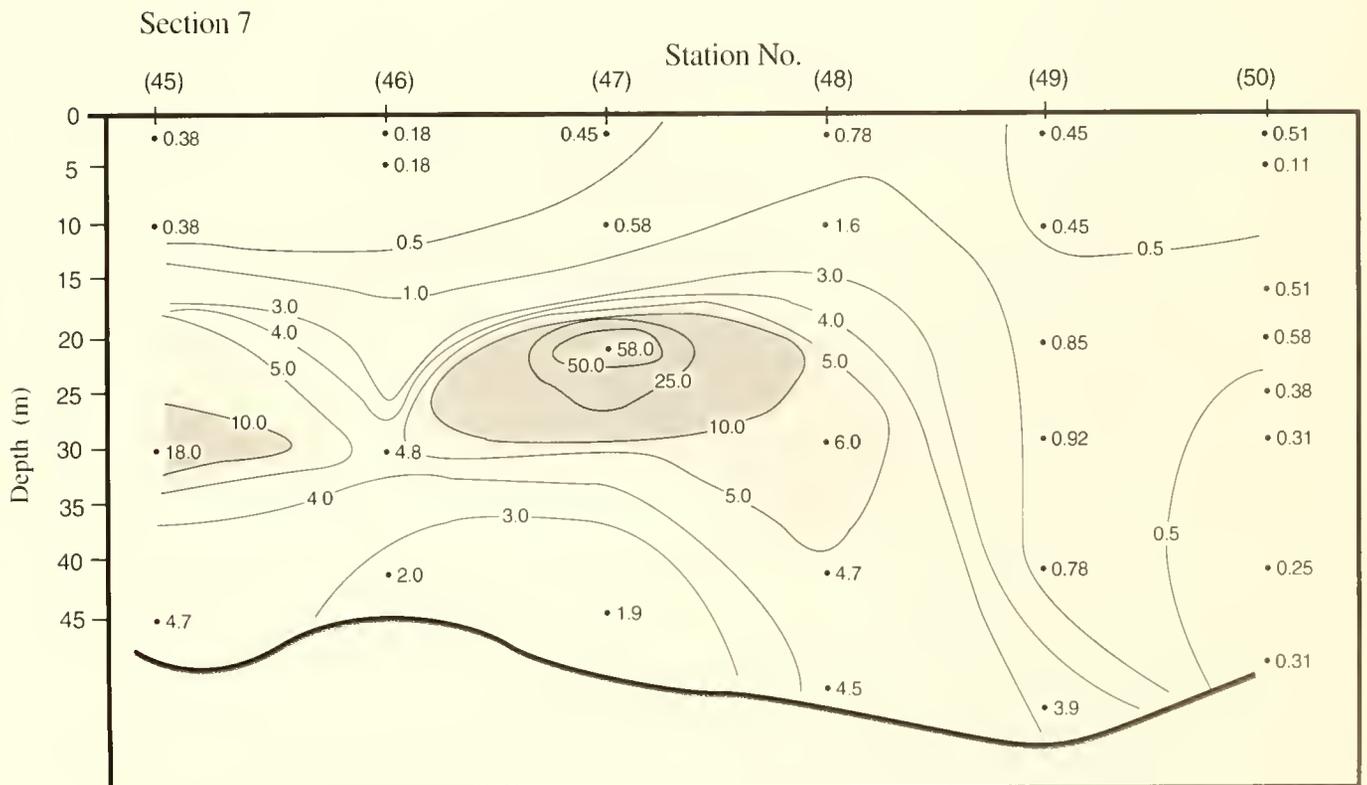


Fig. 11b. Section 7. (Stations 45–50) Distribution of chlorophyll *a* (data from Robie *et al.*, Subchapter 5.1.2, this volume).

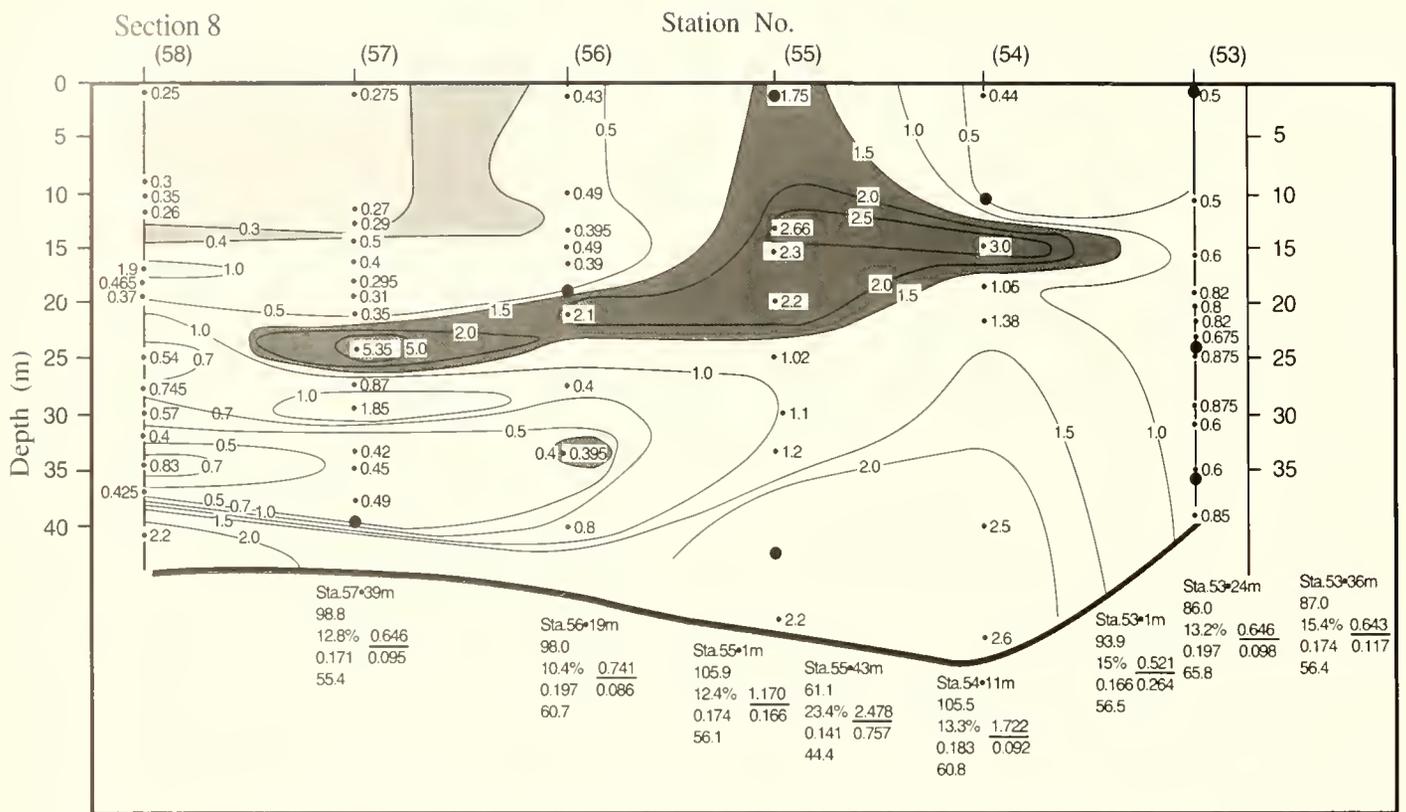


Fig. 12a. Section 8. (Stations 58-53) Vertical structure of transmittance.

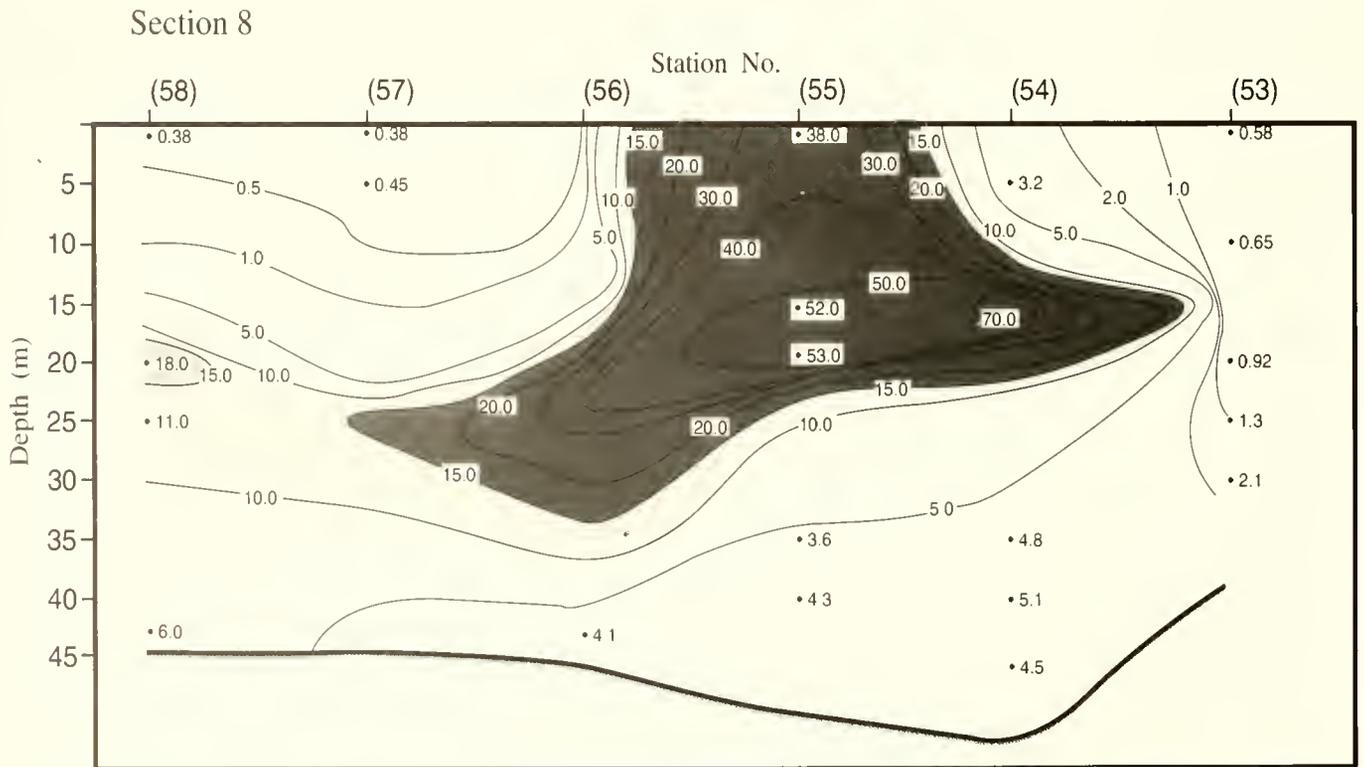


Fig. 12b. Section 8. (Stations 58-53) Distribution of chlorophyll a (data from Robie *et al.*, Subchapter 5.1.2, this volume).

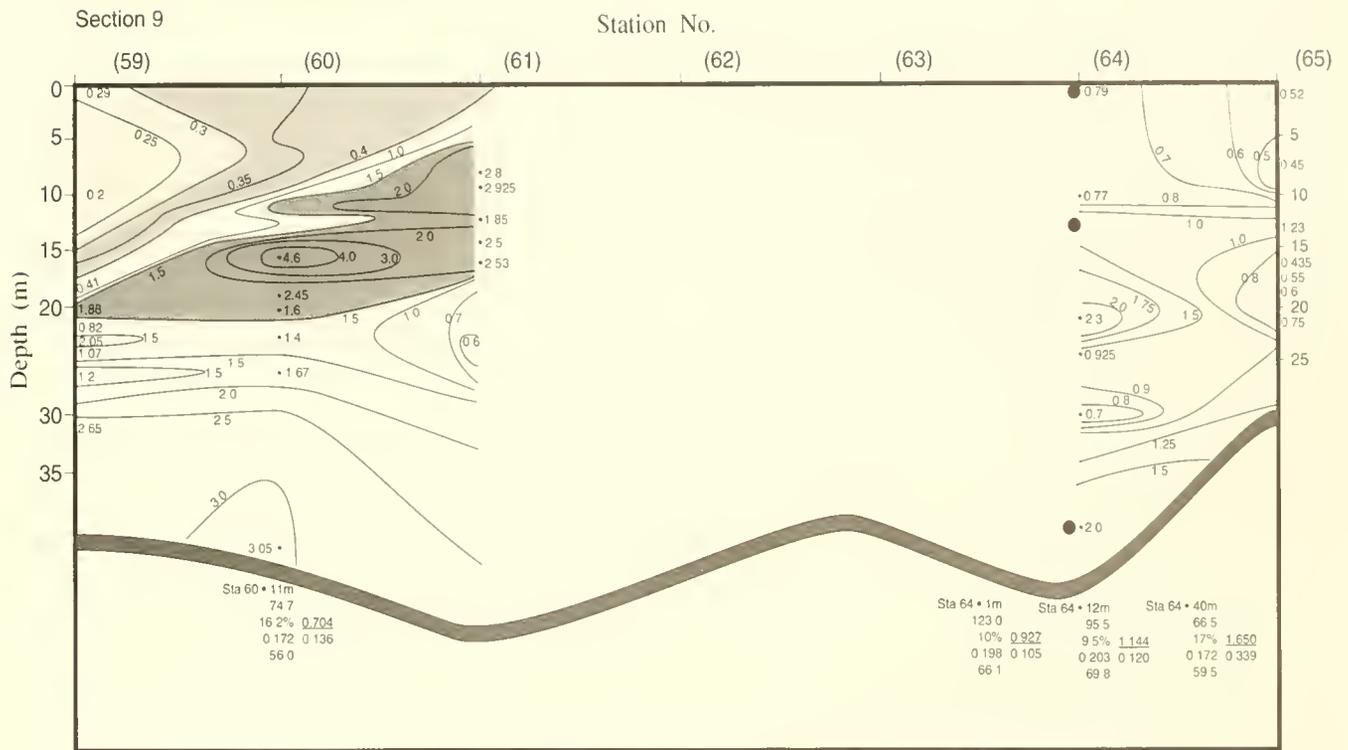


Fig. 13a. Section 9. (Stations 59-65) Vertical structure of transmittance.

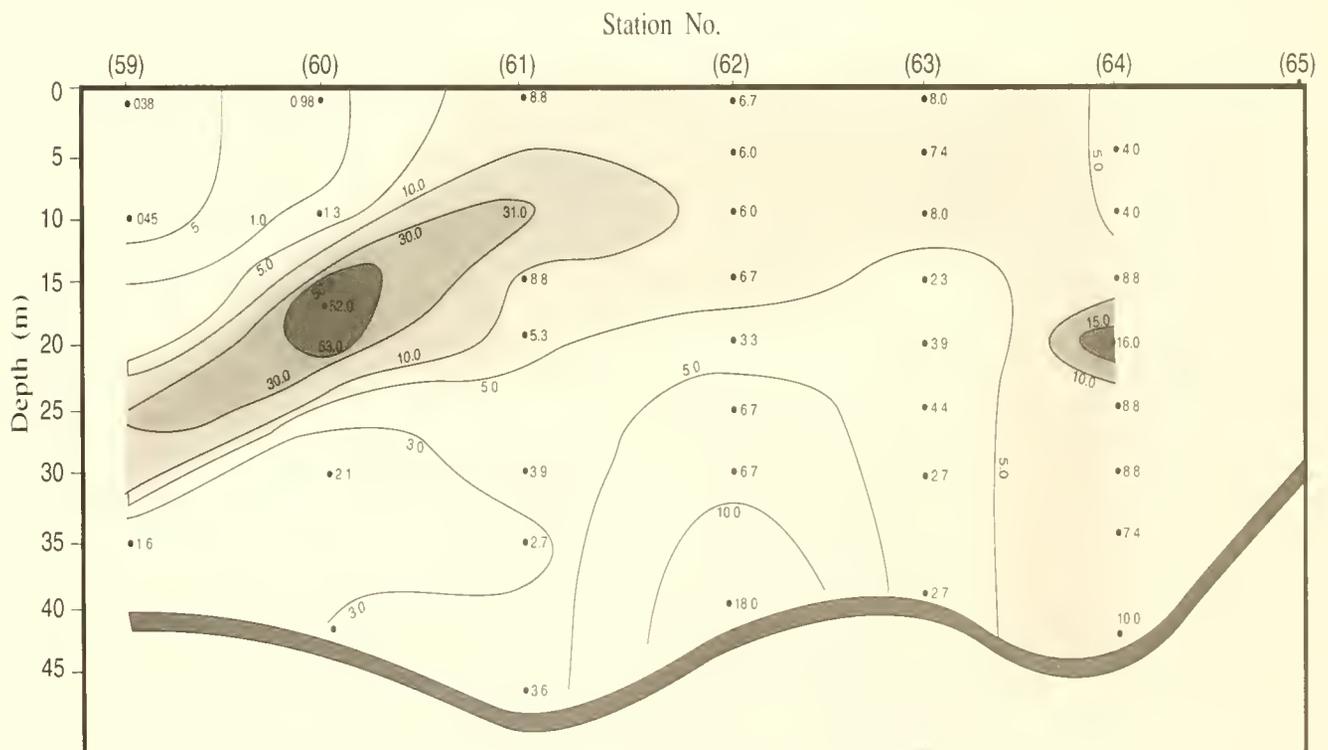


Fig. 13b. Section 9. (Stations 59-65) Distribution of chlorophyll a. (data from Robie *et al.*, Subchapter 5.1.2, this volume).

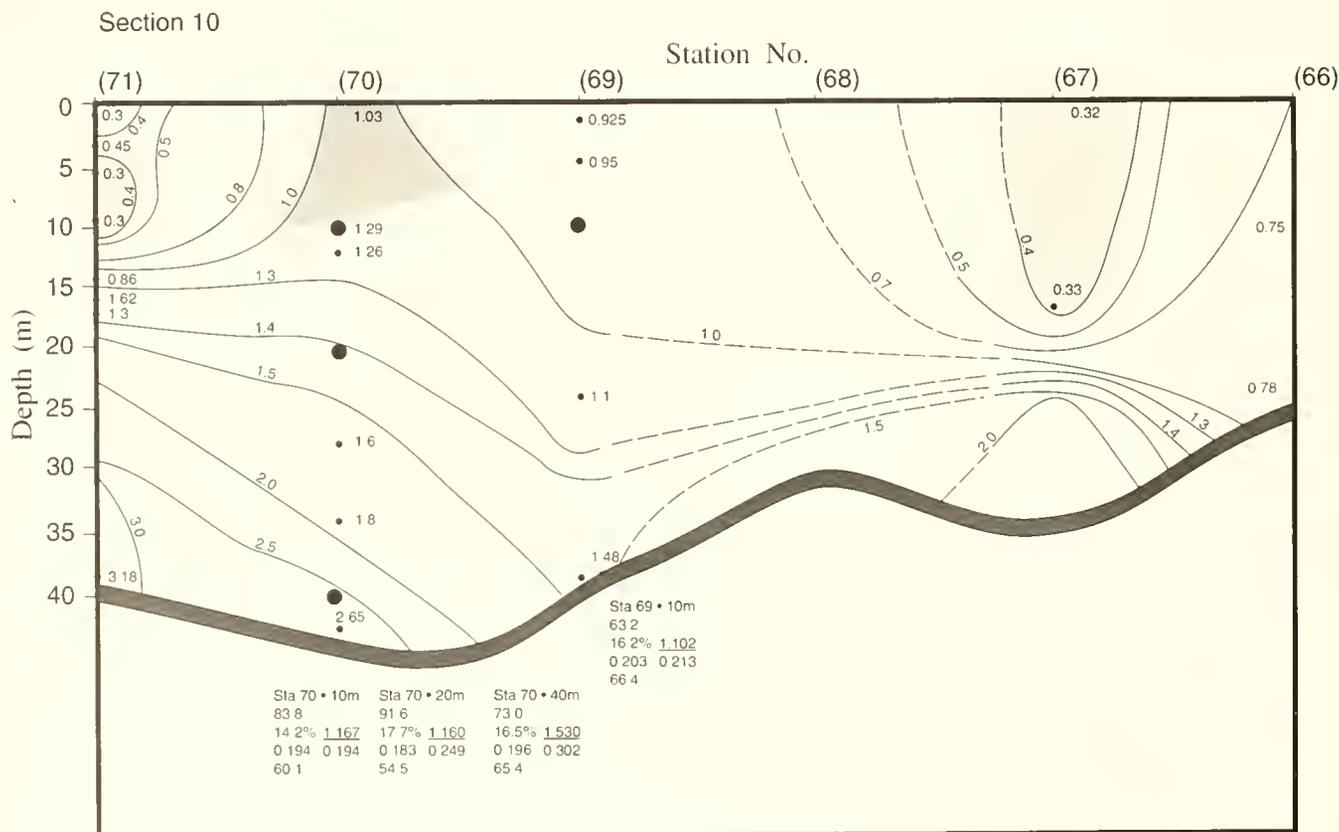
The structure of the suspended matter in the subsurface layer had maximum development, as it surfaced, at Stations 54, 55, 56 (possibly 62), and 70. At Stations 55 and 70, the sea was a brown color. The optical structure that is observed here is typical of local divergence zones; most possibly, it is associated with the cyclonic nature of water circulation in this region of exploration (Sukhovey, 1986).

The integral and angular characteristics of assays, taken from subsurface maximum, corresponded to diatom particulates and were close to the totality of integral characteristics of light scattering in productive water at Station 34 in the Gulf of Anadyr. The spreading of productive water can be assessed by "fitting" totality (14) to integral characteristics of light scattering in all other assays from the Chukchi Sea, thus assessing the areas of productive water spreading. For instance, at Station 53, such water could be traced throughout all depths from surface to bottom. Isoline 1.0, in the eastern part of section 8, points to a generic relationship between Stations 53 and 55. It is not improbable that here, in the same zone of water upflow, some water flows down the sides.

Bottom waters in the Chukchi Sea are very turbid ($\epsilon > 1 \text{ m}^{-1}$). At all stations, where assays were taken from surface and bottom horizons, the highest volumetric contents of coarse and fine particulates, as assessed from (11) and (12), were found at the bottom. Here the integral characteristics of indicatrices had, on the average, relative content of this particulates equal to 16–17%; at Station 55, this parameter rose up to 23%.

An exception was Station 57 where assays, taken from 39 m horizon, gave light-scattering integral characteristics that corresponded to those of productive water. It is certainly of interest that here, as at Station 53, a possible generic relationship between bottom water and productive water of higher layers can be deduced from isolines 0.7–1.0.

Figure 15 shows vertical structure of water transmittance as depicted in the Bering Strait section (this section is the closest one by time: 16.08.88). It is evident that most cloudy waters were spreading along western and eastern coasts of the left strait and also along the eastern coast of the right arm. Qualitatively, however, the composition of particulates differed. In the turbid water along eastern coast of the right arm (the intensity of turbidity is depicted by shading of various denseness), the relative content of fine particulates was high (30%); by their light scattering integral characteristics these waters corresponded to earlier examined waters (sections 3, 4, 5, 6). The coarse and fine fractions here also had rather high concentrations. Turbid waters in the left strait (shown by dense shading) had integral characteristics that related these waters to the productive ones; relatively clear water spread in the upper layer of right strait into the west. By its integral characteristics, this water corresponded to water with diatom particulates. In the central parts of both arms, in mid-depths, clear water cores (designated as I and II) were present; these cores differed from the surrounding waters by integral characteristics and transmittance.



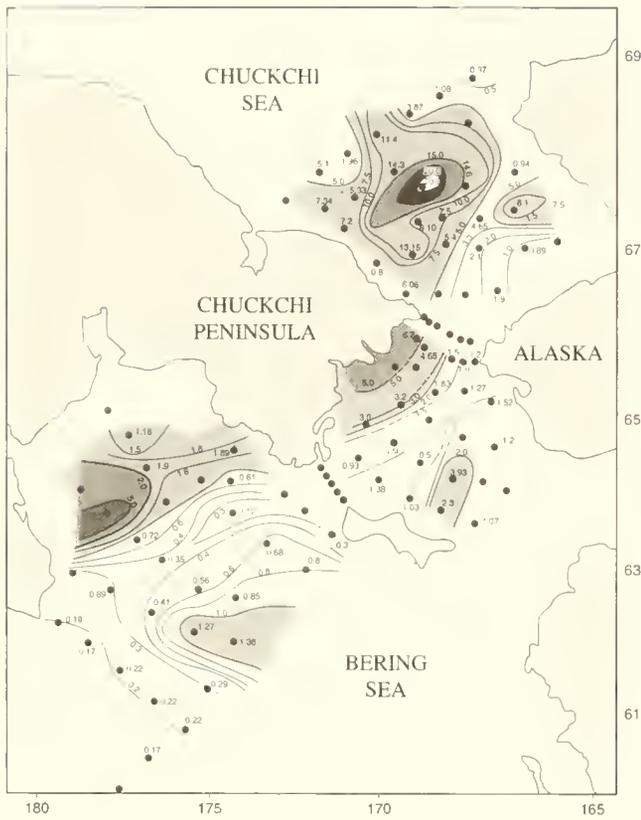


Fig. 16. Zonal distribution of chlorophyll *a* average for a certain layer of water (data from Robie *et al.*, Subchapter 5.1.2, this volume).

the result was negative. However, it was found that promising results (Fig. 18) are obtained by comparing relevant values only within the depths of localized subsurface turbid layer, notable also for higher chlorophyll concentrations (Figs. 11b, 12b, 13b). The correlation of current values of ϵ and Chl *a* can be well expressed by the relation $\text{Chl } a = 20\epsilon + 7$.

Investigating Vertical Structure of Transmittance on Test Areas and Sections

East Polygon. Waters at the area of deeply immersed East Polygon stations have a typical subpolar structure of transmittance. The upper 20–30-m layer was turbid ($\epsilon = 0.4\text{--}1.1 \text{ m}^{-1}$); below 50 m, very clear water ($\epsilon = 0.13\text{--}0.1 \text{ m}^{-1}$). At shallow Stations 131 and 132, near the bottom there appeared a thin turbid layer ($\epsilon = 0.2\text{--}0.25 \text{ m}^{-1}$). At Station 132, there was a reduced content of particulates in the surface layer ($\epsilon = 0.25 \text{ m}^{-1}$ compared to $\epsilon = 0.6\text{--}0.7 \text{ m}^{-1}$ at Station 131).

South Polygon. Optical structures of transmittance at the South Polygon are characterized as subpolar. In the upper 50-m layer, the attenuation index was $\epsilon = 0.25\text{--}0.3 \text{ m}^{-1}$ (at Station 110, $\epsilon = 0.65\text{--}0.7 \text{ m}^{-1}$); lower depths (80 m) had clear water ($\epsilon = 0.11\text{--}0.095 \text{ m}^{-1}$). The attenuation index changed gradually in the intermediate layer. Angular characteristics of light scattering showed that the volumetric content of coarse particulates per 10 m depth interval varied from $0.43 \text{ cm}^3/\text{m}^3$ (Station 111) to $0.59 \text{ cm}^3/\text{m}^3$ (Station 110); fine particulates varied from $0.05 \text{ cm}^3/\text{m}^3$ up to $0.09 \text{ cm}^3/\text{m}^3$ (at the same stations). Assays of deep water from 200 to 2,450 m (Station

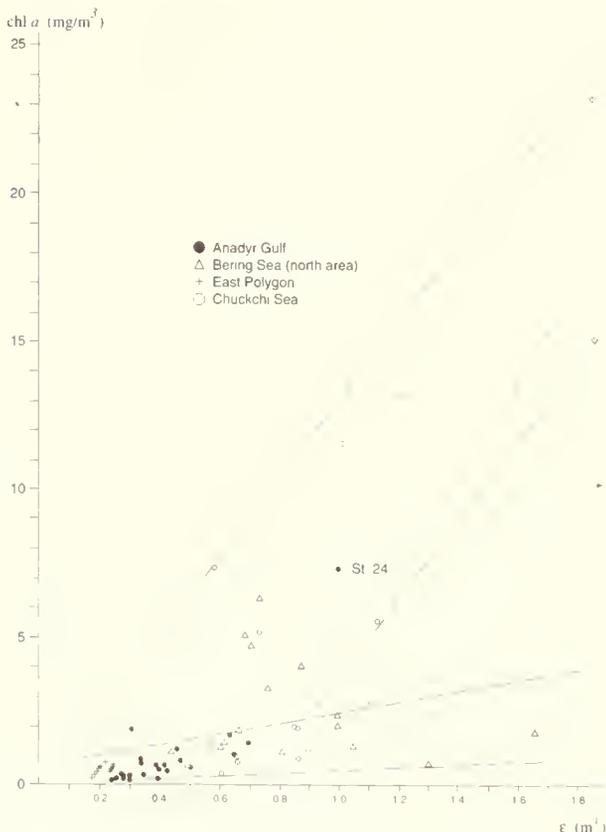


Fig. 17. Relationship (Chl *a*) from (ϵ) in experiments.

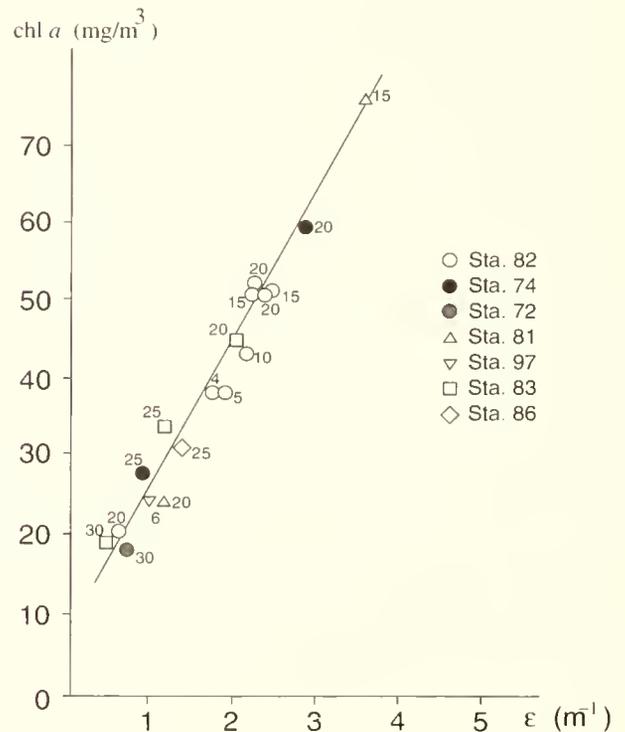


Fig. 18. Dependence Chl *a* from within the depths of localized subsurface cloudy layer.

112) showed small differences in content. Volumetric content was $0.187 \text{ cm}^3/\text{m}^3$ and $0.09 \text{ cm}^3/\text{m}^3$ at 200 m, and $0.218 \text{ cm}^3/\text{m}^3$ and $0.04 \text{ cm}^3/\text{m}^3$ at 2,450 m. The values are typical of deep waters of the Pacific (Kopelevich, 1981). The Secchi depth varied from 10 m (Station 132; most turbid surface waters) to 15 m (Stations 108, 111).

Conclusions

Before stating main conclusions, it should be noted that primary hydrooptic characteristics of the Bering and Chukchi Seas were investigated for the first time.

The northern Bering and Chukchi Seas were discussed in terms of their transmittance and spatial variability in cross-sectional transects.

1. The transmittance of waters in this study decreases with the increase of latitude. The results of instrument-assisted measurements correspond to visual observations of H_δ depths at which a standard white disk disappears (12–22 m in the Gulf of Anadyr, 7–16 m in the northern Bering Sea, and 4–10 m in the Chukchi Sea). The relationship between H_δ and the average value of attenuation index $\langle \epsilon_{\text{H}\delta} \rangle$ may be expressed by the relationship

$$H_{\delta} = \frac{4.5}{\langle \epsilon_{\text{H}\delta} \rangle}.$$

2. The zonal distribution of average transmittance reflects the dynamics of northern seas. It can be utilized to detect cyclonic eddies and to assess areas where waters have different conditions of formation.

3. Increased turbidity of water is accompanied by a higher rate of fine fraction particulates growth.

4. Waters with different qualitative composition of particulates display distinct angular and integral characteristics of light scattering. This feature enables optical properties of such waters to be used as an indicator in regionalizing the waters by their productivity. It is also helpful when investigating the dynamics of currents. It is shown that diatom particulates in potentially bioactive waters of the cross current increases with latitude. These waters are carried to the Chukchi Sea through the eastern portion of the Bering Strait. In the western portion, it was heavily turbid low-productivity water with relatively high content of fine fraction.

5. The waters in the Gulf of Anadyr and divergence zone in the Chukchi Sea are characterized by high productivity. They show similar values of angular and integral light scattering that are specific for diatomic particulates. This signifies the ability of biological particulates for intensive development in the Bering Sea (where beneficial conditions exist). It may also show affinities between the dynamic processes occurring in both the productive zones.

6. In waters with predominant content of diatom particulates (identifiable as a specific combination of angular and integral characteristics of light scattering), the chart of zonal distribution of average transmittance correctly reflects (in qualitative terms) the spatial distribution of chlorophyll content.

7. In high productivity waters of the Chukchi Sea, the relationship between chlorophyll concentration and attenuation index will be $\text{Chl } a_{(\text{H})} = 20\epsilon_{(\text{H})} + 7$.

Subchapter 5.2:

Zooplankton

5.2.1 Ciliate Protozoa in Plankton

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Introduction

Intense growth of protozoa was observed throughout the Bering and Chukchi Seas. The maximum Ciliophora biomass was found to be higher in the Chukchi than in the Bering Sea. Values were 1.22 and 2.33 g/m³, respectively. Most of the infusoria mass occurred in the top 40 m of the water column. Although the taxonomic composition was virtually the same as in 1981, it was substantially different in the two seas. Genus *Strombidium* oligotrichids were predominant in both seas. The degree of Ciliophora development corresponded to chlorophyll levels. Ciliate protozoa are a key factor in the ecosystems of both seas. According to mean data for the layer of maximum concentrations, they may account for as much as 1.5 g of primary nutrient/m³/d circulating in the Bering and 2 g/m³/d in the Chukchi. The production yield of ciliate protozoa is 1 g/m³/d.

Today, as pollution threatens to engulf the world's oceans, the study of sea areas removed from highly industrialized and densely populated regions (i.e., areas such as the Bering and Chukchi Seas) is becoming of increasing interest to researchers (Izrael & Tsyban, 1983). The highly productive waters of these areas are characterized by extremely intense growth of early stages of the food chain, especially of ciliate protozoa (infusoria). As the major constituent of microzooplankton, the infusoria serve as a link between the primary food (algae and bacteria) on the one hand and the larger consumer species on the other. Hence, these organisms in large measure drive the transformation of organic matter in the lower stages of the food chain. In addition, ciliate protozoa are an excellent indicator of water quality or pollution level. Information about this component of the plankton community of the Bering and Chukchi Seas, however, remains meager. Fragmentary early data (Stepanova, 1937) have now been supplemented by more recent findings (Mamaeva, 1983).

The chief purpose of the present study, undertaken within the Third Joint US-USSR Bering & Chukchi Seas Expedition in July–November 1988 during the 47th cruise of the research vessel (R/V) *Akademik Korolev*, was to pursue the investigation of the plankton Ciliophora community. Research areas included 1. species composition; 2. quantitative distribution over the water column and sea areas; 3. links with abiotic and biotic factors in the environment; 4. quantitative role in the food chain; and 5. use as an indicator of the environmental status of a given sea area.

Methods

The Bering and Chukchi Seas have extremely heterogeneous ecosystems. Individual areas of both seas are characterized by distinctive hydrological and hydrochemical parameters. This meant that this study had to be conducted in a discrete manner for each individual subarea chosen (Frontispiece).

Sampling was performed using Niskin samplers. These were employed following preliminary probing to determine sharp temperature discontinuities and to identify water layers characterized by elevated chlorophyll and suspended matter levels. Parallel determinations were made of biogenic component levels, pigment concentration, and traditional organic pollutant concentrations.

Microzooplankton content was determined conventionally. Immediately upon sampling, 10 ml of the water contained in an oblong chamber were examined under the microscope using a succession of magnifications ranging from low to high. These samples were used to examine and count smaller untrapped forms that perished upon filtering and subsequent treatment of the water. One to three liters of the same sample were then reverse-filtered through a 10–15 µm mesh in order to isolate the larger protozoa. Samples were likewise taken using nets. Biomass was determined by measuring immobilized infusoria and comparing their shapes with geometric figures and precalculated volume. The specific weight of the organisms was assumed to be the same. The total number of samples taken in the Bering and Chukchi Seas was 350.

Results

Bering Sea

The East Polygon (Frontispiece) was situated in a complex hydrological setting that included a sharp bottom declivity. Most of the stations had depths of 3,000 m, but the two northernmost ones stood over just 145 and 214 m of water. The water contained large amounts of biogenic components: phosphates ranged from 1.0 to 2.5 µg at/l and silicates from 20 to 30 µm at/l. The species mix within the polygon was varied and differed little from ambient conditions (Table 1). The predominant forms were smaller Strombidia 15–50 µ in size; the principal Tintinnida were *Parafavella denticulate*, *Ptychocyclus urnula*, and *Codonellopsis turgescens*. Also common were larger *Stobilis*, *Didinium* sp., *Mesodinium* sp.,

and *Suctorida* (Table 1). The polygon in question had remarkably abundant infusoria (Fig. 1). In the layer of maximum abundance their numbers ranged from 18 to 67×10^6 individuals/m³ and biomass reached 1.2 g/m³ (Table 2). Station 2, with the least abundant infusoria, was apparently situated in a strong current. The major portion of the Ciliophora mass lay in the top 40 m of the water column, with two density maxima — one at the surface, the other at a depth of 10–20 m (Fig. 2).

The South Polygon lay in the southernmost portion of the Bering Sea, in the vicinity of Aleutian Islands straits, linking it with the Pacific Ocean. The depths at its stations were on the order of 4,000 m, the salinity about 33 ‰. High biogenic component and chlorophyll levels were noted. The hydrological setting was exceedingly complicated, as evidenced by major differences in microplankton content at neighboring stations. The Ciliophora species mix was similar to that of the East Polygon, although some differences were noted. Thus, at Station 110, the species typical of the region were joined by *Tintinnidium* sp. and *Cyclotrichium* sp., while at the two southernmost stations (111 and 112), near the straits, there were some *Steenstrupiella steenstrupii*. Since this characteristically Pacific species was seen nowhere else in the Bering, it probably entered the sea through the straits. The quantitative distribution of Ciliophora both here and in the East Polygon was not uniform. Maximum abundance ranged from $1.9 - 36 \times 10^6$ individuals/m³ and biomass from 70 to 690 mg/m³ (Table 3). Station 113, situated close to the central Aleutian Islands, had the most abundant ciliates. Located near

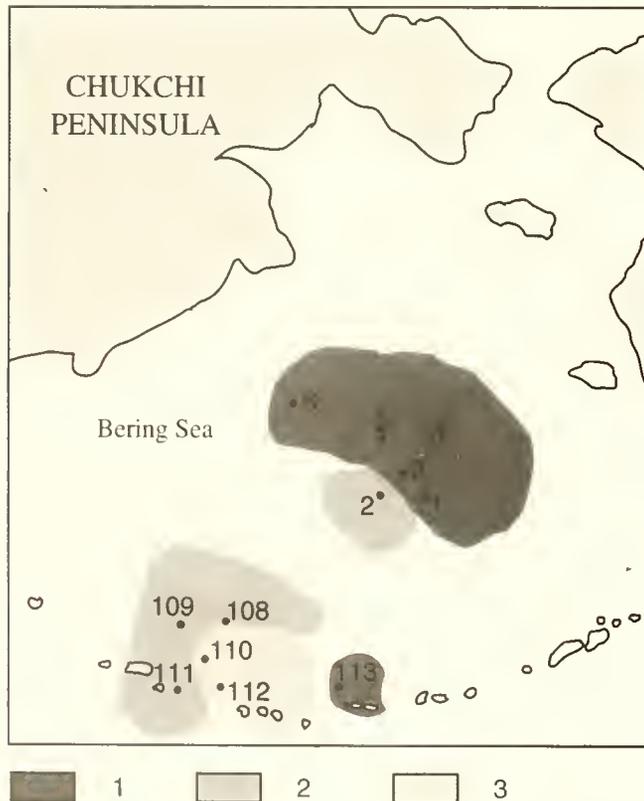


Fig. 1. Infusoria biomass in the layer of maximum abundance in the East and South Polygons. [Legend:] Biomass in mg/m³: 1) 1,220–460; 2) 200–116; 3) 70–25.

TABLE 1

List of dominant infusoria taxa for the Bering Sea.

- Didinium gargantu* Meun.
- Mesodinium rubra* Lohm.
- Strombidium strobilis* Wulff.
- Strombidium* sp.
- Tontonia appendiculariformis* F-F.
- Tontonia* sp.
- Leprotintinnus pellucidus* (Cleve) Jorg.
- Codonellopsis turgescens* K.a.C.
- Parafavella cylindrica* (Jorg.)
- P. denticulata* (Ehrb.)
- Ptychocylis urnula* (C.a.L.) Bdt.
- Canthariella brevis* K.a.C.

Buldir and Semichi Straits, Stations 110 and 112 had little microplankton (see Frontispiece). Most of the infusoria mass was localized in the top 40 m of the water column, with maxima at the surface and subsurface layers and at the temperature discontinuity depth of 10–25 m (Fig. 2).

The Gulf of Anadyr portion of the Bering Sea is relatively shallow, most of it less than 100 m deep. The waters of the gulf are a mixture of seawater and low-salinity Anadyr River runoff. The biogenic component concentrations were high, but

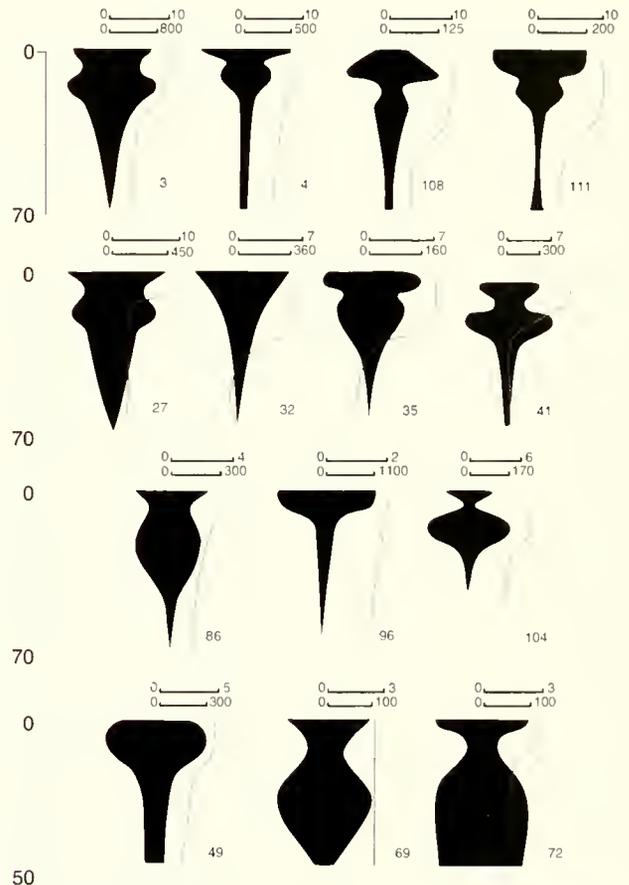


Fig. 2. Vertical distribution of infusoria in the Bering and Chukchi Seas. [Legend:] the ordinate axis is depth in m; the upper abscissas are temperature in °C, the lower abscissas the biomass in mg/m³. Solid curves describe temperature profiles. Numbers from 3 to 111 refer to stations.

TABLE 2

Numbers (N, in 10^6 of individuals/ m^3) and biomass (B, in mg/m^3) of infusoria at Bering Sea stations (N/B).

Station No.	Depth (m)						
	0	5	10	15	25	45	70
1	60.0/1221	55.4/795	19.5/282	21.9/211	8.6/80	5.5/195	0
2	13.7/325	7.7/39	5.2/24	18.0/116	3.4/1211	1.6/11	0.2/6
3	57.8/625	45.1/508	26.0/464	51.7/752	29.5/375	2.8/24	0
4	58.4/462	32.9/117	41.4/256	13.3/137	5.0/77	4.0/22	0.4/2
5	0	25.0/193	32.2/697	14.2/365	15.5/119	4.5/80	0.8/24
6	13.7/236	66.7/910	39.4/394	57.4/444	40.2/314	58.5/435	12.2/61
7	6.0/180	2.0/60	2.0/60	1.5/70	3.5/50	3.5/42	0
9	2.1/70	2.1/70	2.5/82	10.2/94	12.5/75	12.5/60	0
11	46.0/660	46.0/660	58.0/540	12.1/63	64.4/432	0.6/18	3.0/15
13	51.2/336	50.8/324	39.2/276	52.0/360	75.0/790	12.8/84	7.2/36
15	4.0/70	3.0/90	4.6/100	26.1/765	21.2/156	0.5/15	3.0/15
18	2.5/63	3.5/55	6.5/85	2.7/43	1.6/23	1.0/20	0
19	8.0/115	8.3/259	1.4/17	2.0/100	2.0/60	2.0/60	0
22	5.0/145	51.0/330	27.0/330	26.0/260	1.5/45	1.2/12	0
24	0.3/9	9.0/90	54.0/420	8.0/235	3.0/40	1.0/10	0.7/18
27	25.0/450	19.0/270	12.0/220	15.0/400	9.0/210	3.8/230	3.5/35
32	7.1/360	30.0/300	28.0/240	9.0/145	9.0/120	2.0/60	0
35	2.0/60	0.5/5	0.5/5	0.3/3	0.3/3	0.2/2	0.5/15
36	5.0/92	2.0/160	2.1/70	5.7/110	2.2/80	0.3/9	0
41	2.6/182	4.1/132	3.0/60	12.0/280	1.6/55	1.0/30	0
83	2.85/40	2.15/15	2.10/30	1.07/15	3.21/45	10.0/105	0
86	10.0/235	7.03/120	8.03/140	8.15/160	7.15/210	2.05/25	0
92	3.13/120	2.29/75	2.10/15	2.80/25	0.50/5	0	0
96	16.25/1100	12.05/1040	4.13/280	4.03/130	1.63/50	2.1/30	0
100	4.25/100	4.10/195	3.10/65	4.25/200	4.50/40	3.50/20	0
102	2.05/15	1.35/30	1.2/55	1.25/85	2.00/15	0	0
104	8.05/95	2.10/15	2.35/55	4.10/160	2.85/35	0	0
106	2.00/15	2.50/50	1.50/10	0.5/5	0.5/5	2.0/10	0
108	2.15/30	2.53/80	4.05/125	2.08/25	4.1/45	1.65/20	0.53/10
109	0.83/10	8.03/45	6.45/200	4.28/110	4.88/100	1.50/20	0
110	1.50/25	1.90/35	1.20/25	1.60/70	1.00/30	0.70/5	0
111	10.0/200	8.80/190	2.55/75	3.2/100	2.4/30	1.6/10	2.00/20
112	2.80/30	1.50/45	2.43/36	2.83/85	2.03/22	2.05/63	2.0/22
113	36.19/500	35.25/690	14.05/250	10.08/125	5.22/90	1.00/12	0.50/5

markedly lower than in the central portion of the Bering Sea. As with the East Polygon, the predominant species were of the genus *Strombidium* and ranged from 15–50 μm in size. Throughout the gulf there were the large *Strombidium strobilis*, the predatory *Didinium* sp., and Tintinnida (*Ptychocyclus urnula*, *Parafavella denticulata*). In contrast to the central sea, brackish-water species (*Tintinnopsis* sp. and *Leptotintinnus pellucidum*) were also present. The quantitative parameters maintained high values throughout the gulf (Fig. 3). In the maximum-concentration layer, the counts ranged from 6 to 75×10^6 individuals/ m^3 . The highest Ciliophora densities were observed in the southern portion of gulf. The amount of infusoria present declined considerably as one moved out of this area. The biomass distribution, which ranged from 60 to 790 mg/m^3 in the layer of maximum concentration, followed the same pattern (Fig. 3). Most of the infusoria were localized in the top 30 m of the water column, with one or two maxima either at the surface or at a depth of 10–25 m (Fig. 2).

Comparative analysis indicated that the infusoria distribution closely matched chlorophyll levels. The most infusoria-abundant stations (Stations 11, 13, 15, 19, 24, 27) were associated with an area rich in chlorophyll and phosphates. Ammonia as a by-product of microplankton metabolism was also plentiful.

The portion of the Bering Sea situated north of St. Lawrence (Chirikov basin) is shallow with depth ranging from 27 to 49 m. The hydrological setting is very intricate, since it is a zone where three currents (water from the Gulf of Anadyr, Alaskan Coastal water, and water from the Bering Sea Shelf) meet and mingle. The Anadyr water is very salty and cold (temperature ranging down to $2^\circ C$ at Station 96). Greatly diluted by the Yukon, the Alaskan Coastal waters are of low salinity and high temperature (29.7 ppt and $11.2^\circ C$ at Station 92). These waters undergo only very slight mixing and flow into the Chukchi Sea mostly intact. The flows in the eastern and western portions of the strait differ greatly in both biogenic element and chlorophyll levels. The coastal waters of Alaska are many times poorer in

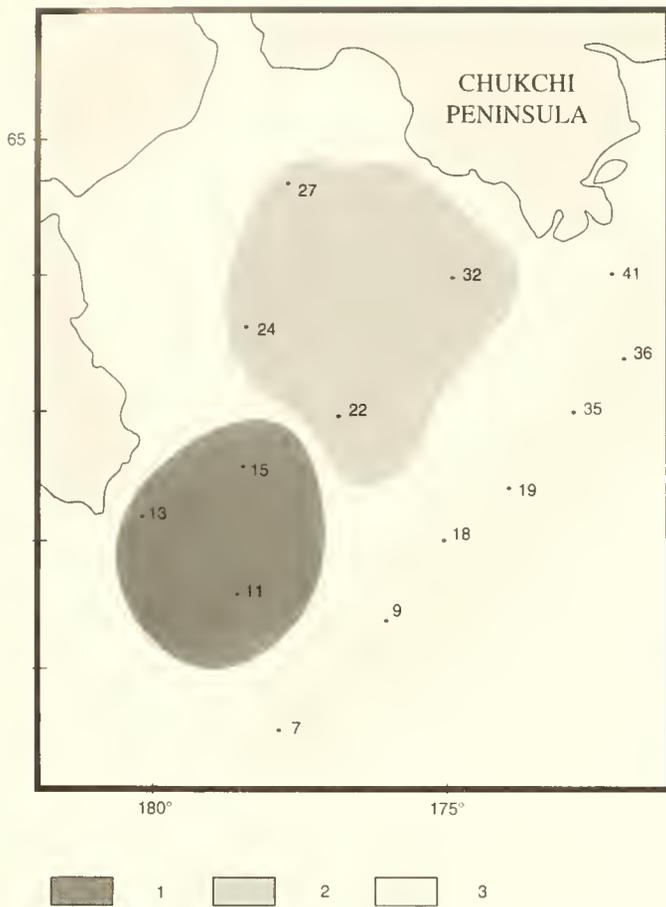


Fig. 3. Distribution of infusoria biomass in the layer of maximum abundance for the Gulf of Anadyr. [Legend:] Biomass in mg/m^3 : 1) 790–660; 2) 450–330; 3) 280–60. Numbers from 7 to 41 denote stations.

biogenic elements. The heterogeneous character of the flows makes for an exceedingly complicated picture of microzooplankton distribution in regard to both actual species present and their quantities (Figs. 4–7). The species composition and ciliate counts for the western and eastern portions of the Bering Strait differed considerably. Dominant in the east were smaller *Strombidia* and the *Tinnopsis* sp. characteristic of less saline water. The bottom layers exhibited degraded algal debris, as was confirmed by chlorophyll *a* level analysis (1.3 mg/l in the surface layer and 2.7 mg/l at the bottom). Species variety and abundance were much greater by the western shore. The presence of heterogeneous flows in the Chirikov basin is evidenced by such things as closely placed Stations 100 and 102 exhibiting completely different infusoria species mixes. The distinctiveness in question remains in evidence all the way to the neck of the strait (Fig. 7). The same may be said of the quantitative characteristics. The infusoria counts and biomass off Alaska were found to be several times lower than off the eastern coast of the Soviet Union (Figs. 4–7). The biomass in the most abundant layer of the strait ranged from 15 to 1,100 mg/m^3 , with counts from 2.0 to 16.25×10^6 individuals/ m^3 . The richest station (Station 96) was situated off the western shore, the poorest off the Gulf of Anadyr. Waters within the infusoria-rich stations exhibited high chlorophyll *a* concentrations (Fig. 7). The same sea areas showed elevated ammonia levels with a maximum of to

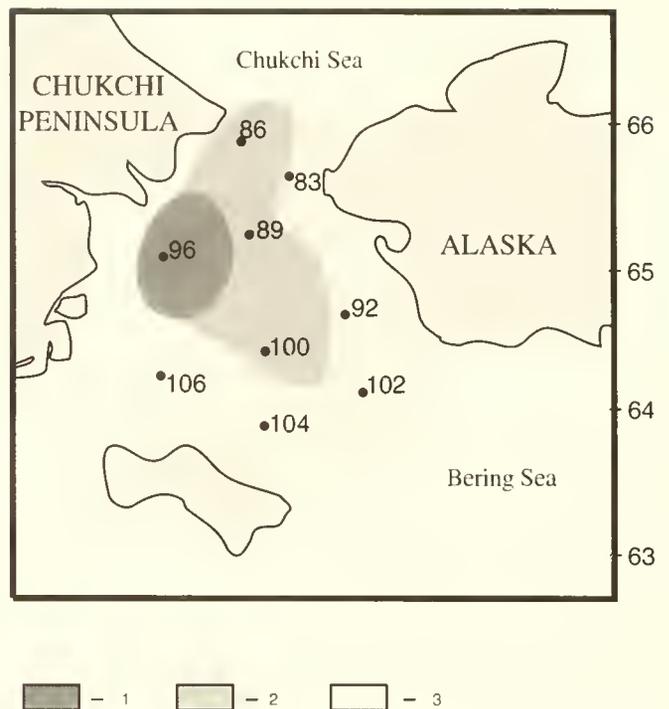


Fig. 4. Biomass in the layer of maximum abundance for Bering Strait. [Legend:] Biomass in mg/m^3 : 1) 1,100; 2) 280–200; 3) 160–15. Numbers from 83 to 106 denote stations.

2 mg/m^3 . The distribution of infusoria over depth in this shallow portion of the sea did not conform to any single pattern. With some stations the density maxima occurred at the surface and at a depth of 10–15 m (Fig. 2). The amount of ciliates at several stations increased considerably with depth, whereas in other instances the distribution with respect to depth was uniform.

Chukchi Sea

The sampling station in the southern portion of the Chukchi Sea constitutes a direct extension of the Bering Sea, inasmuch as three distinct flows enter it through the Bering Strait without undergoing much intermingling. These flows come from the Gulf of Anadyr, the Bering Sea Shelf, and the less saline Alaska Coastal waters (Coachman *et al.*, 1975). The area in question is shallow, with depths at particular stations ranging from 35 to 55 m. Water temperature and salinity vary markedly, the water containing high concentrations of biogenic elements. Against a background of intense algal bloom (*Chaetoceros*, *Thalassiosira*, *Rhizosolenia*, and dinoflagellates), the ciliate community of the Chukchi Sea was quite discrete. It consisted of very large (up to 300- μm long) genus *Strombidium* infusoria, often of brownish and greenish pigmentation, and very large individuals of genera *Cyclotrichium*, *Askenasia*, *Didinium*, *Peritromus*, et al. Sucking infusoria (Suctorida) and *Mesodinium* sp. were quite common. Tintinnida were scarce and few in number (Table 3). Clusters of *Chaetoceros socialis* often included smaller infusoria and dinoflagellates to form a kind of microcoenosis. The numbers and biomass of infusoria were very high throughout the region (Table 4, Fig. 8). In the layer of maximum abundance, the counts ranged from 2.5 to 25.1×10^6 individuals/ m^3 , and the biomass from 85 to 2,330 mg/m^3 , higher than in the Bering Sea. The highest

TABLE 3

List of dominant infusoria taxa for the Chukchi Sea.

- Didinium* sp.
- Mesodinium rubra* Lohm.
- Cyclotrichium* sp.
- Askenasia* sp.
- Peritromus ovalis* F-F
- Strombidium strobilis* Wulff
- Strombidium* sp.
- Tontonia appendiculariformis* F-F.
- Tontonia* sp.
- Leprotintinus pellucidus* (Cleve) Jorg.
- Tintinnopsis* sp.
- Ptychocyclus* sp.

biomass was noted in the northern portion of the sea (Fig. 8), with vertical distribution varying considerably from station to station. The most frequent case was that of a single maximum, either at the surface or at a depth of 5–10 m. Occasionally the maximum number of ciliates occurred in the 15–25-m layer or at the bottom (Fig. 2). In our view, the high biological productivity of the Chukchi Sea is attributable largely to local processes, because shelf waters are actively enriched by organic matter through primary productivity in the presence of high biogenic levels.

Discussion and Conclusions

Our study of ciliate protozoa in the Bering and Chukchi Seas showed their development to be extremely intensive, which places both seas among the most productive of the world's oceans. The ciliate distribution over the sea areas of the

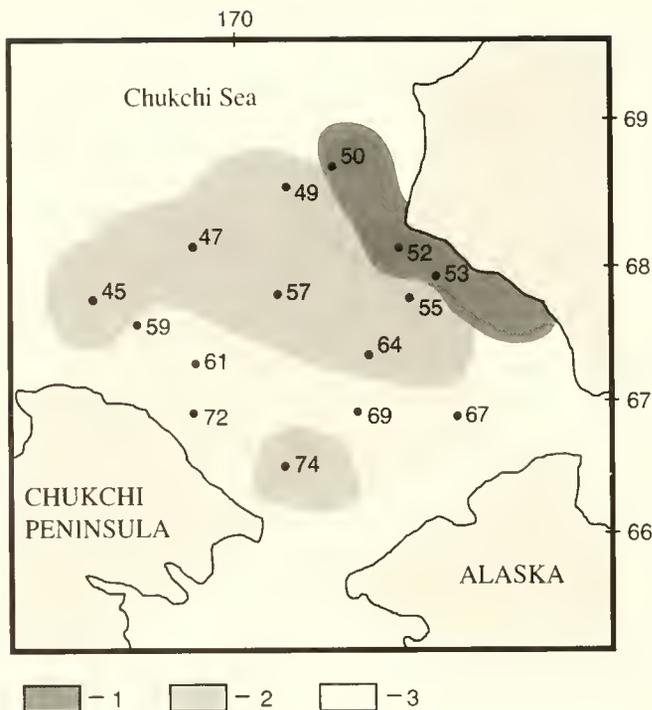


Fig. 8. Biomass distribution (mg/m³) in the layer of maximum abundance at Stations 45–74 in the Chukchi Sea. [Legend:] Biomass: 1) 2330; 2) 450–250; 3) 198–85.

Bering and Chukchi may be described as a mosaic that reflects the heterogeneous character of their ecosystems. The principal mass of infusoria with depth occurred in the top 40 m, with one or two maxima. The species composition and quantitative characteristics of the Bering Sea infusoria during the present study (summer of 1988) were little different from those of spring 1981, which seems to indicate that the marine ecosystems in question had not experienced much deterioration as a result of human pressure. It was discovered that the Chukchi Sea is

TABLE 4

Numbers (N, in millions of individuals/m³) and biomass (B, in mg/m³) of infusoria for the Chukchi Sea (N/B).

Station No.	Depth (m)					
	0	5	10	15	25	45
45	1.20/60	2.10/150	2.70/115	8.11/350	3.62/180	2.11/116
47	4.31/295	1.10/80	1.15/70	1.70/100	2.15/130	3.50/175
49	4.30/172	6.05/305	5.50/288	5.10/170	2.60/85	2.05/70
50	3.25/180	20.00/827	25.00/1765	17.00/630	5.10/117	1.00/5
52	16.40/1208	12.05/380	5.14/170	0.50/15	2.30/100	0.70/50
53	25.05/755	15.25/495	24.23/740	25.10/2330	1.60/60	2.60/25
55	10.20/260	5.10/300	12.70/425	10.10/150	1.90/48	3.00/150
57	5.10/160	3.20/180	6.10/180	5.20/175	6.37/250	7.00/450
59	1.40/50	2.40/72	4.00/50	5.50/110	1.00/80	2.50/150
61	2.10/60	3.20/135	4.35/170	2.10/80	3.20/115	5.00/150
64	8.10/220	10.50/320	6.13/285	11.00/270	3.20/30	3.20/180
67	8.00/138	5.40/110	4.20/75	1.6/35	1.00/5	0.80/4
69	2.18/85	1.20/46	0.80/34	1.00/50	2.50/35	1.50/15
72	1.50/100	0.80/34	2.50/35	2.00/70	3.20/100	3.00/90
74	5.13/60	8.10/250	2.10/50	1.55/20	0.55/10	2.00/100

characterized by a very special species mix that includes numerous larger species. A particular microcoenosis was found to occur within *Chaetoceros* clusters. Also dominant were species of the genus *Strombidium*. The two seas differed considerably with respect to species structure.

The level of ciliate development in the Bering and Chukchi Seas is very high. The maximum biomass in the former case was noted in the East Polygon and in the Bering Strait (1.22 and 1.10 g/m³, respectively). Studies conducted in 1981 yielded similar values. The infusoria community in the Chukchi Sea developed no less intensively, with maximum biomass assays exceeding even those of the Bering Sea.

A positive correlation was noted between ciliate biomass and chlorophyll concentration. Areas with very abundant ciliates showed elevated ammonium levels. These levels are a result of metabolic activity. Developing as intensively as they do, ciliate protozoa play a major role in plankton community metabolism in both seas. Thus, in the layer of maximum

abundance averaged over the whole of the Bering Sea, they are capable of involving 1.5 g of primary and bacterial production per cubic meter of water per day in the food chain, yielding 0.5 g of product per cubic meter over the same period. In the Chukchi Sea with a total biomass of 600 mg/m³ in the layer of maximum abundance, the corresponding figures are 2 g of organic primary nutrient and 1 g of production, respectively. The findings of the present study indicate that infusoria are reliable indicators of the hydrological and hydrochemical characteristics of seawater. Thus, in the straits in the southern portion of the Bering Sea, we noted infusoria species that pointed to the connection with Pacific Ocean water. Distinct water masses passing through the Bering Strait are characterized both by distinctive species mixes and differing quantitative characteristics.

The author is grateful to engineer O. N. Levina of the Oceanology Institute of the USSR Academy of Sciences (Southern Branch) for her contribution to the present study.

5.2.2 Characteristics of Zooplankton Communities

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Introduction

The Third Joint US–USSR Bering & Chukchi Seas Expedition, on board the research vessel (R/V) *Akademik Korolev* (July–August, 1988), carried on investigations of mesozooplankton of the Bering Sea that had been started in 1977 on the Second Joint US–USSR Bering Sea Expedition on the R/V *Volna* (Izrael, 1983). During the 1988 expedition, investigations of mesozooplankton of the Chukchi Sea were also carried out. Along side previously investigated sampling areas East, North, and South Polygons (expeditions of Kolosova *et al.*, 1987; Kulikov, 1990), sampling stations in the Anadyr Bay, the Chirikov basin, and Bering Sea were investigated.

Materials and Methods

Samples of mesozooplankton were collected with 30-l Niskin bottles and, at the same time, at the majority of stations, with Big Jedy net (BJN) with 37-cm inlet diameter and filtering cone (168-mm mesh synthetic net). Sampling depths were those determined for combined hydrobiologic research (Timoshenkova & Kulikov, 1988)—that is, 5, 10, 25, 45, 70, and 100 m. In shallow regions, the lower level was determined by the bottom depth at the station. Because of a special

investigation of zooneuston carried out during the cruise, no samples from zero level were collected. A BJN was used for vertical tows to 100 m depth.

Samples from the Niskin water sampler were filtered through 100-mm mesh gauze. All samples of mesozooplankton were fixed by formalin to the final concentration at 4% in the sample. Identification of species found in the sample and their total number calculation were carried out in a large Bogorov chamber (10-ml) with stereoscopic binocular microscope MSC-9 (LOMO). Samples collected with water bottles were checked for individuals of size range 0.1–2.0 mm, and samples collected with nets, 2.0–20.0 mm. Fresh biomass was calculated on the basis of average individual weights of organisms and their total number (Lubny-Herzyg, 1953; Chislenko, 1968).

Mesozooplankton sampling stations were classified using the polytetic conjugating method of isolated adjunction of hierarchic nonintersectional cluster analysis on the basis of values of Checanovsky-Sjerensen generality indices (Pesenko, 1982) for quantitative data:

$$I_{cs} = \min (P_{ij}; P_{ik}); \quad (1)$$

where P_{ij} , P_{ik} is the percent of i species in the total number of mesozooplankton per m² in 0–100 m layer at j - and k -stations; and for qualitative data:

$$I_{cs} = \frac{2a}{(a+b) + (a+c)}, \quad (2)$$

where a is the number of species common for j - and k -stations; b is the number of species to be found only at station j ; and c is the number of species to be found only at station k .

Results

Species Composition and Species Complexes

Seventy-four units of hydrobionts were found as a result of analysis of samples of mesozooplankton collected in the 100-m upper layer of the Bering and Chukchi Seas (Table 1). The most diverse and numerous group of organisms—copepods (*Copepoda*)—counted 26 species and dominated plankton on the majority of stations both in number and biomass. Data in Table 1 shows that epipelagic zones of all of the investigated water areas of the Bering and Chukchi Seas are marked by an active development of populations of two eurybiontic epipelagic species of copepods (i.e., *Pseudocalanus minutus* and *Oithona similis*). Plastic species also could be found in the samples: the hydromedusa *Aglantha digitale*, appendicularians *Oikopleura labradoriensis* and *Fritillaria borealis*. Some regions are

characterized by abundance of individuals of subarctic and boreal species of organisms that form a number of species complexes (Table 2).

The calculated regions were defined on the basis of common character of taxonomic composition of the plankton (equation 2). Results of J_{cs} cluster analysis are shown in Fig. 1. At the index value of 0.75, the stations were combined into three groups; their geographic position provided for the division of the northern part of the Bering Sea into four regions with relatively homogenous taxonomic composition of mesozooplankton community. Species composition of the southern part of the Chukchi Sea had more similarity than the northern part of the Bering Sea, which is why the former was regarded as the region inhabited with taxonomically homogeneous plankton fauna.

Distribution of Mass Species Across the Study Region

Oithona similis was the most numerous of the investigated populations. It was most developed at the East Polygon, the number of copepodites of this species alone averaged 911,000 ind/m². A somewhat lower concentration was found at the South Polygon—765,000 ind/m². The number of *O. similis* in the northern part of the Bering Sea was considerably

TABLE 1

Species composition of mesozooplankton and frequency (%) of occurrence in the Bering and Chukchi Seas.

No.	Species	Areas of the Bering Sea (Station Nos.)						Chukchi Sea
		South Polygon (108-112)	East Polygon (105)	Gulf of Anadyr (7,9,11, 13,15,24, 27,32,36)	Central shelf of region (18,19, 22,35)	Western region of Chirikov basin (86, 69,96,100, 104,106)	Eastern region of Chirikov basin (83, 92,102)	
PROTOZOA								
1.	FORAMINIFERA	87	77	8				
2.	RADIOLARIA	62						
3.	<i>Noctiluca</i> sp.	31	4					
HYDROMEDUSAE								
4.	<i>Aglantha digitale</i>	69	19	27	14	27	75	20
5.	<i>Aeginopsis laurentii</i>	25	8	5		8		2
6.	<i>Platocnide borealis</i>							2
7.	<i>Rathkea octopunctata</i>			2	5	15		42
8.	<i>Obelia flabellata</i>				9			6
9.	<i>Tiaropsis multicirrata</i>			2				
10.	<i>Euphisa</i> sp.			7		8		5
11.	<i>Cunine</i> sp.						25	
SIPHONOPHORA								
12.	<i>Dimophyes Arctica</i>	25	27	2				
13.	CTENOPHORA	6	4	2	5	4		3
ROTATORIA								
14.	<i>Synchaeta</i> sp.			13	27	35	17	55
15.	<i>Trichocerca marina</i>			6				
16.	NEMERTINI	19		3	27	38	42	48
17.	<i>Nematoda</i>							3
POLYCHAETA								
18.	<i>Tomopteris pacifica</i>	63	8					
19.	<i>Thyphloscolex</i> sp.	37	12					
20.	<i>Polychaeta</i> (larvae)	50	12	42	64	100	100	92

TABLE 1 - continued

MOLLUSCA								
21.	<i>Gastropoda</i> (larvae)	56	8	10		19	33	6
22.	<i>Atlanta</i> sp.	13	15					
23.	<i>Limacina helicina</i>	69	15	10		4		11
24.	<i>Clione limacina</i>	44	15	20	14	4	11	
25.	<i>Bivalvia</i> (larvae)	31		35	27	88	75	91
CLADOCERA								
26.	<i>Evadne nordmanni</i>					8	58	2
27.	<i>Podon leuckartii</i>						42	
OSTRACODA								
28.	<i>Conchoecia</i> sp.	31	8					
COPEPODA								
29.	<i>Calanus cristatus</i>	69	15	12				
30.	<i>C. Plumchrus</i>	63	54	40		23		
31.	<i>C. glacialis</i>	19	23	48	64	58	25	53
32.	<i>Eucalanus bungii</i>	69	73	58		77	25	25
33.	<i>Pseudocalanus minutus</i>	87	81	97	100	100	100	100
34.	<i>Microcalanus pygmaeus</i>	69	53	50		23		22
35.	<i>Pleuromamma scutullata</i>	13						
36.	<i>Aetidis pacificus</i>							2
37.	<i>Racovitzanus antarcticus</i>	6						
38.	<i>Scolecithricella minor</i>	63	27	13		12		
39.	<i>Eurytemora herdmani</i>						17	6
40.	<i>E. pacifica</i>			5		27	50	2
41.	<i>Metridia pacifica</i>	87	69	67	59	58		61
42.	<i>Centropages mcmurricini</i>			2		15	83	28
43.	<i>Tortanus discaudatus</i>					15	50	5
44.	<i>Gaetanus intermedius</i>	13						
45.	<i>Epilabidocera amphitrites</i>						8	
46.	<i>Acartia longiremis</i>	19	46	48	73	100	100	87
47.	<i>A. clausi</i>					15	17	13
48.	<i>A. tumida</i>			23		46	8	34
49.	<i>A. pacifica</i>							2
50.	<i>Oithona similis</i>	100	100	95	77	96	100	91
51.	<i>O. plumifera</i>	44	19	7				
52.	<i>Oncaea borealis</i>	81	81	55	28	58	17	59
53.	<i>On. minuta</i>		8					9
54.	<i>Microsetella rosea</i>	81	31	12		4		25
55.	CIRRIPIEDIA (larvae)	6		5	9	85	100	92
HYPERIIDEA								
56.	<i>Hyperia galba</i>			2				
57.	<i>Parathemisto pacifica</i>	63	35	12		12		
58.	<i>P. libellula</i>			3	18			
EUPHASIACEA								
59.	<i>Thysanoessa longipes</i>	6	15					
60.	<i>Th. inermis</i>	25	4					3
61.	<i>Euphausiacea</i> (larvae)	25	27	22	14	38	8	28
DECAPODA								
62.	<i>Macrura</i> (larvae)		8	3		8	8	5
63.	<i>Anomura</i> (larvae)			13	5	8	17	16
64.	<i>Brachiura</i> (larvae)	6	8	25	5	12		11
65.	BRYOZOA (larvae)							6
ECHINODERMATA								
66.	<i>Ophiopluteus</i>	25		18	32	69	92	75
67.	<i>Ophiura</i> sp. Juv.	6		18	12			
68.	<i>Echinopluteus</i>	6		12		50	92	63
69.	<i>Aurigularia</i>					19	75	22
CHAETOGNATHA								
70.	<i>Parasagitta elegans</i>	69	54	28	55	46	50	44
71.	<i>Eukrohnia hamata</i>	31						
TUNICATA								
72.	<i>Oikopleura labradoriensis</i>	50	54	32	59	88	92	86
73.	<i>Fritillaria borealis</i>	56	35	23		85	100	91
74.	<i>Ascidia</i> (larvae)					19		9

Station Numbers

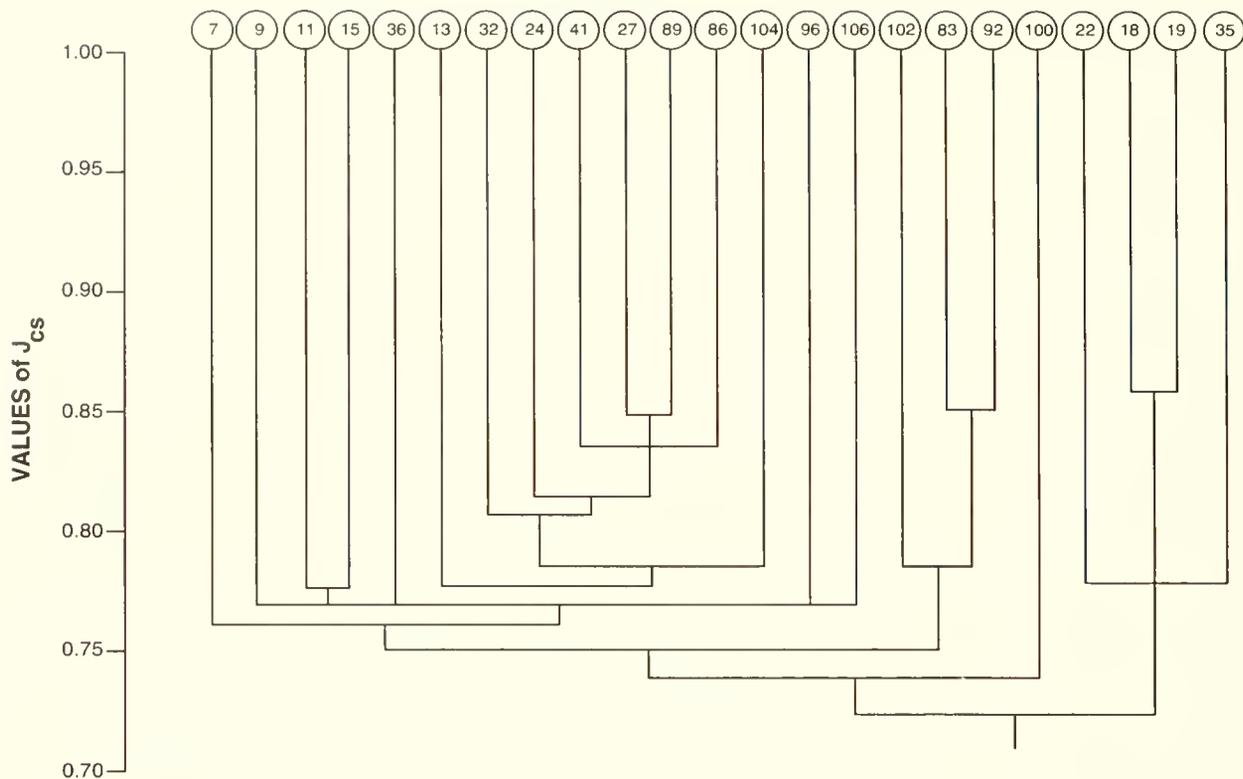


Fig. 1. Dendrogram of J_{cs} values (as for qualitative data) at stations in the Bering Sea.

TABLE 2

Composition of groups of species (complexes) of the Bering Sea mesozooplankton.

Name	Composition
South Bering Sea oceanic group (Vinogradov, 1956)	<i>Calanus cristatus</i> , <i>C. plumchrus</i> , <i>Eucalanus bungii</i> , <i>Microcalanus pygmaeus</i> , <i>Metridia pacifica</i> , <i>Scolecithricella minor</i> , <i>Oncaea borealis</i> , <i>Microsetella rosea</i> , <i>Parathemisto pacifica</i> .
North Bering Sea oceanic group (Vinogradov, 1956)	<i>Calanus glacialis</i> , <i>Parathemisto libellula</i> .
Neritic group	<i>Synchaeta</i> sp., <i>Podon leuckartii</i> , <i>Evadne normanni</i> , <i>Centropages mcmurricchi</i> , <i>Tortanus discaudatus</i> , <i>Eurytemora herdmani</i> , <i>E. pacifica</i> , <i>Acartia longiremis</i> , <i>A. clausi</i> , pelagic larvae of benthic organisms.
Anadyr group	<i>Euphisa</i> sp., <i>Acartia tumida</i> .

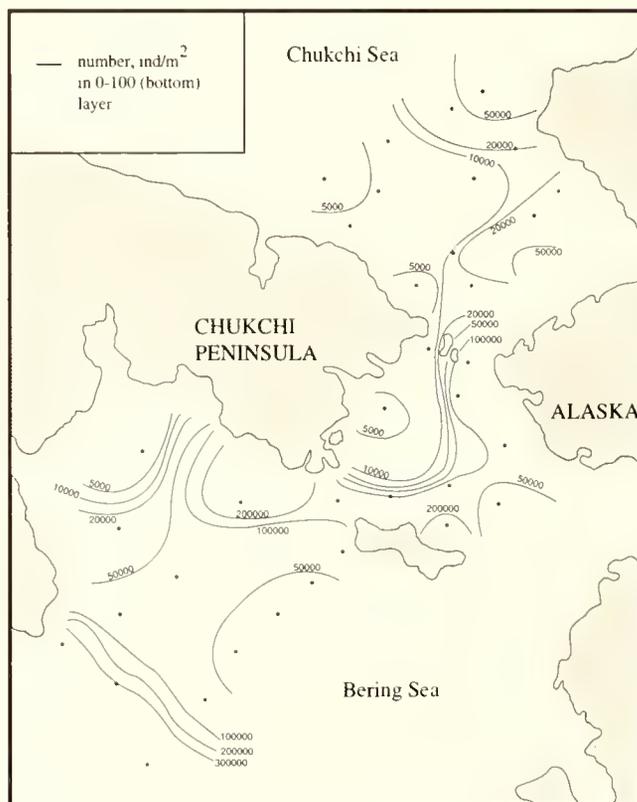


Fig. 2. Distribution of *Oithona similis* (copepodite stages) in the northern Bering and southern Chukchi Seas.

lower than in central and southern regions (Fig. 2). Deep-water stations of the region (Stations 7, 11, and 15) showed a copepod accumulation density of 330,000 ind/m². Most probably, conditions of the shelf waters of the Bering and Chukchi Seas exert a negative effect on population development. In the Gulf of Anadyr, western regions of Chirikov basin, and in Bering Strait as well as in the Chukchi Sea, population abundance did not exceed 50,000 ind/m².

Figure 3 shows the character of distribution of levels of the *Pseudocalanus minutus* population. This species is most developed in the northwest regions of investigations in the Chukchi Sea where the number of *P. minutus* population reached 470,000 ind/m². In general, the population of the shallow regions of the Chukchi Sea is two to three times more than that of the Bering Sea pelagic zone. The scattered character spatial location of populations and different sizes of copepods, which are bigger in the Chukchi Sea and smaller in the Bering Sea, suggest that there are at least two separate populations inhabiting the Bering and Chukchi Seas. The size of the Bering Sea population of *P. minutus* varies from 13 to 20,000 ind/m²; there was no significant difference between density of deep-sea and shelf accumulations. We should note that there was a coincidence of regions of the Bering Sea with decreased abundance of *P. minutus* and *O. similis* total numbers.

There was a similar distribution pattern of *Aglantha digitale* (Fig. 4). Their numbers varied from 10 to 4,000 ind/m². Developmental peaks of this species were determined by water masses situated over the depth gradient in the northwest Bering Sea, shallow regions of eastern Chirikov basin, and Bering Strait, and northwest center of the Chukchi Sea. Centers of accumulation of populations of the appendicularian *Oikopleura*

labradoriensis were found in the Bering and Chukchi Seas on the shelf. Waters of these seas are characterized by extremely low temperatures. Thus maximal abundance, over 300,000 ind/m², was found in the western Chukchi Sea that is subjected to the effect of cold arctic waters. It should be noted that the location of most numerous groups of appendicularians coincides with the region of lowest density of copepods (*O. similis* and *P. minutus*). The abundance of this species in the epipelagic zone of the Bering Sea deep-water regions did not exceed 1,000 ind/m² (Fig. 5).

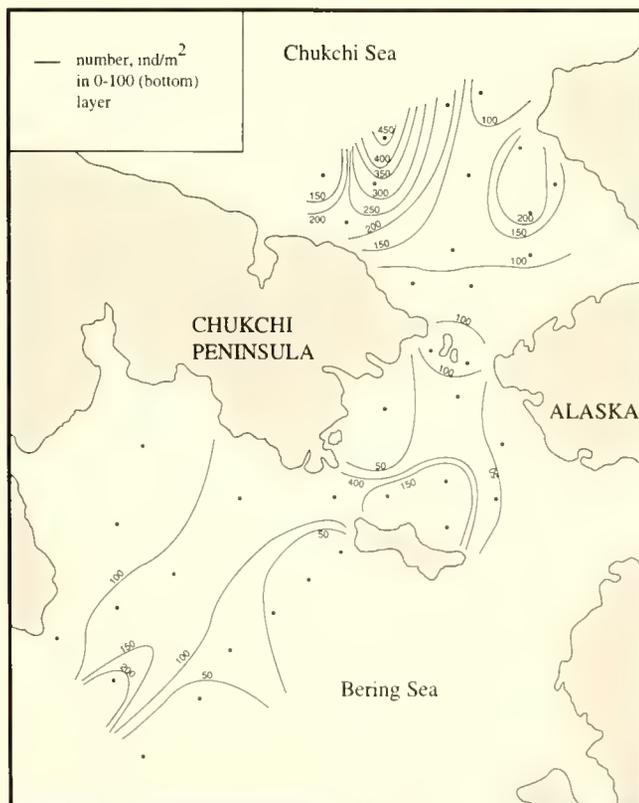


Fig. 3. Distribution of *Pseudocalanus minutus* in the northern Bering and southern Chukchi Seas.

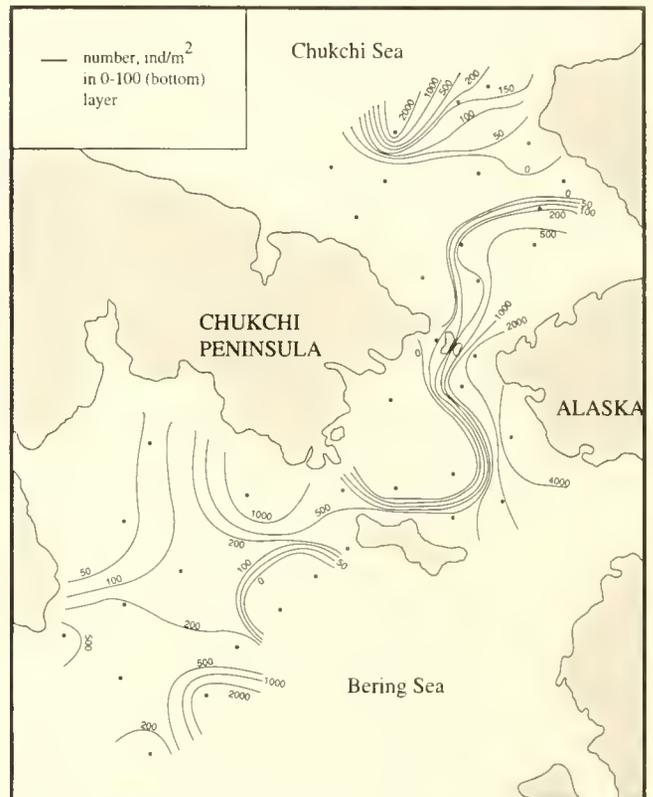


Fig. 4. Distribution of *Aglantha digitale* in the northern Bering and southern Chukchi Seas.

Another species of appendicularians, *Fritillaria borealis*, resembled the distributional pattern of *O. labradoriensis* and was found only in shelf water plankton of the Bering and Chukchi Seas (Fig. 6). Still, the boundary between regions with favorable and unfavorable conditions for *Fritillaria borealis* was situated much farther to the north, along the boundary of the central shelf region of the Chirikov basin. The highest number of *F. borealis* in the central basin equaled 300,000 ind/m². The number of this species in the Chukchi Sea did not exceed 90,000 ind/m².

Species of the south Bering Sea oceanic group showed a similar distributional pattern in the study area. As northbound oceanic waters drifted across the shallow shelf region, the number of species of the complex decreased gradually, reaching its minimum in the southern Chukchi Sea. They were transported via the western Chirikov basin and the Bering Strait.

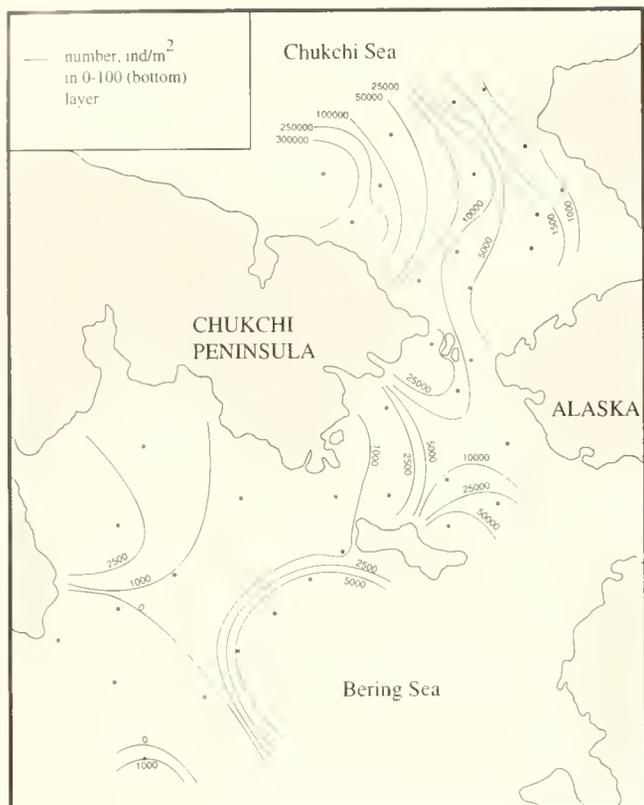


Fig. 5. Distribution of *Oikopleura labradoriensis* in the northern Bering and southern Chukchi Seas.

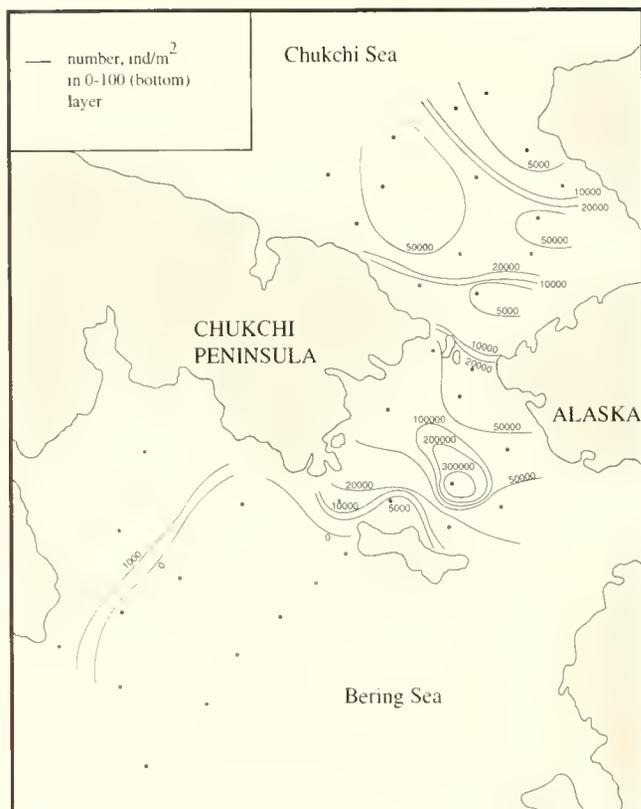


Fig. 6. Distribution of *Fritillaria borealis* in the northern Bering and southern Chukchi Seas.

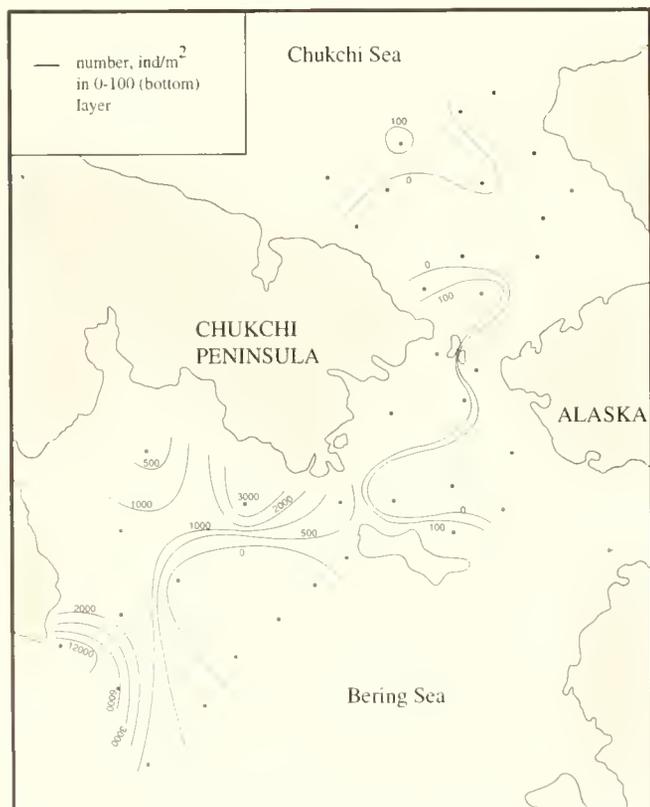


Fig. 7. Distribution of *Calanus plumchrus* in the northern Bering and southern Chukchi Seas.

The number of copepods of the outer shelf of the Gulf of Anadyr reached 3,500 ind/m². Individuals of *Eucalanus bungii* were also concentrated predominantly at deep-water sampling stations of the northwest Bering Sea (Fig. 8). In that region, the total number equaled 42,000 ind/m², while at South and East Polygons, it did not exceed 22,000 ind/m². The number of naupliar and copepodite stages of *E. bungii* reached only 16,000 ind/m².

One of the most numerous species of the southern Bering Sea oceanic group—*Metridia pacifica*—formed high conglomerations at the East Polygon (210,000 ind/m²), in northwest deep-water regions of the Bering Sea (130,000 ind/m²), and in the northern part of the study area of the Chukchi Sea (96,000 ind/m²) (Fig. 9).

Areas of habitation of Anadyr group species are limited to the shelf regions of the Bering and Chukchi Seas. The major representative of this group, *Acartia tumida*, was situated in the inner part of the Gulf of Anadyr, where this species counted 53,000 ind/m². At other stations, the number of *A. tumida* did not exceed 5,000 ind/m² (Fig. 10).

A large number of species of the northern Bering Sea oceanic group was found in the outer zone of the central shelf region (Fig. 11). The highest number of *Calanus glacialis* specimens was 35,000 ind/m²; the maximum for *Parathemisto libellula* was 190,000 ind/m². Older copepodites, *C. glacialis*, were found in the epipelagic zone of the deep-water part of the Bering Sea (Polygons East and South) only occasionally. Characteristic features of habitation of species of the neretic group across the water area of the Bering and Chukchi Seas were

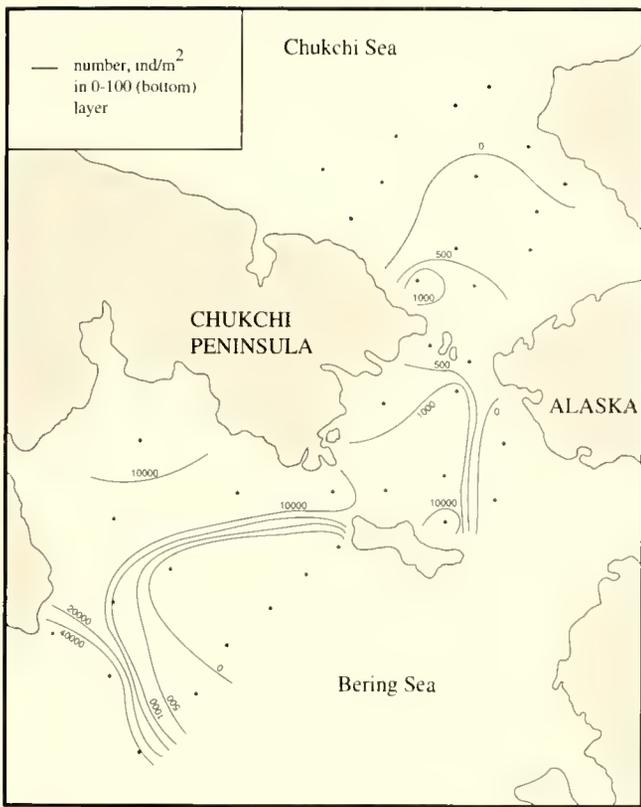


Fig. 8. Distribution of *Eucalanus bungii* in the northern Bering and southern Chukchi Seas.

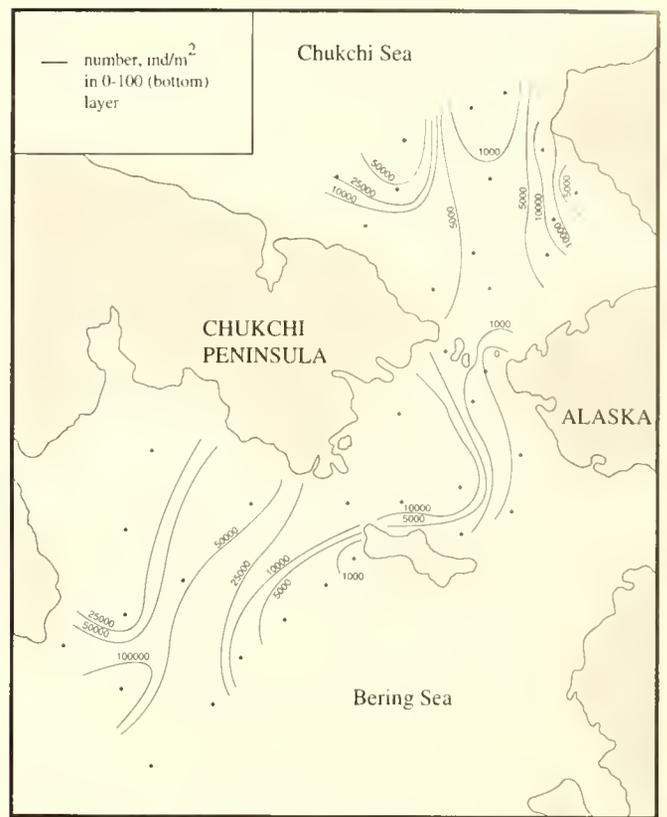


Fig. 9. Distribution of *Metridia pacifica* in the northern Bering and southern Chukchi Seas.

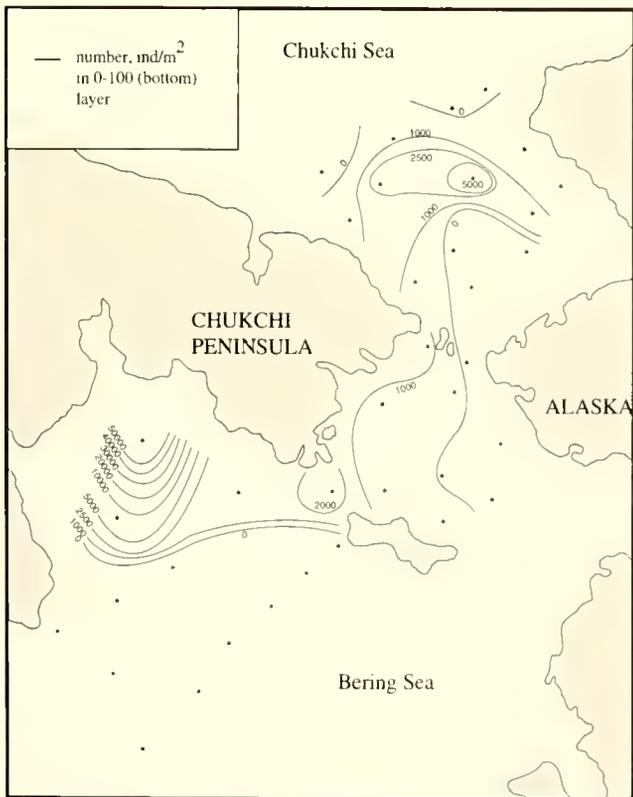


Fig. 10. Distribution of *Acartia tumida* in the northern Bering and southern Chukchi Seas.

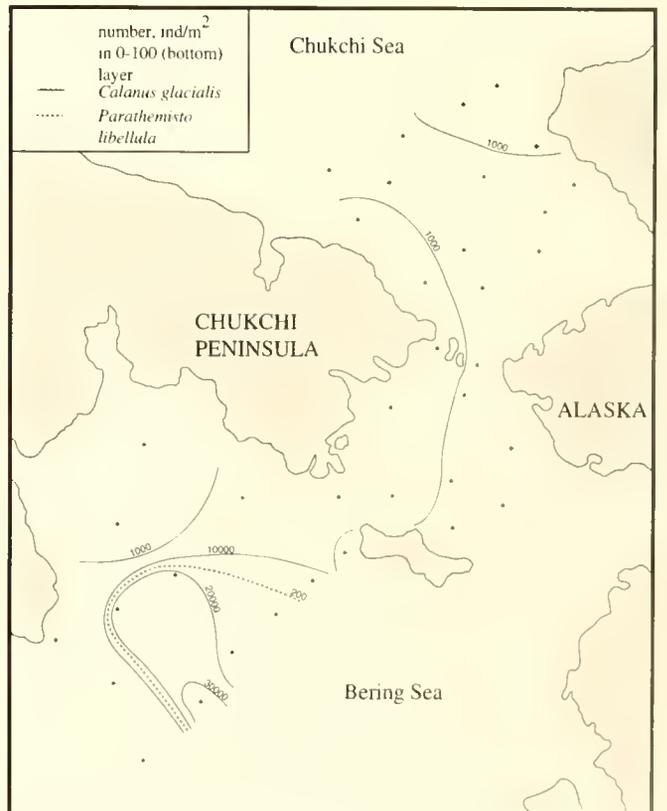


Fig. 11. Distribution of *Calanus glacialis* and *Parathemisto libellula* in the northern Bering and southern Chukchi Seas.

in a way similar. *Centropages mcmurrichi*, which is quite typical of this group, formed maximal conglomerations in the eastern Chirikov basin, the Bering Strait, and in the southern Chukchi Sea, where its total number reached 5,500 ind/m² (Fig. 12).

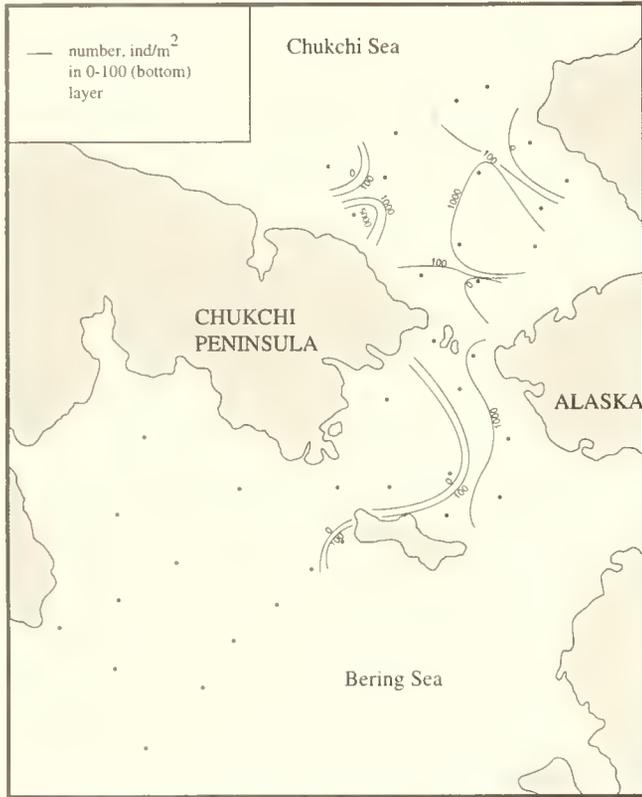


Fig. 12. Distribution of *Centropages mcmurrichi* in the northern Bering and southern Chukchi Seas.

Distribution of Total Number and Biomass of Mesozooplankton

In the central part of the Bering Sea at the eastern boundary of deep-water and shelf regions (East Polygon), the amount of the total number of mesozooplankton varied from 0.9 to 2.2×10^6 ind/m² (averaging 2.1×10^6 ind/m²) (Fig. 13). The low level of the index was attributed to the outer shelf region where the depth increased to 140 m. The highest total numbers were found at deep-sea stations of this polygon (about 3,000 m). Total biomass of the community at these stations varied within a not significant range of 25.8–31.4 g/m² (an average of 29.0 g/m²) (Fig. 14).

Total number of mesozooplankton at the South Polygon reached a somewhat lower value than that of the East Polygon — 1.8×10^6 ind/m²; biomass was at the same level — 28.7 g/m² average. In the northeastern Bering Sea, abundance of the mesozooplankton community was considerably lower than those of central and southern regions (Fig. 13). The index varied from 118 to 857×10^3 ind/m². Relatively numerous conglomerations of organisms were found in the epipelagic zone of southern and northern parts of the study area. Distribution of total biomass of animals was the same as the distribution of total abundance. At the same time, the highest biomass was in the northwest deep-sea region and totaled

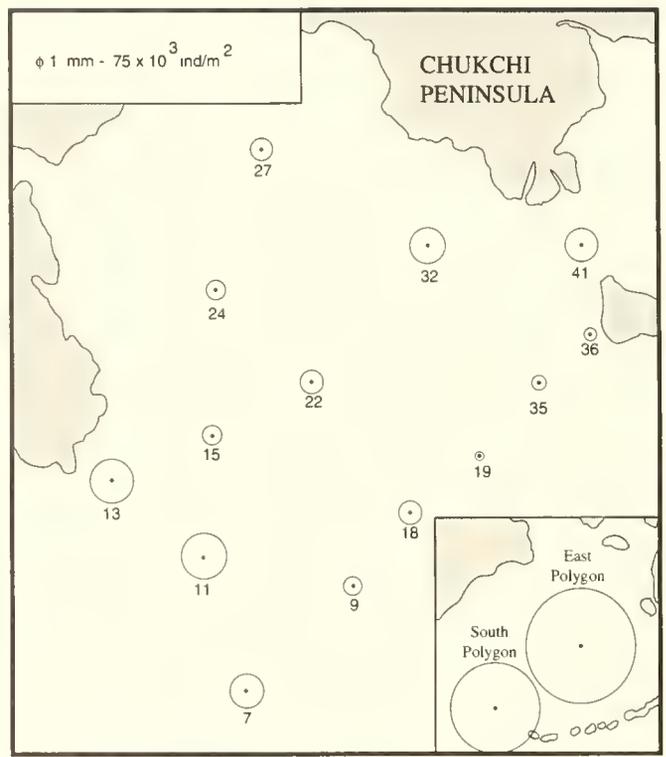


Fig. 13. Levels of total number of mesozooplankton at South and East Polygons and in the northwest part of the Bering Sea.

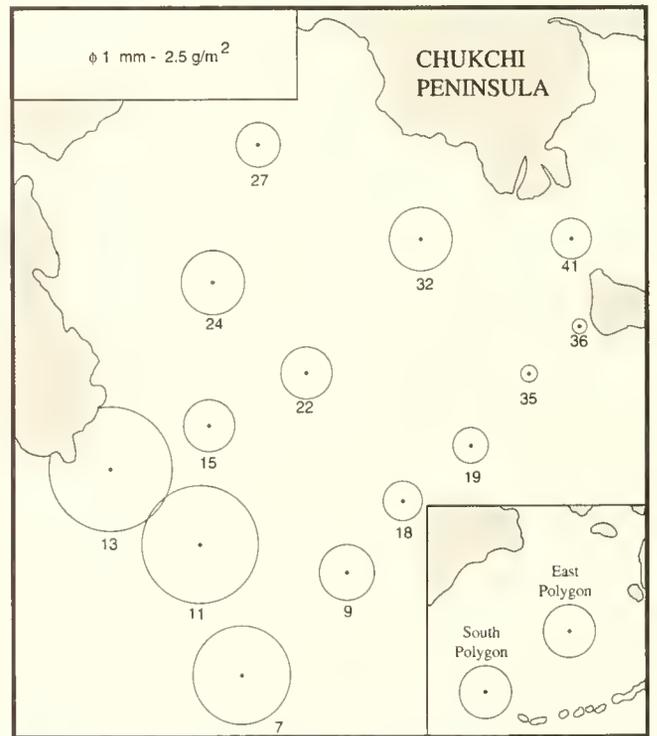


Fig. 14. Levels of total biomass (wet weight) of mesozooplankton at South and East Polygons, and in the northwest part of the Bering Sea.

65.4–82.9 g/m²; this is the highest value found during the cruise (Fig. 14).

Variability of abundance of the mesozooplankton in the Chirikov basin was enormous. In the eastern part of this region, abundance was much higher than in the western part — from 2,712,000 to 182,000 ind/m² (Fig. 15). Total biomass variation was not significant, still in the southern part of the region, they

were higher than in the north (34.9 and 6.6 g/m², respectively) (Fig. 16). Total number and biomass of mesozooplankton in the southern Chukchi Sea were small (Figs. 17,18) and equaled 696,000 ind/m² and averaged 14.8 g/m².

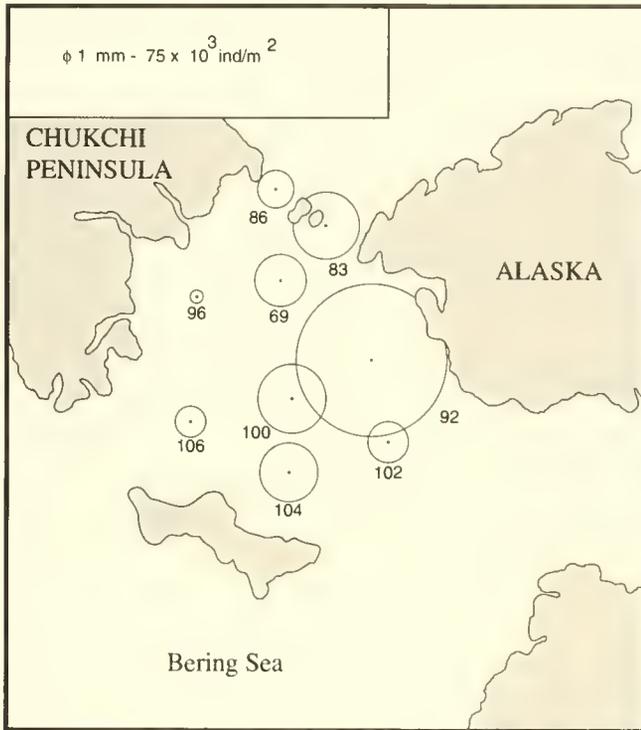


Fig. 15. Levels of total number of mesozooplankton in Chirikov basin.

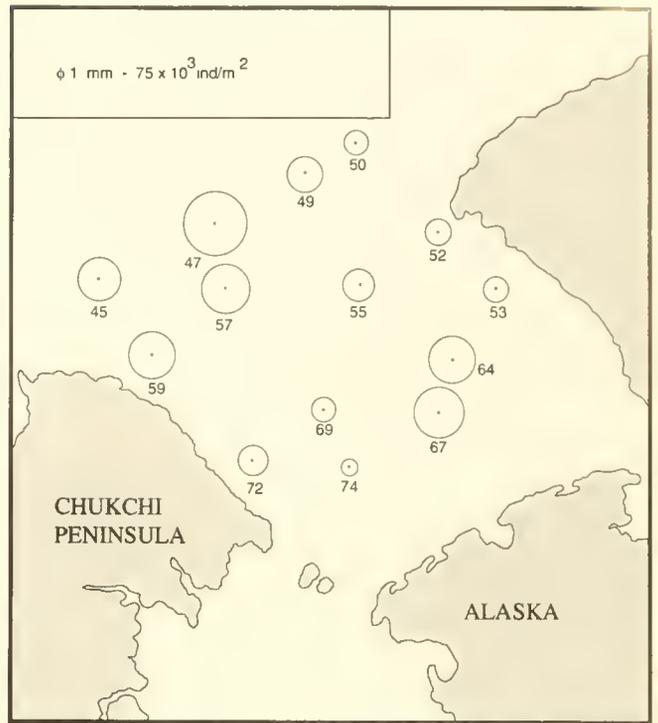


Fig. 17. Levels of total number of mesozooplankton in the southern part of the Chukchi Sea.

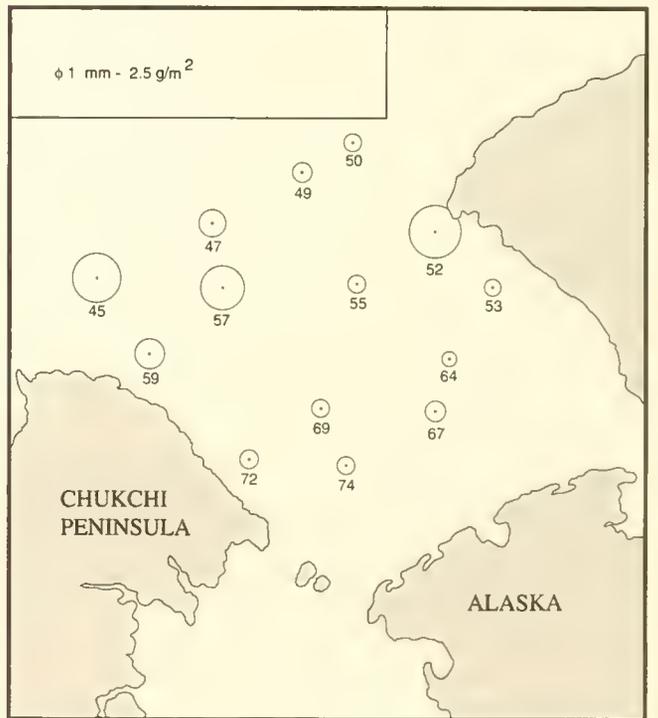


Fig. 18. Levels of total biomass (wet weight) of mesozooplankton in the southern part of the Chukchi Sea.

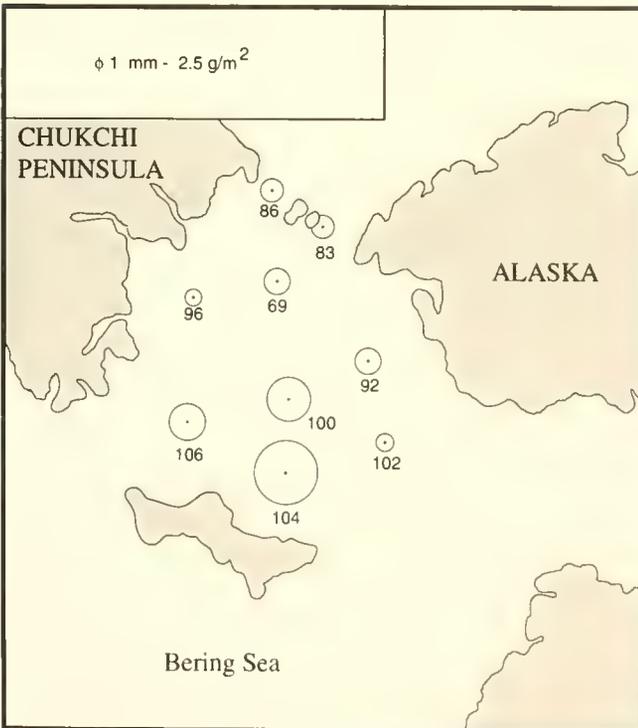


Fig. 16. Levels of total biomass (wet weight) of mesozooplankton in Chirikov basin.

Structure of Mesozooplankton Communities

On the basis of data on mesozooplankton community species composition, distribution of groups, and individual species, as well as on overall quantitative indices of condition of the mesozooplankton in epipelagic zones of the Bering Sea, several regions were defined to describe the heterogeneous character of environmental conditions (Figs. 19, 20). Analyzing the structure of the mesozooplankton community inhabiting

the epipelagic zone of the deep-water of the southwest Bering Sea, the striking similarity of species composition, dominating taxa, similar abundance, and biomass allow assessment of this vast area as a homogeneous region; that is, a continuation of the North Pacific Ocean. At the East and South Polygons, mesozooplankton abundance is considerably influenced by a population of *Oithona similis*: their number totaled 80% of the overall average. Species of the south Bering Sea oceanic group constituted only 8%. Still, these organisms, especially *Eucalanus bungii*, dominated the biomass accounting for 60% of the total weight. *Oithona similis* biomass constitutes only 13% of the total biomass of the community.

Off Cape Navarin, at depths more than 100 m (Stations 7, 11, and 13), abundance of mesozooplankton was relatively low (800,000 ind/m³). In 0–100 m water columns, total biomass reached maximum values, averaging 75 g/m³. This was attributed to a concentration of large interzonal oceanic copepods, *Calanus plumchrus* and *Eucalanus bungii*. Taken together with other species from the south Bering Sea oceanic group, they equal 24% of the total number and 78% of the total biomass of zooplankton. *Oithona similis* formed the most numerous group here totaling 59%, as well as at other deep-water Bering Sea stations. There was a tremendous increase of the absolute and relative abundance of species of *Pseudocalanus minutus* (up to 13%). At the same time, it was noted that composition of zoocenosis was influenced by the vicinity of the vast shallow shelf area. The pelagic zone of this area is inhabited with a specific plankton fauna. This influence was manifested in the presence of large numbers of hydromedusa, *Aglantha digitale*, decapod larvae, the copepods *Calanus glacialis* and *Euphausiida* larvae. Appendicularians that are abundant in shelf areas rich with phytoplankton were scarcely traced in samples.

The status of the mesozooplankton community in the southern part of the Gulf of Anadyr at the stations situated over 100-m-isobath (Stations 9 and 15) was obviously determined by hydrographic conditions of the frontal zone that separates deep-sea and shelf waters. The same frontal zone covers the outer boundary of the eastern shelf (McRoy *et al.*, 1986). While qualitative composition of the community in this region is fairly similar to that of the oceanic type, its quantitative structure is completely different. The percentage of abundance of *O. similis* in the population is drastically decreased. The amount of *P. minutus* in the community increased to 30%, and the amount of the north Bering Sea oceanic group, to 12%. Biomass of the latter totaled 73% of the overall value. Levels of abundance and biomass decreased by 1.5 times, if compared to those in the neighboring deep-sea area.

We believe that to analyze data on the distribution of the structural characteristics of the mesozooplankton community in the Gulf of Anadyr, it is necessary to take into account complexity of the hydrographic process in this region. Penetration of a branch of the Bering Slope Current into the Gulf of Anadyr from the deep-water areas of the Bering Sea, origination of the Kamchatka Current flowing southward along the coastline of Siberia, and origination of the Anadyr Current flowing along Chukchi Peninsula in the direction of the Bering Strait — all of these factors surely influence conditions and

distribution of the zooplankton community in the Gulf of Anadyr (Coachman *et al.*, 1975).

Results of the studies showed that the area of the gulf and the shelf that are adjacent to the east can be divided into two regions. The pelagic zones of these regions are inhabited by the various zooplankton communities (Figs. 19,20). In the outer waters of the gulf and the neighboring western part of the central shelf regions (Stations 18, 19, 22, 35, and 36), the number of species of the south Bering Sea oceanic group constitutes only 75% of the abundance and 3% of biomass. Larvae of benthic organisms (meroplankton) and appendicularians (respectively, 10 and 2%) were found. Appendicularians constituted up to 30% of the biomass. Eurybiontic species, *O. similis* (37%) and *P. minutus* (28%), dominated the abundance; north Bering Sea species (28%) prevailed in terms of biomass.

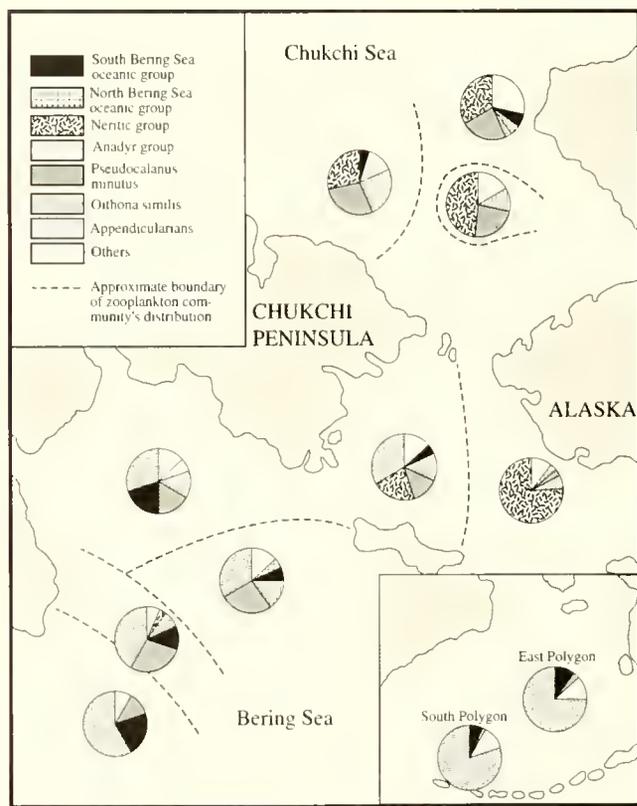


Fig. 19. Structure of mesozooplankton communities in the defined regions of the Bering and Chukchi Seas (number).

The inner part of the gulf (Stations 24, 27, and 32) was inhabited by a specific community that was marked by large differences from the community found at the stations of the outer shelf. Most of the biomass (53%) was constituted by a species of the oceanic species complex dominated by *Eucalanus bungii*. The most numerous species was *O. similis* (32%). The plankton community was characterized by the presence of the Anadyr group that includes *Euphisa* sp. and a copepod *Acartia tumida*. Their share in the total number and biomass of organisms reached 5 and 7%, respectively. One-tenth of the total value fell on meroplankton organisms. The qualitative composition of the community suggests a close relation between zoocenosis of the pelagic zone of this region and zoocenosis of

deep-water regions of the Bering Sea. It is obviously determined by penetration of waters of the Bering Slope Current into the Gulf of Anadyr. At the same time, the gulf was characterized by favorable developmental conditions of the specific Anadyr species complex. In this location, values of the total number and biomass were higher than in other areas of the northern shelf region and equaled 440,000 ind/m² and 40 g/m².

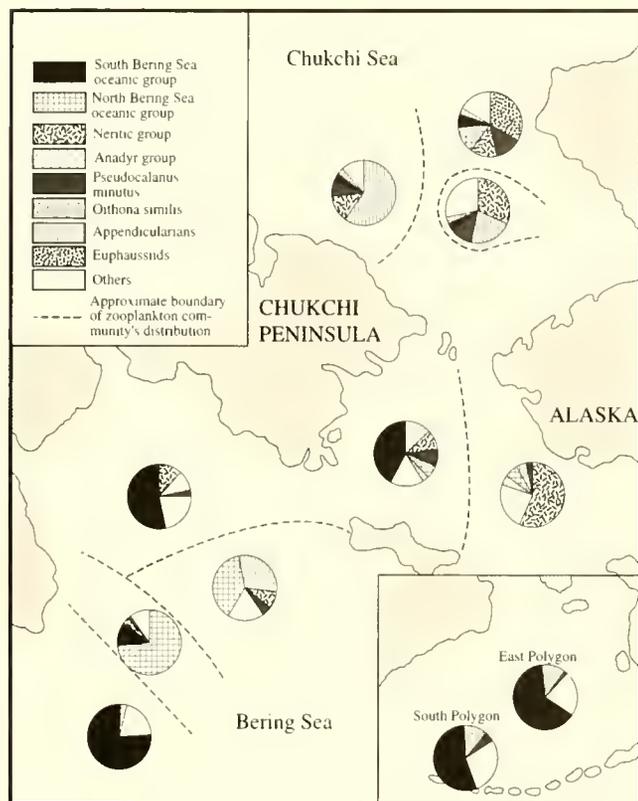


Fig. 20. Structure of mesozooplankton communities in the defined regions of the Bering and Chukchi Seas.

Another type of community similar to the Anadyr community was found in the Strait of Anadyr (Station 41). Waters of the Anadyr Current originate in the gulf and flow through the strait. Due to mixing with north Bering Sea Shelf water, we observed a decrease of the content of the south Bering Sea oceanic species that lead to the decrease of zooplankton biomass to 25 g/m² and the increase of content of the appendicularian, *Oikopleura labradoriensis*. Effects of the Anadyr waters that are inhibited with the Anadyr type communities are also marked in the western Chirikov basin and the Bering Strait (Stations 86, 89, 96, 100, 104, and 106; Figs. 19,20). The average values of quantitative indices of the community status of the region are similar to those of the Anadyr Strait. Total number of species was predominantly influenced by eurybiontic species and meroplankton (*O. similis*, 32%; *P. minutus*, 15%; meroplankton, 19%). About 50% of the zooplankton biomass of this region was constituted by the south Bering Sea species; 14%, appendicularian *O. labradoriensis*; 10%, meroplankton organisms. One can usually find small quantities of the Anadyr complex species. The highly dynamic nature of hydrographic processes in this

region cause wide ranges of variability of quantitative zooplankton parameter levels. The amplitude of variation of organism abundance equaled 182–1,001,000 ind/m², and total biomass, 12–35 g/m², while the density of plankton conglomerations per cubic meter reached the maximum value for the study period, 1.4 g at Station 104.

The mesozooplankton community in the eastern Chirikov basin and Bering Strait (Stations 83, 92, and 102) was characterized by a predominance of a neretic group of species that includes larvae of benthic animals (73% of abundance and 55% of biomass): copepods *Acartia longiremis*, *A. clausi*, *Centropages memurrichi*, *Tortanus discaurdatus*, *Eurytemora herdmanni*, *E. pacifica*; the cladocera *Evadne nordman*, and *Podon leuckartii*. These species are primarily features of the summer season (Kun, 1975). Mesozooplankton samples showed practically no species from the south Bering Sea and Anadyr complexes, nor euphasiid larvae. As a result of formation of numerous agglomerations of small neretic organisms, the total number was considerably larger than that of the western basin and equaled $1.2\text{--}2.7 \times 10^6$ ind/m², while the biomass was smaller, averaging 14 g/m².

As it was shown above, results of statistic analysis of common character of species composition of the community of mesozooplankton sampled at stations in the southern Chukchi Sea demonstrated qualitative homogeneity of the plankton fauna of the region. At the same time, the structure of the community (i.e., relative content of elements, their part in the monitored levels of total quantitative characteristics) was marked by considerable differences. Classification of stations on the basis of I_{cs} value calculated according to equation 1 allowed differentiation into three groups of stations in terms of value of the index of 0.6 (Fig. 21).

We should note that, in general, the mesozooplankton community of the Chukchi Sea Shelf was greatly affected by zoocenosis of the northern Bering Sea. It was manifested in the presence of the south Bering Sea oceanic and Anadyr groups of species at the pelagic zone. These groups were transported there most obviously by waters of the Anadyr Current (Coachman *et al.*, 1975). Although, their number was not significant and never exceeded the average of 5% of the total number and biomass of the community. Density of conglomerations of *Oithona similis* population in the Bering Sea was at the same level. Mesozooplankton of the Chukchi region of investigation had another common feature; that is, prevalence of pelagic larvae of benthic animals (average of 35% of abundance and 20% of biomass) and *Pseudocalanus minutus* (27% of abundance and 14% of biomass).

In addition to the pronounced similarity of community structure, there were certain differences in some regions. In the northwest Chukchi Sea (Stations 45, 47, 57, and 59), we detected an intensive development of population of the appendicularian *Oikopleura labradoriensis* that totaled 20% of the abundance and 57% of biomass (Figs. 19,20). This formed total index levels that are unusually high for the Chukchi Sea. The structure of community in the northwest (Stations 49, 50, 52, and 53) and south (Stations 69 and 74) regions most of all showed good agreement with the average assessments for the Chukchi Sea in general. Mesozooplankton

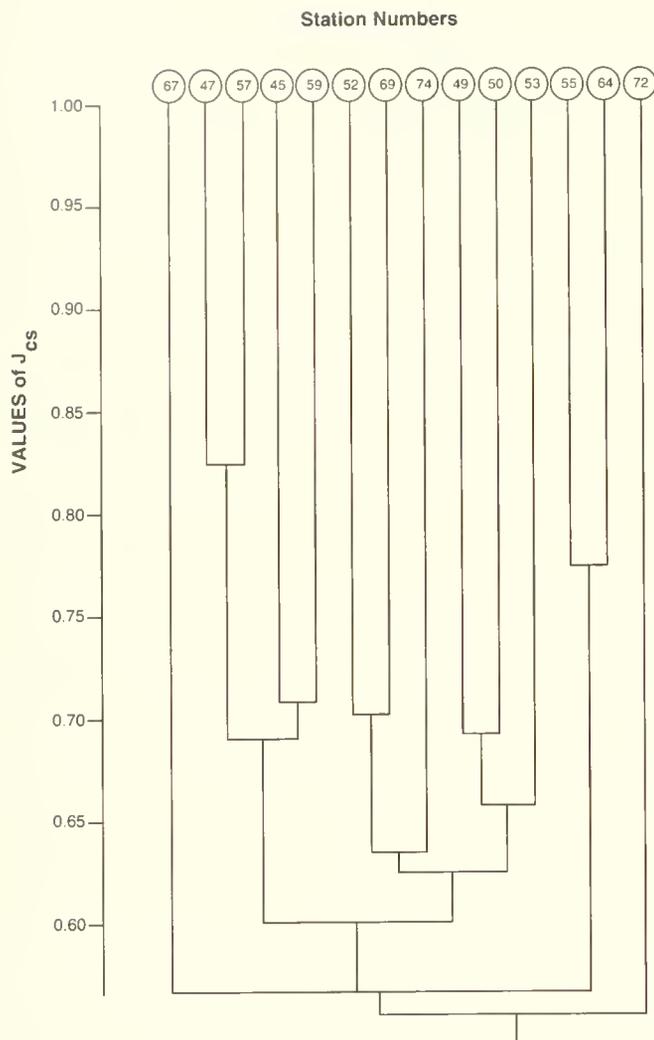


Fig. 21. Dendrogram of J_{cs} values (as for qualitative data) at stations in the Chukchi Sea.

in this pelagic zone is characterized by mass conglomerations of furcilia of euphausiids. Their share in the total biomass of zoocenosis averaged 33%.

The community of waters of central stations (Stations 55 and 64) was inhabited by meroplankton organisms (45% of number and 30% of biomass). It is believed essential to note a relatively high amount of appendicularians *Fritillaria borealis*, whose biomass exceeded the biomass of another mass species of appendicularians, *Oikopleura labradoriensis*, which dominated in the northwest region of the sea.

Discussion

Comparison of the study data and materials obtained during previous multipurpose ecologic expeditions of LAM in the Bering Sea in June 1981 and July 1984 (Kosolova *et al.*, 1987; Kulikov, 1990) testifies to an insufficient variability of qualitative and quantitative parameters of mesozooplankton communities as a result of their seasonal development. At the East Polygon (1988, August), the *Oithona similis* population reached its maximum leading to a 1.5–2.0 increase of mesozooplankton abundance. Total biomass values showed the same rate of decrease due to seasonal migration of older copepodite stages of *Calanus plumchrus* and *C. cristatus*. To the west of St. Lawrence Island, in the region of sampling stations of earlier expeditions, at the North Polygon (1988, August — Stations 32, 35, 36, and 41), we defined a zone with a high level of zooplankton biomass that was formed due to transport of a great amount of large oceanic species of copepods with the Anadyr Current. Compared to July of 1981, the situation has changed. The abundance level decreased three times, while the biomass increased two times. In the southern part of the sampling area there was a similar pattern of variation of organism abundance; still, their peak value was three times larger. Total biomass of community in this region remained relatively the same between the years.

5.2.3 Some Characteristic Features of Epipelagic Necrozooplankton Distribution

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Introduction

One of the most important indices of the biological component state of marine ecosystems at the organismic population and community level is biological characteristics, including ecological mortality (Odum, 1975). Ecological or

realizational mortality is considered to be the destruction of organisms; in particular, the conditions of the environment and its changing characteristics, in accordance with the firm conditions of habitat and state of affected populations and communities (Koval, 1984). Mortality is expressed both by the

number of organisms having died during a specific period of time and by specific death in connection with the whole number of population of organisms (Odum, 1975).

The importance of the present trend towards investigation of marine ecosystems is evident. Results from the study of mortality make it possible to estimate a number of functional characteristics of pelagic communities (Beklemishev, 1969; Vinogradov, 1970), parameters of biosedimentational processes (Zhelezinskaya, 1969; Scott, 1977; Stepanov & Svetlichnii, 1978; Lebedeva *et al.*, 1982), and peculiarities of specific and temporal distribution of plankton animals (Zhelezinskaya, 1968, 1969; Koval, 1978; Kulikov, 1990). Given the large array of negative influences by environmental factors, as well as anthropogenic ones, the process of mortality in hydrobenthic research is important in studying the ecological consequences of oceanic contamination (Sheehan, 1984; Izrael *et al.*, 1989). In this context, it is necessary to note that the show of anthropogenic effects should be preceded by determining the background of natural variability. This is realized by means of long-term baseline investigations in broad regions in the World Ocean (Izrael & Tysban, 1983). Once sufficient data on marine zooplankton mortality levels are accumulated, it is possible to determine the approximate natural mortality levels in individual areas of the ocean, thus making it possible to identify regions of mass destruction of marine organisms.

Investigations of A. F. Pasternak in the Black Sea determined that the number of dead mesozooplanktonic organisms averaged 5% of the total number of animals and 2% of their biomass (Sazjin, 1985). Similar characteristics were observed during a period of detailed ecological investigations in the Baltic Sea where the average number of dead copepods was about 5–6% of the numbers and biomass of animals (Kulikov, 1990). Mass destruction of plankton was caused by necrogenic factors from both anthropogenic and natural origins. Intensive losses of marine organisms were discovered in areas exposed to oil pollution (Vinogradov, 1970; Mironov, 1973), as well as areas of unregulated waste discharge (Grinbart *et al.*, 1976). Areas of the Baltic Sea showing levels of sulphurated hydrogen indicated high levels of death in copepods, averaging up to 13% of the total numbers and biomass of the community (Kulikov, 1990). Dead copepods found in frontal areas of upwelling, close to the shore of northwest Africa, reach 16% of total numbers (Weikert, 1977). Mortality conditions exist where brackish-water and marine planktonic complexes formed in the fronts of large rivers (Beklemishev, 1969; Koval, 1970a,b, 1984).

Present investigations into the complex Bering and Chukchi Sea ecosystems were conducted to determine the variables of mortality in the population of mesoplankton communities. They will also determine the disturbance areas showing significantly higher concentrations of dead organisms, as well as any reasons for the increases.

Materials and Methods

Mesozooplankton samples were collected using 30-l plastic Niskin bottles during the Third Joint US–USSR Bering & Chukchi Seas Expedition aboard the Soviet research vessel

Akademik Korolev (July–August, 1988). Permanent depths of sampling were 5, 10, 25, 45, 70, and 100 m. In the shallow areas, the lower horizon was determined by the depth to bottom of the station (Timoshenkova & Kulikov, 1988).

Physiological state indicators for organisms were carried out by means of painting samples with neutral or red dyes for the duration of their lifetimes in accordance with Fleming and Couchman's (1978) method (Crippen & Perrier, 1974). Samples were brought up to a volume of 100 ml and were inserted into glass jars with screw tops. Then 2 ml (0.05%) of dye was added to each sample (1:2,000) and the capped jars were put into deep water with wastewater extract for the period of 1 h. Samples were then fixed using a neutral formula with a peak concentration of 4%. Calculations measuring differences between dead and live organisms were determined by means of a microscope having a 2×8 magnification. During the course of study, the following indices were used: number of dead individuals (ind/m^2 and ind/m^3); biomass of dead organisms (mg/m^3 , mg/m^2); percent of number, identity, and biomass of dead fraction versus the total number (dead and alive); identity and biomass of the mesozooplankton community (%); ratio of the number and biomass of the dead fraction versus total number (dead and alive); and the biomass types of the total population (%). Since mesozooplankton groups of 0.1–2.0 mm intervals averaged 97% of all communities (of 0.1–2.0 mm sizes) and their total biomass was 35%, the priority was in the description of the mesozooplankton state at all levels in the pelagic community for the number of characteristics that most fully accessed the situation in the investigated areas.

Results

The vertical distribution of quantitative indices of necrozooplankton in the euphotic zone of the Bering and Chukchi Seas were distinguished by type as well as the place and location of the station in relation to the hydrographical characteristics of water masses, degree of development of zooplankton communities, depth of layers and their quantitative extremes, etc. Zooplankton numbers differed during the investigations from 0 to $7,500 \text{ ind}/\text{m}^3$ (Station 11, 25 m), and biomass reached $100.3 \text{ mg}/\text{m}^3$. The corresponding contents of dead marine organisms in zooplankton communities varied from 0 to 44.3% (Station 96, 25 m), and biomass varied from 0 to 49.9% (Station 32, 10 m).

Some general features of distribution were found. Stations that were situated in more than 2,500 m (Stations 2 and 108, East and South Polygons) had high accumulations of dead animal bodies, up to $2,800 \text{ ind}/\text{m}^3$, were related to the upper warm layer (Fig. 1), and coincided with the accumulation of the maximum number of live organisms at that depth. However, the peak percentages of dead animals in the plankton were deeper in the layer of the thermocline, the cold intermediate layer, where their numbers reached 25% of the total zooplankton. Similar vertical distribution characteristics of necrozooplankton were found in the deep region of the continental shelf (East Polygon). At other stations situated on the outer slope of the eastern (East Polygon) and northwestern shelf regions, the highest values of absolute and relative characteristics of the

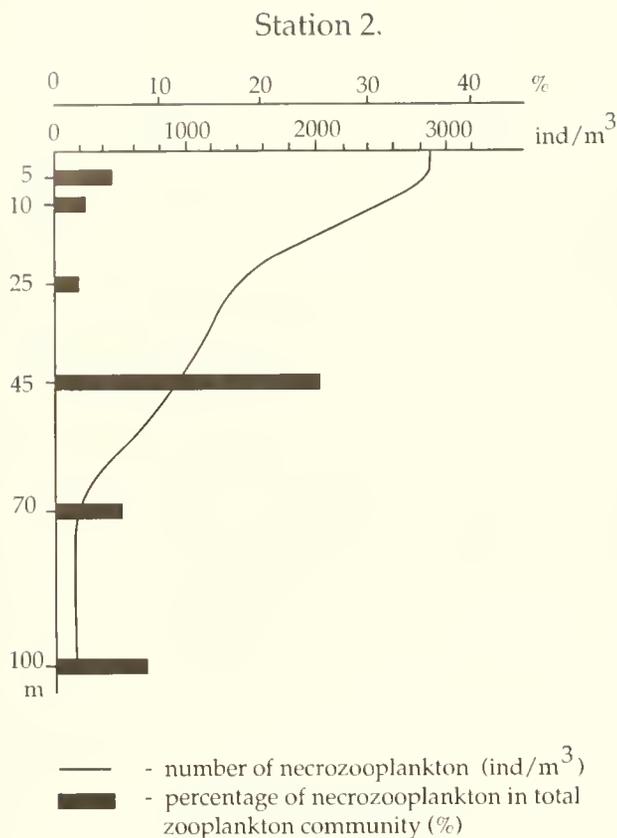


Fig. 1. Vertical distribution of necrozooplankton at Station 2.

vertical distribution of necrozooplankton coincided with depth. At Stations 5, 11, and 15, dead organisms were concentrated in the warm upper layer and upper layer of the thermocline (10 and 25 m). Here, their numbers reach 7,500 ind/m³ which constitutes 34% of the zooplankton (Fig. 2), and biomass was 100 mg/m³ or 40% of the total. The vertical structure of necrozooplankton at Stations 7, 9, and 13 were characterized by maxima in the cold intermediate layer (70–100 m; Fig. 3). The accumulation of dead animals numbered 1,100 ind/m³ (39%), and biomass, 31 mg/m³ (38%).

The vertical distribution of necrozooplankton in the shelf regions of the Bering and Chukchi Seas was similar to those found in the deep-water regions. Accumulation of dead organisms, as a rule, was located either at the surface to the discontinuous layer at a depth of 25–45 m (which divided warm upper and intermediate cold water masses) or to the 70 m layer (where there was a boundary of distribution for intermediate cold and near-bottom warm layers, as at Station 24). In the absence of stratification of water masses (homothermal and homosalinal)—for example, at Station 96—necrozooplankton were concentrated in large amounts at the near-bottom horizon, 5,400 ind/m³, forming 44% of the total number, and 27 mg/m³, comprising 35% of the total biomass. In most cases, significant high absolute numbers coincided in depth with peak percentages of the dead fractions.

Analysis of the variability in the levels of quantitative indices for necrozooplankton distribution under a square meter of surface to the layer of 0–100 m enabled the identification of zones with increased concentrations in the Bering and Chukchi

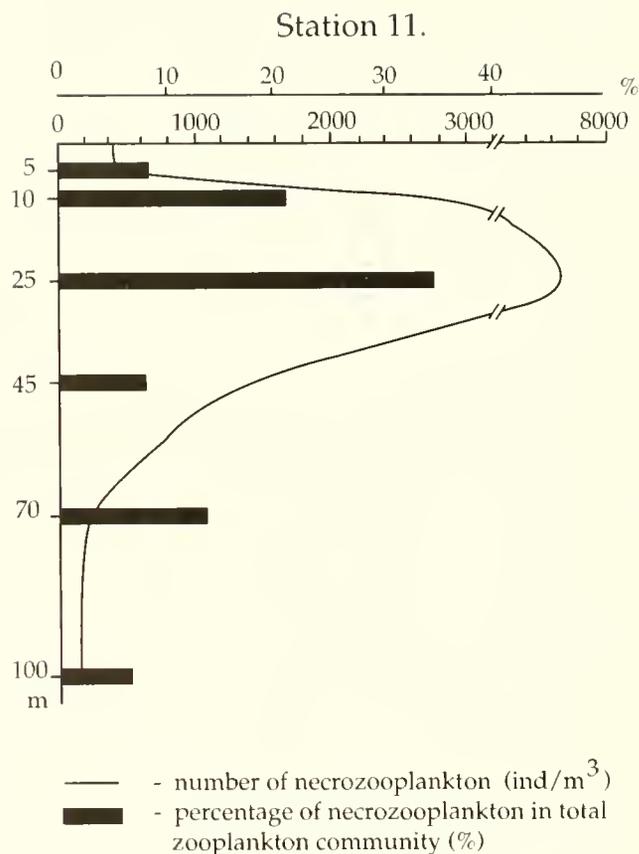


Fig. 2. Vertical distribution of necrozooplankton at Station 11.

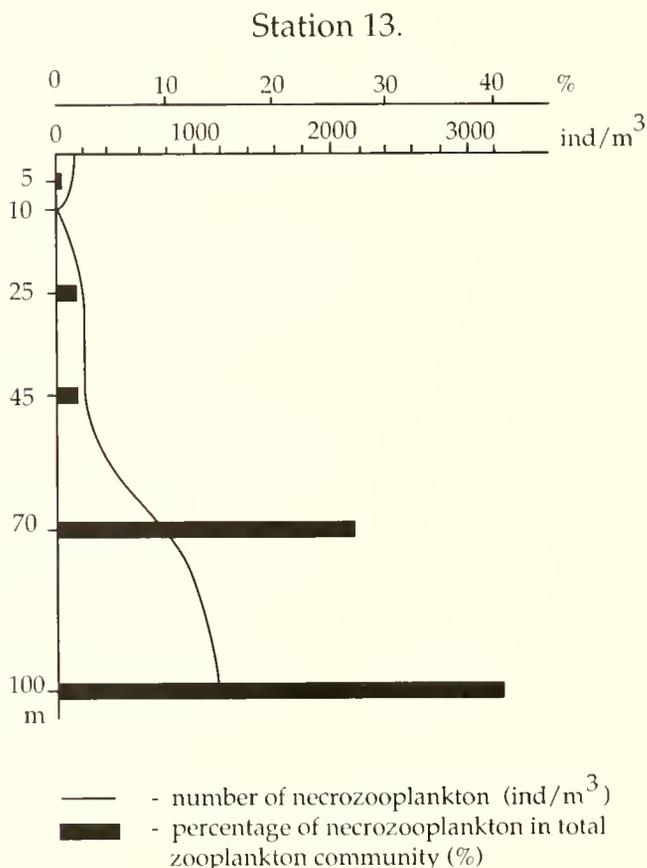


Fig. 3. Vertical distribution of necrozooplankton at Station 13.

Seas (Fig. 4). The number of dead planktonic organisms at the East and South Polygons changed from 35,100 to 93,400 ind/m², and the average was 56,900 ind/m². This feature corresponded with the total amount (3.3%) of zooplankton. Estimated biomass showed a similar percentage of the necrozooplankton.



Fig. 4. Percentage of necrozooplankton in total zooplankton community in the northern Bering and southern Chukchi Seas.

The waters of the northwestern part of the Bering Sea differed widely in these characteristics. If, at Station 7, the farthest from the edge of the shelf, readings of both the absolute and related indices coincided with those considered at the East and South Polygons, then their characteristics increased several times in those stations situated over the slope of the continental shelf. At Station 11, the number and biomass of necrozooplankton reached the highest value during the period of investigation, to reach 196,300 ind/m² and 1,534 mg/m², respectively; the percentage of dead organisms to total number of zooplankton was 20%.

The frontal zone, which covered water masses composed of deep water and shelf water and extended over the 100-meter isobath (Stations 9, 15; Coachman, 1990), differed by low levels of absolute and high levels of relative values of necrozooplankton. At the same time, when the number of dead organisms was not higher than 21,600 ind/m², their proportion in the community was 8%.

Extreme conditions inhabited by zooplankton communities in the cold water masses of the central shelf region (including Stations 18, 19, 22, 35, and 36) determined levels of dead organisms. Thus, the number of necrozooplankton, as a result

of the total lack of pelagial community, was comparatively low-to-medium, 12,100 ind/m², though about 7% of the whole community, both by number and by biomass, were not living.

The content of dead organisms in zooplankton communities in the waters of the Gulf of Anadyr, Chirikov basin, Bering Sea, and the Chukchi Sea Shelf were negligible and, except in a few individual cases, didn't exceed 5% of number or biomass. Abnormally high mortality rates, with strong evidence of desiccation phenomenon, were seen at Station 96 in the western part of the Chirikov basin. The number and biomass of necrozooplankton at this station were 22 and 19%, respectively. Some increase in mortality of plankton organisms was found in the Gulf of Anadyr, at Stations 24 and 41.

The lowest mean levels of indices were found in the shelf waters of the Chukchi Sea. Necrozooplankton in this region averaged 9,500 ind/m², and biomass, 88 mg/m² (1.7 and 1.6%, respectively). Lower total background indices were found at the central meridional section line (Stations 50, 55, and 69). The average number of dead organisms at these stations was 21,800 ind/m² (4%), and mean biomass was 223 mg/m² (4%).

The taxonomic composition of necrozooplankton in epipelagic waters of the Bering and Chukchi Seas include the major types of planktonic organisms (Table 1) and reflect the regularity of change of the types of live mesozooplankton in the study regions. A majority of the dead organisms (approximately 80%) belong to two types of copepods, *Oithona similis* and *Pseudocalanus minutus* (Fig. 5). The correlation of the number

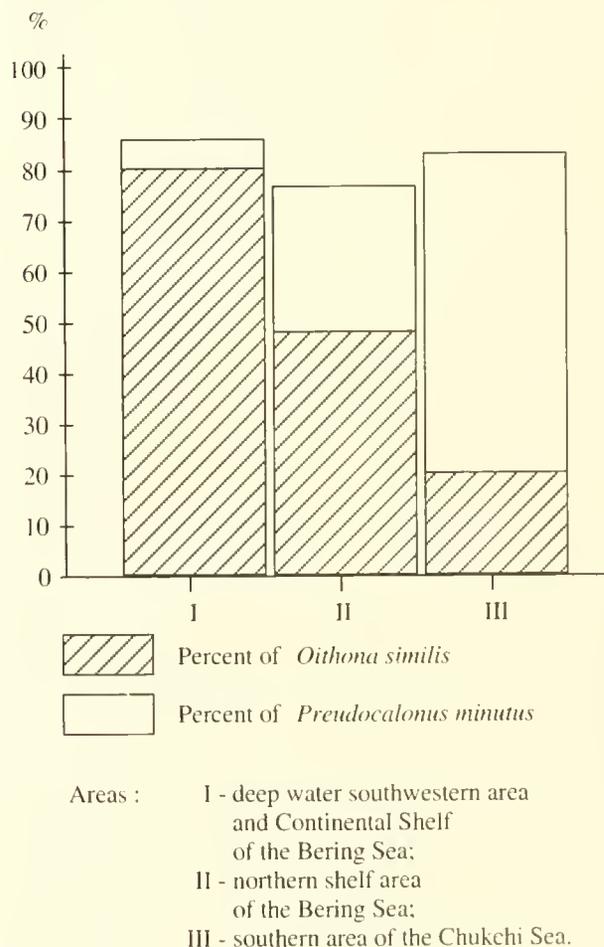


Fig. 5. Dominating types of necrozooplankton composition.

TABLE 1

Average rates of biomass contents (%) of dead organisms in populations of dominant species of zooplankton in the Bering and Chukchi Seas. [() - data gathered at one station of the area.]

Sta. No.	Species	Southwest deep water Sta. 2,4,5, 7 & 108	Continental Slope, Sta. 11 & 13	Outer shelf frontal zone Sta. 9 & 15	Gulf of Anadyr Sta. 24,27 32 & 41	West part of the Chirikov basin, Sta. 86,89,96,100 104 & 106	Central shelf Sta. 18,19,22, 35 & 36	East part of the Chirikov Sta. 83,92 & 102	Shelf of the Chukchi Sea, Sta. 45-75
1	<i>Evadne nordmanni</i>					(79.3)			
2	<i>Eucalanus bungii</i>		7.5		1.1	(100.0)	(100.0)	(50.4)	
3	<i>Pseudocalanus minutus</i>	4.8	5.7	1.4	4.7	5.8	7.0	10.5	4.1
4	<i>Microcalanus pygmaeus</i>	2.0	12.0		4.6	(15.9)			
5	<i>Metridia pacifica</i>	1.9	8.9	3.9	4.4	3.9	10.2	9.0	
6	<i>Acartia</i> sp.	47.4			3.6	2.1	(27.3)	5.4	4.3
7	<i>Acartia tumida</i>				1.1	(23.6)			
8	<i>Centropages momurrichi</i>					(100.0)		(25.3)	
9	<i>Oithona similis</i>	4.1	18.0	13.4	3.9	11.6	10.4	4.7	4.1
10	<i>Oncaea borealis</i>	4.9	20.6	9.7	8.5	27.9	1.3	(100.0)	2.2
11	<i>Cirripectida larvae</i>					16.5		0.2	0.6
12	<i>Echinodermata larvae</i>					(95.3)		1.2	
13	<i>Fritillaria borealis</i>					11.9		2.9	2.5

of dead to living species types depends upon the degree of development of the population. In the upper deep-water regions in the Bering Sea, as well as the outer zone of the northeastern shelf, the size of the dead population of *O. similis* averaged 80% of the total number of necrozooplankton, while the size of the dead population of *P. minutus* was only 6%. The shoal waters in the shelf of the Bering Sea contained 49% and 27%, respectively, of these dead organism types. In the Chukchi Sea, dead populations of *P. minutus* predominated (61%). A number of other major types, such as *Eucalanus bungii* (juveniles), *Microcalanus pygmaeus*, *Metridia pacifica*, and *Acartia* sp., also contributed significantly to the formation of zooplankton accumulation; in higher latitudes, *Oncaea borealis* made up about 10% of the total number. At the stations listed above, the structure of the necrozooplankton was destroyed and dominance was gained from types whose dead species were rarely found. In the western part of the Chirikov basin (Station 96), 73% of the dead portion of organisms were echinoderm larva; in the Gulf of Anadyr (Station 27), 36% were dead specimens of the neritic copepod, *Acartia tumida*.

Data collected on the death of specific populations of marine organisms will enable understanding of certain features of ecological relations in the study areas of the Bering and Chukchi Seas. These data are connected with the mass destruction as a result of the influence by negative external factors. In our opinion, the population condition of major types in the deep-water regions of the Bering Sea was favorable. There was a comparatively low population of dead organisms found in these areas, 5% on the average. The exception was a number of neretic copepods, *Acartia* sp., that constituted about half of the dead organisms in the biomass. High mortality was found in *O. borealis* and *O. similis*—23% and 30%, respectively. Similar situations to the two species noted were found in the middle front zone of the northwestern shelf of the Bering Sea (100 m). The western part of the Chirikov and the Gulf of Anadyr was the area of highest mortality. The high content of

dead organisms belonged to populations such as *Eucalanus bungii*, *Microcalanus pygmaeus*, *Centropages memurrichi*, *Acartia tumida*, and *Fritillaria borealis*. At Station 96, the dead population was 76% *E. nordmanni*, 43% *O. similis*, 73% *O. borealis*, and 95% echinoderm larvae. Populations of major oceanic types were affected by the strong influence of illumination in the total area northern shelf of the Bering Sea.

The high mortality level, up to 14% in areas of shelf water mass (central shelf area and eastern part of the Chirikov basin), is a characteristic feature of populations of *P. minutus*. The shallow shelf of the Chukchi Sea had low averages of necrozooplankton. The only high mortality rates found in this area were for *Metridia pacifica*, 87% (Station 55); *Eucalanus bungii*, 50% (Station 55); and *Oithona similis*, 17% (Station 45).

Conclusions

During the investigation, the number and biomass of dead organisms varied widely, from 0 to 7,500 ind/m³ and 100.3 mg/m³, respectively. The content of zooplankton communities reached 44.3% in number and 46.9% in biomass. The nature of the vertical distribution of necrozooplankton depended on the position of the stations. At deep-water stations (more than 2,500 m), dead remains of organisms accumulated, through the process of biosedimentation; in colder deep layers, these remains were from animals that died in the upper warm layer, the layer of highest concentration of living organisms. At the majority of the stations situated on the outer shelf of the eastern and northwestern Bering Sea, necrozooplankton concentrated in the horizons where mortality occurred. The reasons for this may be low biosedimentational rates or the high intensity of organism death. In the stratified waters of the shallow shelf regions of the Bering and Chukchi Seas, the ratio of dead animals was related to water mass boundaries, due to the absence of near-bottom horizons. Highest levels of

necroplankton relative to communities in the northwestern part of the Bering Sea were, at the outer continental shelf, 20% of the total number; at the frontal zone over the 100-m isobath, 8% of the total; and 7% of the total in the cold water mass of the central shelf area. These regions are joined either by extreme characteristics of the plankton community in the North Bering Sea Shelf and Pacific basin or in the extremely low temperature conditions of the water, which are near freezing.

In the deep water area of the Bering Sea, the condition of the major oceanic populations were normal. The average of

total dead specimens was 5% of total numbers. On the outer and northwestern shelf of the Bering Sea, the population of oceanic species appeared here together with Anadyr Current waters. As a result of the impact of unfavorable factors and intensive illumination, it is necessary to note that there is a high level of dead organisms of both oceanic and neritic types associated with the Anadyr Current. In the Chukchi Sea, necrozooplankton were at background levels with low mean values found during the entire period of study.

5.2.4 Carbon Isotope Ratios in Zooplankton as Markers of Aging and Habitat Usage for the Bowhead Whale (*Balaena mysticetus*)

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Introduction

The Third Joint US-USSR Bering & Chukchi Seas Expedition was used to obtain zooplankton samples from the two seas for stable isotope abundance studies. This paper presents the $d^{13}C$ and $d^{15}N$ data acquired from the cruise on board the Soviet research vessel *Akademik Korolev*, in context with previous data on stable isotope values in arctic zooplankton. Although the nitrogen isotope data are also listed, we have confined the discussion to the more comprehensive carbon isotope data. Recent findings have shown that distinctive gradients exist in the stable isotope ratios of carbon in zooplankton from the Bering to the eastern Beaufort Seas. With increasing latitude, the heavier isotope is less abundant in the phytoplankton and this "signature" is passed up the food chain. We have been using these natural tracers to determine critical feeding habitats for bowhead whales (*Balaena mysticetus*) and to aid in separating US and USSR polar bear stocks that commingle in the Chukchi Sea during the winter months. The work on bowhead whales has been described in Schell *et al.* (1989a,b) and Saupé *et al.* (1989). The study on polar bears is still in progress.

Isotope Ratios in Food Web Studies

Ecosystem studies involving biochemical systems usually depend upon two approaches. One approach is to construct budgets or mass balances of a key element and attempt to determine which fluxes dominate these budgets. The second approach measures the key rates or processes within the system and then attempts to relate the findings to the overall goal. Although ideally the two approaches should be complementary and finally coalesce into a better understanding of the ecosystem, this goal is usually difficult to attain. There may be mismatches

between time and space scales of the two approaches or processes that cannot be determined to the required accuracy. Many of these quandaries are evident in any attempt at estimating the feeding requirements of bowhead whales. Because stable isotope ratios can contribute both source (tracer) information and process information, they are ideally suited for the measurement of elemental movements, which in this case is carbon.

The field of stable isotope tracers has steadily expanded and a wealth of information on terrestrial and aquatic applications is now available. Fry and Sherr (1984) and Peterson and Fry (1987) review these applications and discuss the strengths and weaknesses of the many studies. There will be no attempt here to review all of these applications, but several pertinent findings will be presented. Rundel *et al.* (1989) presented a series of papers on various applications including several multiple isotope tracer studies.

The fidelity of consumers to the isotopic compositions of diet underlies all ecological studies using stable isotopes. DeNiro and Epstein (1978) plotted diet versus consumer isotope ratio and found that the transfer was conservative with regard to the whole animal. A small enrichment occurs of about one part per thousand per trophic step, typically slightly larger with herbivores and less with carnivores. This has been documented in both field and laboratory studies (see review by Peterson & Fry, 1987; McConnaughey & McRoy, 1979). A succinct report by Jones *et al.* (1981) documents the change in isotope ratios of cattle fed C-3 plants, then changed to C-4 plants, and then switched back again. Within 70 days, newly grown hair had reached equilibrium with the new diet after each change. Since the hair required several days to reach the surface of the skin following shaving, actual response was faster than the isotope ratios in the shavings indicated.

Within organisms, the complex pathways of biosynthesis can alter the isotope ratios in the end products relative to starting materials. The distribution of carbon isotopes has been studied by several authors (DeNiro & Epstein, 1978; Jones *et al.*, 1981; Tieszen *et al.*, 1983; Mizutani & Wada, 1988). Muscle tissue tends to closely approximate diet whereas keratinous proteins (hair, feathers, and hooves) are typically enriched by 2–3 ‰ relative to diet. Schell *et al.* (1989b) found that keratin in baleen averaged about one part per thousand heavier than muscle, which in turn was about 6 ‰ heavier than lipids. Polar bears, which are 1–2 trophic levels above bowhead whales, also show an enrichment in keratin $\delta^{13}\text{C}$ of 1–2 ‰ relative to the whales. As more and more studies are performed on ecosystem processes, the usefulness of stable isotope ratios as tracers has become increasingly evident.

Background

The initial work on this project commenced in 1985 and sought to establish the significance of the eastern Alaskan Beaufort Sea in the annual energy budget of bowhead whales. One approach to answering this question was to use the geographical differences in the stable isotope ratios (carbon and nitrogen) in whales and their prey organisms as natural tracers of food sources.

Natural history investigations of the large baleen whales present formidable problems due to the difficulties in observing the animals in their natural environments. Schell *et al.* (1989a) demonstrated, however, that bowhead whales have marked annual oscillations in stable carbon and nitrogen isotope ratios along the length of the baleen plates in the mouth. These oscillations result from the annual migration of the animals from wintering grounds in the Bering Sea to the summering areas of the Canadian Beaufort Sea. Zooplankton along the migrational path have differing isotopic ratios of carbon and nitrogen, which are reflected in the composition of the keratin in the continuously growing baleen plates. Since up to 20 years feeding record may be present in the plate of a large bowhead whale, considerable insight may be gained on the natural history of the whales and their habitat usage. We have reported (Schell *et al.*, 1989a,b; Saupe *et al.*, 1989) on the isotopic ratios in zooplankton prey that produce the large variations in *B. mysticetus* and a revised growth rate for *B. mysticetus*, determined through isotopic aging techniques.

The stable isotope abundances in baleen oscillate in a regular pattern along the length of the plate in response to the compositional changes in the whale food (zooplankton) as the animal migrates. The isotope ratios in the baleen — and especially in the muscle and visceral fat of animals killed in the spring compared to those killed in fall — show that the greatest amount of food consumed by *B. mysticetus* matches the isotopic abundances typical of prey species in the western and southern areas of the migratory range. The average ^{13}C isotope value in visceral fat and muscle tissue from spring-killed *B. mysticetus* was enriched by 2.1 ‰ relative to two fall-killed animals, implying that a major fraction of the total carbon of the animal was derived from the western and southern parts of their annual range. Although it is impossible to accurately estimate the

relative amounts of food that the whales obtain from the Beaufort versus Chukchi versus Bering Seas (because of the close similarity of zooplankton isotope ratios in the Bering and Chukchi), these data contrast with previous feeding scenarios that suggested that bowheads fed in the summer in the eastern Beaufort Sea and relied almost entirely on stored reserves for the winter (Lowry & Frost, 1984).

The isotopic data from three adult whales analyzed indicate that these large whales have an average isotopic composition derived from prey obtained almost entirely in the western and southern parts of their range (Schell *et al.*, 1989b). This might mean that the eastern Beaufort Sea is not nearly as important a feeding area for this segment of the population as the western Chukchi and the Bering Seas.

The findings listed above are based on a limited number of whale samples. Nevertheless, the results are sufficiently contrary to previously accepted growth rates and feeding scenarios that it is important that the data base be expanded to substantiate or disprove the indicated findings. The work performed on the cruise in 1988 sought to expand the zooplankton data from around the range of the bowhead, especially from the missing areas in the western Chukchi and the northwest Bering Seas, and to provide further insight regarding the cause of the isotopic shift between the southwestern and northeastern segments of the migratory range. The data collected on this cruise are part of the necessary samples required to fill the data gaps in the natural history of important marine mammals living in waters shared by the United States and the Soviet Union.

Objectives of the 1988 Akademik Korolev Cruise

Our overall goal was to use the isotopic gradients in the Bering–Chukchi–Beaufort Seas to determine the habitat dependencies and feeding strategies of the bowhead whale. By comparing the carbon isotope ratios in bowhead tissues with that in their prey organisms along the migratory route, we can establish, at least qualitatively, the importance of the various habitats to the animals. The objectives of this expedition were to:

1. Obtain zooplankton for isotope analysis from the western (USSR) sector of the Bering and Chukchi Seas for comparison with zooplankton from eastern waters.
2. Interpret and synthesize new data in context with past findings to confirm or deny current interpretations of bowhead whale natural history with special reference to the role of the Bering–Chukchi Seas as feeding habitat.

Methods

Zooplankton were collected using ring nets with 505 mesh at the stations shown on Fig. 1 and listed in Table 1. Upon collection, samples were sorted to major taxonomic groups and to species where identification was feasible in the field. Samples were then frozen for later processing in the laboratory at Fairbanks. Procedures for sample handling and mass spectrometry are described in Schell *et al.* (1987). Milligram amounts of dried zooplankton were ground with CuO (750 mg) and sealed into evacuated quartz tubes. Following combustion

at 900°C for 1.5 h, the tubes were cooled and opened on a high-vacuum line. The carbon dioxide and nitrogen gases were cryogenically separated and the ratios of $^{13}\text{C}:^{12}\text{C}$ and $^{15}\text{N}:^{14}\text{N}$ determined with a VG ISOGAS isotope ratio mass spectrometer.

region. Figures 1 and 2 show $\delta^{13}\text{C}$ values for euphausiids and copepods from the stations sampled on board the *Akademik Korolev*. These data are compared with the previous findings by Saupé *et al.* (1989).

The isotope data do reveal that the mean $\delta^{13}\text{C}$ values of both copepods and euphausiids were depleted by approximately 1 ‰ when compared to the Bering Sea data of Saupé *et al.* (1989). Also substantiating the findings of Saupé *et al.* (1989), the euphausiids were again enriched by 1.1 ‰ relative to copepods from the same area. The lack of regional differences in the Bering–Chukchi data would seem to indicate that the observed depletions in the 1988 samples were areawide. It is noteworthy that the $\delta^{13}\text{C}$ values in the baleen plates of the bowhead whales collected over the past few years show multi-year trends that are similar between animals. This would indicate that the shifts in $\delta^{13}\text{C}$ are caused by an environmental or floristic change at the primary producer level and are not due to shifts in biomass fraction in the zooplankton prey of the whales or shifts in feeding preferences by the whales. We do not yet know the cause of these changes.

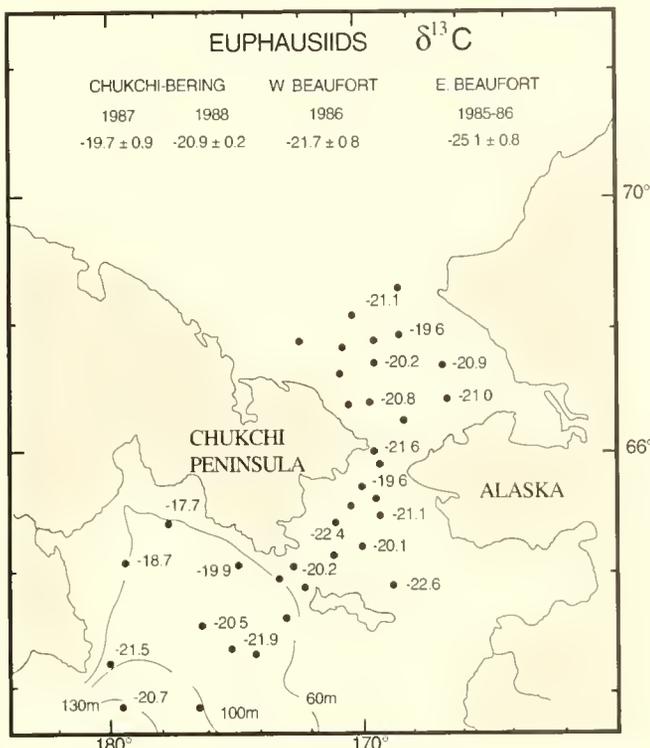


Fig. 1. Station locations and distribution of euphausiid $\delta^{13}\text{C}$ values from the 1988 *Akademik Korolev* cruise. Average $\delta^{13}\text{C}$ values listed are from Chukchi–Bering, western and eastern Beaufort Seas from 1985 to 1988, (from Saupé *et al.*, 1989).

Results and Discussion

The samples collected from the *Akademik Korolev* in 1988 are listed in Table 1. The data confirm the general patterns found by Saupé *et al.* (1989) and show that a consistently enriched $\delta^{13}\text{C}$ fauna are present in the Bering Sea relative to the Beaufort Sea. The data were separated into general taxonomic groups and compared by region (Chukchi Sea versus Bering Sea) and by subregions (eastern versus western Bering Sea, etc.) using nonparametric statistics. The comparisons showed that no significant regional differences exist in the isotope ratios of the zooplankton from the Bering and Chukchi Seas. Although the samples span both the Anadyr and Alaska Coastal water masses, no significant difference was found between any of these adjacent waters. However, there are significant differences in the isotopic ratios when similar taxa are compared from the Bering–Chukchi region and the eastern Beaufort

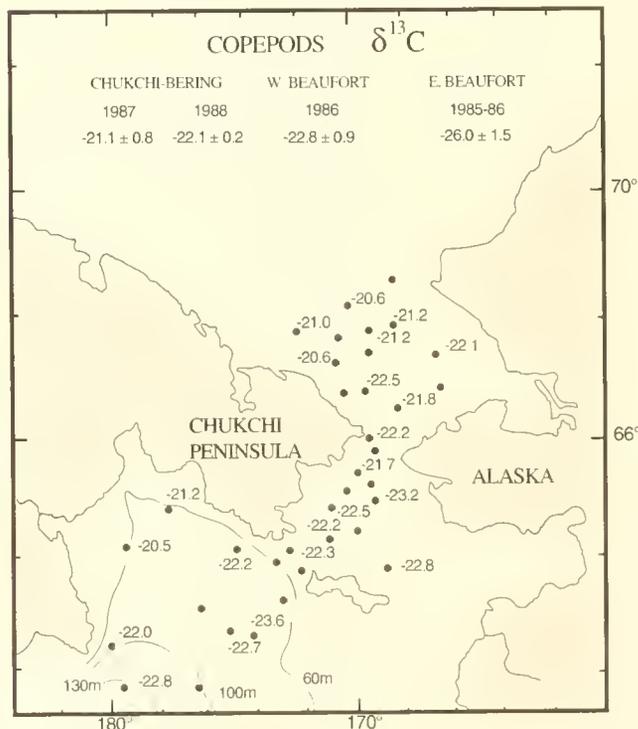


Fig. 2. Station locations and distribution of copepod $\delta^{13}\text{C}$ values from the 1988 *Akademik Korolev* cruise. Average $\delta^{13}\text{C}$ values listed are from Chukchi–Bering, western and eastern Beaufort Seas from 1985 to 1988 (from Saupé *et al.*, 1989).

TABLE 1

Samples collected from the *Akademik Korolev* in 1988.

TAXA	STATION	LAT. °N	LONG. °W	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
<i>Ampelisca</i> sp.	61	67 20.0	169 45.0		8.58
<i>Ampelisca</i> sp.	69	67 00.0	168 43.9	19.18	9.36
Amphipod, <i>Gammaridae</i>	45	67 44.0	172 50.0	19.60	
Amphipod, <i>Gammaridae</i>	59	67 09.2	172 59.8	17.86	13.47
Amphipod, <i>Gammaridae</i>	100	64 22.6	169 10.9		12.27
Amphipod, <i>Gammaridae</i>	100	64 22.6	169 10.9	20.22	8.17
Amphipod, <i>Gammaridae</i>	25	64 00.0	179 20.0	19.99	8.50
Amphipod, <i>Gammaridae</i>	61	67 20.0	169 45.0	17.76	12.19
Amphipod, <i>Hyperiididae</i>	6	59 30.0	179 30.0	21.71	8.20
Amphipod, <i>Hyperiididae</i>	104	63 50.7	169 12.3		9.54
Amphipod, <i>Hyperiididae</i>	38	63 55.0	173 35.0	21.62	9.58
Amphipod, <i>Hyperiididae</i>	22	63 00.4	176 00.1	24.82	11.57
Amphipod, <i>Hyperiididae</i>	20	62 34.7	175 03.5	23.68	
Amphipod, <i>Hyperiididae</i>	32	64 00.0	175 00.0	22.19	9.85
Amphipod, <i>Hyperiididae</i>	95	64 58.2	169 58.6	21.60	11.23
Amphipod, <i>Hyperiididae</i>	11	61 35.0	178 39.0	20.61	11.56
Amphipod, <i>Hyperiididae</i>	40	64 07.5	172 32.2	22.85	9.90
Amphipod, <i>Hyperiididae</i>	9	61 20.1	176 03.2	22.36	12.01
Amphipod, <i>Hyperiididae</i>	107	64 23.0	171 39.0	22.01	
Amphipod, <i>Hyperiididae</i>	13	62 11.0	179 51.0	21.88	11.03
Amphipod, <i>Hyperiididae</i>	110	53 55.6	176 00.0E	24.87	
Amphipod, <i>Hyperiididae</i>	27	64 43.3	177 48.2	21.23	9.98
Amphipod, <i>Hyperiididae</i>	88	65 21.6	169 59.3	23.22	
Amphipod, <i>Hyperiididae</i>	86	65 56.3	169 22.9	23.75	
Amphipod, <i>Hyperiididae</i>	74	66 33.0	168 36.0	23.16	
<i>Sagitta elegans</i>	47	68 06.0	170 53.0	20.74	12.82
<i>Sagitta elegans</i>	22	63 00.4	176 00.1	22.63	11.98
<i>Sagitta elegans</i>	107	64 23.0	171 39.0	21.29	9.96
<i>Sagitta elegans</i>	61	67 20.0	169 45.0	20.19	11.18
<i>Sagitta elegans</i>	56	67 44.2	169 55.6	21.27	8.84
<i>Sagitta elegans</i>	58	67 30.5	172 11.4	20.33	12.58
<i>Sagitta elegans</i>	6	59 30.0	179 30.0	22.22	11.33
<i>Sagitta elegans</i>	96	65 05.0	170 44.0	21.45	
<i>Sagitta elegans</i>	110	53 55.6	176 00.0E	23.99	
<i>Sagitta elegans</i>	86	65 56.3	169 22.9	20.40	10.94
<i>Sagitta elegans</i>	9	61 20.1	176 03.2	21.58	15.13
<i>Sagitta elegans</i>	85	65 50.0	169 10.0	20.92	10.70
<i>Sagitta elegans</i>	32	64 00.0	175 00.0	21.36	14.84
<i>Sagitta elegans</i>	73	66 44.0	171 05.0	19.92	13.53
<i>Sagitta elegans</i>	60	67 15.7	170 49.6	20.73	
<i>Sagitta elegans</i>	50	68 39.7	168 20.0	20.22	11.20
<i>Sagitta elegans</i>	11	61 35.0	178 39.0	21.30	11.01
<i>Sagitta elegans</i>	38	63 55.0	173 35.0	21.24	11.65
<i>Sagitta elegans</i>	13	62 11.0	179 51.0	21.16	12.66
<i>Sagitta elegans</i>	19	62 25.5	174 00.2	20.67	11.93
<i>Sagitta elegans</i>	20	62 34.7	175 03.5	22.26	15.49
<i>Sagitta elegans</i>	87	65 24.5	170 21.5		11.39
<i>Sagitta elegans</i>	95	64 58.2	169 58.6	20.50	12.68
<i>Sagitta elegans</i>	64	67 17.8	166 42.6	22.17	10.78
Composite Zooplankton	47	68 06.0	170 53.0	21.61	8.98
Composite Zooplankton	87	65 24.5	170 21.5	20.52	9.28
Composite Zooplankton	85	65 50.0	169 10.0	22.14	10.89
Composite Zooplankton	86	65 56.3	169 22.9	20.85	10.44
Composite Zooplankton	71	66 44.0	171 05.0		9.69
Composite Zooplankton	97	64 44.9	171 29.7	21.45	9.41
Composite Zooplankton	40	64 08.0	172 30.0	21.99	9.89
Composite Zooplankton	57	67 42.6	171 20.7	21.14	8.96

TABLE 1 - continued

Samples collected from the *Akademik Korolev* in 1988.

TAXA	STATION	LAT. °N	LONG. °W	$\delta^{13}\text{C}$ ($^{\circ}/_{\text{‰}}$)	$\delta^{15}\text{N}$ ($^{\circ}/_{\text{‰}}$)
Composite Zooplankton	70	66 55.0	169 55.0	19.54	8.73
Composite Zooplankton	99	64 32.0	170 01.0	21.19	10.50
Composite Zooplankton	38	63 55.0	173 35.0	21.15	9.15
Composite Zooplankton	104	63 50.7	169 12.3	21.52	10.72
Composite Zooplankton	27	64 43.3	177 48.2	19.32	8.61
Composite Zooplankton	107	64 23.0	171 39.0	20.30	10.29
Composite Zooplankton	78	65 51.0	169 13.0	21.77	9.69
Composite Zooplankton	88	65 21.6	169 59.3	20.85	10.84
Composite Zooplankton	25	64 00.0	179 20.0	18.92	8.76
Composite Zooplankton	64	67 17.8	166 42.6	20.97	9.05
Composite Zooplankton	58	67 30.5	172 11.4	19.68	8.32
Composite Zooplankton	6	59 30.0	179 30.0	22.62	7.07
Composite Zooplankton	42	63 55.2	172 04.4	22.80	9.67
Composite Zooplankton	98	64 43.1	170 52.4	22.24	9.58
Composite Zooplankton	32	64 00.0	175 00.0	23.38	9.92
Composite Zooplankton	13	62 11.0	179 51.0	23.04	10.45
Composite Zooplankton	95	64 58.2	169 58.6	22.68	10.44
Composite Zooplankton	50	68 39.7	168 20.0	21.45	11.68
Composite Zooplankton	20	62 34.7	175 03.5		11.76
Composite Zooplankton	106	64 14.0	170 54.7	22.50	9.91
Composite Zooplankton	9	61 20.1	176 03.2	24.16	10.17
Composite Zooplankton	11	61 35.0	178 39.0	23.45	10.69
Composite Zooplankton	96	65 05.0	170 44.0	22.04	11.33
Composite Zooplankton	67	66 56.0	165 50.0	20.65	10.68
Composite Zooplankton	110	53 55.6	176 00.0E	25.87	
Composite Zooplankton	35	63 00.0	173 00.0	23.34	12.12
Composite Zooplankton	22	63 00.4	176 00.1		11.04
<i>Calanus</i> sp.	72	66 44.0	171 05.0	22.90	
<i>Calanus</i> sp.	96	65 05.0	170 44.0	22.34	11.77
<i>Calanus</i> sp.	35	63 00.0	173 00.0	23.61	12.27
<i>Calanus</i> sp.	22	63 00.4	176 00.1	24.25	10.99
<i>Calanus</i> sp.	50	68 39.7	168 20.0	21.98	12.47
<i>Calanus</i> sp.	9	61 20.1	176 03.2	24.18	10.62
<i>Calanus</i> sp.	45	67 44.0	172 50.0	20.98	10.60
<i>Calanus</i> sp.	40	64 08.0	172 30.0		8.37
<i>Calanus</i> sp.	47	68 06.0	170 53.0	20.62	10.72
<i>Calanus</i> sp.	67	66 56.0	165 50.0	22.29	14.18
<i>Calanus</i> sp.	58	67 30.5	172 11.4	20.61	10.78
<i>Calanus</i> sp.	25	64 00.0	179 20.0	19.25	10.86
<i>Calanus</i> sp.	104	63 50.7	169 12.3	22.79	10.47
<i>Calanus</i> sp.	20	62 34.7	175 03.5	23.57	13.54
<i>Calanus</i> sp.	55	67 44.1	168 26.4	21.25	10.63
<i>Calanus</i> sp.	98	64 43.5	171 11.0	21.73	11.57
<i>Calanus</i> sp.	59	67 09.2	172 59.8	21.80	10.43
<i>Calanus</i> sp.	64	67 17.8	166 42.6	22.12	13.95
<i>Calanus</i> sp.	74	66 33.0	168 36.0	21.78	10.87
<i>Calanus</i> sp.	57	67 42.6	171 20.7	20.73	10.34
<i>Calanus</i> sp.	85	65 50.0	169 10.0	23.64	10.72
<i>Calanus</i> sp.	61	67 20.0	169 45.0	22.04	11.21
<i>Calanus</i> sp.	6	59 30.0	179 30.0	22.91	7.52
<i>Calanus</i> sp.	42	63 55.2	172 04.4	22.99	
<i>Calanus</i> sp.	88	65 21.6	169 59.3	23.22	
<i>Calanus</i> sp.	11	61 35.0	178 39.0	23.20	
<i>Calanus</i> sp.	27	64 43.3	177 48.2	20.82	8.10
<i>Calanus</i> sp.	86	65 56.7	169 22.9	23.12	7.89
<i>Calanus</i> sp.	32	64 00.0	175 00.0	23.34	6.89

TABLE 1 - continued

Samples collected from the *Akademik Korolev* in 1988.

TAXA	STATION	LAT. °N	LONG. °W	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
<i>Calanus</i> sp.	107	64 23.0	171 39.0	23.34	8.07
<i>Calanus</i> sp.	87	65 24.5	170 21.5	21.35	10.51
<i>Calanus</i> sp.	104	63 50.7	169 12.3	22.85	
<i>Calanus</i> sp.	97	64 44.9	171 29.7	22.42	8.44
<i>Calanus</i> sp.	70	66 55.0	169 55.0	23.22	
<i>Calanus</i> sp.	25	64 00.0	179 20.0	20.67	8.93
<i>Calanus</i> sp.	38	63 55.0	173 35.0	22.99	6.58
<i>Calanus</i> sp.	95	64 58.2	169 58.6	22.60	10.59
<i>Calanus</i> sp.	110	53 55.6	176 00.0E	26.77	
<i>Calanus</i> sp.	85	65 50.0	169 10.0	22.61	8.57
<i>Calanus</i> sp.	98	64 43.5	171 11.0	22.12	11.80
<i>Calanus</i> sp.	6	59 30.0	179 30.0	24.70	8.58
<i>Calanus</i> sp.	70	66 55.0	169 55.0	22.08	15.00
<i>Calanus</i> sp.	13	62 11.0	179 51.0	22.21	12.15
<i>Calanus</i> sp.	40	64 08.0	172 30.0	22.62	9.75
<i>Calanus</i> sp.	87	65 24.5	170 21.5	20.88	9.90
<i>Calanus</i> sp.	107	64 23.0	171 39.0	21.67	12.59
<i>Calanus</i> sp.	76	65 58.0	169 35.0	22.30	11.14
<i>Calanus</i> sp.	11	61 35.0	178 39.0	21.71	9.21
<i>Calanus</i> sp.	27	64 43.3	177 48.2	22.07	7.28
<i>Calanus</i> sp.	25	64 00.0	179 20.0	20.44	9.46
<i>Calanus</i> sp.	110	53 55.6	176 00.0E	25.27	
<i>Calanus</i> sp.	61	67 20.0	169 45.0	21.20	9.11
<i>Calanus</i> sp.	32	64 00.0	175 00.0	21.05	8.57
<i>Calanus</i> sp.	38	63 55.0	173 35.0	22.31	10.73
<i>Calanus</i> sp.	110	53 55.6	176 00.0E	25.63	3.97
<i>Calanus</i> sp.	40	64 08.0	172 30.0	21.99	10.25
<i>Calanus</i> sp.	11	61 35.0	178 39.0	23.53	10.54
<i>Calanus</i> sp.	6	59 30.0	179 30.0	22.87	5.77
<i>Calanus</i> sp.	97	64 43.5	171 11.0	23.29	7.46
<i>Calanus</i> sp.	6	59 30.0	179 30.0	22.16	7.67
<i>Calanus</i> sp.	27	64 43.3	177 48.2	20.83	8.27
<i>Calanus</i> sp.	32	64 00.0	175 00.0		9.78
<i>Calanus</i> sp.	25	64 00.0	179 20.0	21.78	6.93
<i>Calanus</i> sp.	38	63 55.0	173 35.0	21.30	9.01
<i>Calanus</i> sp.	88	65 21.6	169 59.3	23.71	
<i>Calanus</i> sp.	70	66 55.0	166 55.0	22.12	10.60
<i>Calanus</i> sp.	19	62 25.5	174 00.2	22.69	14.88
<i>Calanus</i> sp.	85	65 50.0	169 10.0	22.40	9.55
<i>Calanus</i> sp.	42	63 55.2	172 04.4	23.62	
<i>Calanus</i> sp.	56	67 44.2	169 55.6	21.16	10.66
<i>Calanus</i> sp.	107	64 23.0	171 39.0	21.46	10.22
<i>Calanus</i> sp.	60	67 15.7	170 49.6	20.58	11.02
<i>Calanus</i> sp.	6 *	59 30.0	179 30.0	23.66	8.98
<i>Calanus</i> sp.	110	53 55.6	176 00.0E	25.55	
<i>Calanus</i> sp.	95	64 58.2	169 58.6	23.85	
<i>Calanus</i> sp.	13	62 11.0	179 51.0	21.87	10.12
<i>Calanus</i> sp.	76	65 58.0	169 35.0	22.18	
<i>Calanus</i> sp.	61	67 20.0	169 45.0	21.58	11.41
<i>Calanus</i> sp.	86	65 56.3	169 22.9	20.86	10.72
<i>Calanus</i> sp.	87	65 24.3	170 21.7	22.83	
<i>Calanus</i> sp.	6	59 30.0	179 30.0	23.99	8.17
<i>Calanus</i> sp.	60	67 15.7	170 49.6	21.12	13.50
<i>Calanus</i> sp.	61	67 18.0	170 00.3	21.07	
Euphausiid	70	66 55.0	169 55.0	20.75	8.42

TABLE 1 - continued

Samples collected from the *Akademik Korolev* in 1988.

TAXA	STATION	LAT. °N	LONG. °W	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
Euphausiid	87	65 24.5	170 21.5	19.64	8.54
Euphausiid	67	66 56.0	165 50.0	20.95	9.18
Euphausiid	86	65 56.3	169 22.9	20.32	6.55
Euphausiid	64	67 17.8	166 42.6	20.92	8.62
Euphausiid	95	64 58.2	169 58.6	21.11	8.99
Euphausiid	88	65 21.6	169 59.3	21.50	8.94
Euphausiid	98	64 43.5	171 11.0	22.44	12.28
Euphausiid	85	65 50.0	169 10.0	21.03	8.95
Euphausiid	22	63 00.4	176 00.1	20.46	10.94
Euphausiid	50	68 39.7	168 20.0	21.09	9.58
Euphausiid	6	59 30.0	179 30.0	21.52	8.09
Euphausiid	104	63 50.7	169 12.3	22.65	8.64
Euphausiid	55	67 44.1	168 26.4	19.63	9.04
Euphausiid	61	67 20.0	169 45.0	20.18	9.26
Euphausiid	99	64 32.0	170 01.0	20.13	10.87
Euphausiid	13	62 11.0	179 51.0	21.53	10.84
Euphausiid	73	66 44.0	171 05.0	20.06	9.44
Euphausiid	42	63 55.2	172 04.4		8.12
Euphausiid	25	64 00.0	179 20.0	18.71	8.43
Euphausiid	107	64 23.0	171 39.0	21.97	
Euphausiid	110	53 55.6	176 00.0E	23.41	
Euphausiid Large	27	64 43.3	177 48.2		8.83
Euphausiid Large	11	61 35.0	178 39.0	20.63	9.51
Euphausiid Large	6	59 30.0	179 30.0	21.88	8.78
Euphausiid Large	50	68 39.7	168 20.0	21.00	
Euphausiid Large	20	62 34.7	175 03.5	21.94	13.50
Euphausiid Small	11	61 35.0	178 39.0	20.74	10.77
Euphausiid Small	32	64 00.0	175 00.0	19.91	8.97
Euphausiid Small	76	65 58.0	169 35.0	21.57	8.64
Euphausiid Small	40	64 08.0	172 30.0	20.21	9.41
Euphausiid Small	38	63 55.0	173 35.0	20.77	8.28
Euphausiid Small	27	64 43.3	177 48.2	17.73	7.81
Phytoplankton	71	66 44.0	171 05.0	20.52	5.92
Phytoplankton	24	63 42.6	178 28.8	19.01	7.17
Phytoplankton	44	67 24.1	173 21.7	21.69	9.56
Phytoplankton	76	65 58.0	169 35.0	19.96	5.85
Phytoplankton	55	67 44.1	168 26.4	18.71	7.22
Phytoplankton	59	67 09.2	172 59.8	22.48	
Phytoplankton	45	67 44.0	172 50.0	21.90	6.39
Phytoplankton	76	65 58.0	169 35.0	25.01	11.55
Phytoplankton	20	62 34.7	175 03.5	24.12	11.80
Hippolytid Larvae	55	67 44.1	168 26.4	19.04	9.54
Hippolytid Larvae	42	63 55.2	172 04.4	20.54	
Pandalid Larvae	50	68 39.7	168 20.0	19.93	11.21
Decapod Larvae	86	65 56.3	169 22.9	19.96	8.65

5.2.5 Zooneuston

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Introduction

Samples of zooneuston were taken at 33 stations in the Bering Sea and at 14 stations in the Chukchi Sea (see scheme with stations). The equipment for collecting zooneuston samples included a two stage plankton-neuston net PNS-2 and a fish fry trawl MNT (Zaitsev, 1971). A synchronous hauling of the upper two microhorizons, the neuston layer (0–5 cm) and the subneuston layer (5–25 cm) was performed.

The MNT is a high speed equipment device for collecting hydrobiological material (rate of trawling up to 3 m/sec) in the 0–25 cm layer. The PNS-2 was hauled at a distance of several tens of meters at a velocity of 25 cm/sec. The volume of filtered water was determined taking into consideration the time of filtration and speed, as well as the working area of the net. Ninety-four samples altogether were taken in the Bering and Chukchi Seas, 47 samples each from the neuston layer and the subneuston layers (Table 1).

TABLE 1

Zooneuston samples taken in the Bering and Chukchi Seas.

Region	Chukchi Sea	Bering Sea			
		Chirikov Gulf	Gulf of Anadyr	Polygon East	Polygon South
Amount of Stas.	14	8	14	5	6
Samples	28	16	28	10	12

The area of sampling embraced a large water mass including the south part of the Chukchi Sea, Chirikov Gulf, and Gulf of Anadyr of the Bering Sea, as well as the oceanographic East and South Polygons. The most northerly station was situated at a latitude of 68°39'7"N, the most southerly, 57°25'7"N. Thus the study of zooneuston was carried out in the near polar and far polar waters.

As a result of the interaction of the ocean and atmosphere on the ocean-atmosphere boundary, certain specific conditions of life are created. One of the contours of the biotopes of the halosphere is found here. The neuston population has much species diversity and in the abundance of organisms, and plays an important part not only in the life of the water layer, but in the sea bottom, especially in the shelf zone (Zaitsev, 1971).

The study of neuston in high latitude sea waters—in this case, the Bering and Chukchi Seas—is important from many points of view. First of all, the neuston of extreme north as well as extreme south seas has not been studied. Secondly, the

Bering and Chukchi Seas are known as background regions of the World Ocean (Tsyban *et al.*, 1985), and thus neuston from these waters will most certainly react to it (Zaitsev, 1986).

The first preliminary investigations of zooneuston in the Bering Seas were carried out in the summer of 1962 (Chebanov, 1965; Zaitsev, 1971). A more profound study of neuston was performed by L. N. Polishchuk and B. G. Alexandrov under the guidance of Yu. P. Zaitsev in July 1984. The same authors studied zooneuston from 28 July to 31 August 1988 during the Third Joint US-USSR Bering & Chukchi Seas Expedition on board the research vessel (R/V) *Akademik Korolev*. This was the first time neuston was studied in the waters of the Chukchi Sea.

The animal population of the Bering and Chukchi Seas differs in species composition and high density of populations (Tables 2,3).

It should be noted that because of specific natural conditions in those seas, such as low temperatures, ice formation, lengthy winter season, etc., only temporary forms of zooneuston developed that were capable of terminating their ontogenesis during the short period of hydrological summer. First of all, these include the larvae of bottom invertebrates (bivalves, gastropods, cirripeds, polychaetes, echinoderms, phoronides, nemertines), decapod larvae, euphausiid larvae, juvenile forms of chaetogaths, as well as early stages (eggs, nauplii, copepodites), the majority of copepods, the cladoceran *Evadne nordmanni*, the pelagic polychaete *Tomopteris pacifica*, pteropods (*Clione limacina*, *Limacina helicina*), tunicates (*Fritillaria borealis*, *Oikopleura labradoriensis*), hydrozoans (*Taghkea octopunctata*, *Aglantha digitale*, *Obelia* sp., *Pantachogon haeckeli*), and the siphonophore *Dimophyes arctica*.

Adult copepods such as *Oncea borealis*, *Tortanus discaudatus*, *Eurytemora pacifica*, *Acartia longiremis*, and *Pseudocalanus minutus* behaved like neustophils. The most northern representative of the pontellid family *Epilabidocera amphitrites* proved to be a typical neuston.

The average number of organisms in the neuston layer in the East Polygon amounted to 118,284 specimens/m³, which is about 4.5 times greater than the amount discovered here in the summer of 1984. It is not difficult to give the reason for this significant difference. As to the ratio of the abundance of organisms in the neuston and subneuston layers, in 80% of the cases, there were more in the former layer (Table 4).

Tintinnids, pteropods, nauplius eggs and, early copepodite stages of Copepoda (*Ointhona similis*, *Acartia longiremis*, *Pseudocalanus minutus*, *Eucalanus bungii*), decapod larvae, and juvenile polychaetes prevailed in the neuston layer.

TABLE 2

Qualitative composition of zooneuston of the Bering and
Chukchi Seas in the period July 28–August 29, 1988.

Taxa	Bering Sea			Chukchi Sea
	Anadyr Gulf	Chirikov Gulf	Eastern Region	
Protozoa				
<i>Globigerina</i> sp.	-	+	+	+
<i>Tintinnoina</i>	+	+	+	+
Rotatoria				
<i>Synchaeta</i> sp.	+	+	-	-
Coelenterata				
Hydroidea				
<i>Aglantha digitale</i>	+	+	+	+
<i>Rathkea octopunctata</i>	+	+	-	-
<i>Obelia</i> sp.	-	-	-	-
<i>Pantaeogon haeckeli</i>	-	-	+	-
Scyphozoa				
<i>Cyanea</i> sp.	-	+	-	-
Siphonophora				
<i>Dimophyes arctica</i>	+	-	-	-
Polychaeta				
<i>Tomopteris pacifica</i>	+	-	-	-
<i>Polychaeta</i> , larvae	+	+	+	+
Pteropoda				
<i>Limacina helicina</i>	+	+	+	+
<i>Clione limacina</i>	+	-	+	+
Bivalvia, larvae	+	+	-	+
Gastropoda, larvae	-	+	-	-
Cirripedia				
<i>Balanu</i> , larvae	+	+	-	-
<i>Lepas</i> , juv.	-	-	-	+
Nemertini, larvae	-	-	-	+
Ophiura, larvae	+	+	-	+
Echinoidea, larvae	+	+	-	-
Asteroidea, larvae	-	+	-	-
Phoronidea, larvae	-	+	-	-
Bryozoa, larvae	-	+	-	-
Copepoda				
<i>Oithona similis</i>	+	+	+	+
<i>Acartia longiremis</i>	+	+	+	+
<i>Pseudocalanus elongatus</i> (= <i>minutus</i>)	+	+	+	+
<i>Calanus glacialis</i>	+	+	-	+
<i>Calanus plunchnrus</i>	+	+	+	+
<i>Eucalanus bungii</i>	+	+	+	+
<i>Eurytemora herdmanni</i>	+	-	-	-
<i>Eurytemora pacifica</i>	-	+	-	-
<i>Oncea borealis</i>	-	+	-	-
<i>Centropages mcmurrici</i>	-	+	-	-
<i>Tortanus discaudatus</i>	-	+	-	-
<i>Epilabidocera amphitrites</i>	+	+	-	-
<i>Harpacticoida</i> sp.	+	+	+	+

TABLE 2 - continued

Qualitative composition of zooneuston of the Bering and Chukchi Seas in the period 28 July–29 August 1988.

Taxa	Bering Sea				Chukchi Sea
	Anadyr Gulf	Chirikov Gulf	Eastern Region	Southern Region	
Cladocera					
<i>Evadne nordmanni</i>	-	+	-	+	+
<i>Podon leuckartii</i>	-	+	-	-	+
Amphipoda					
<i>Parathemisto japonica</i>	+	+	+	-	+
<i>Hyperiididae</i>	-	+	+	+	+
Decapoda					
<i>Brachiura</i> ova, larvae	+	+	+	-	+
Euphausiacea, larvae	+	-	-	+	+
Chaetognatha					
<i>Sagitta elegans</i>	+	+	+	+	+
Tunicata					
<i>Oikopleura labradoriensis</i>	+	+	+	+	+
<i>Fritillaria borealis</i>	+	+	-	+	+
Pisces, ova, larvae	+	+	+	+	+

TABLE 3

Average abundance (specimens/m³) of organisms in the neuston (0–5 cm) and subneuston (5–25 cm) layers of the Chukchi and Bering Seas in the period of July 28–August 29, 1988.

Sea, region	Neuston layer	Subneuston layer
Chukchi Sea	43,464	19,775
Bering Sea		
Polygon East	118,235	48,314
Polygon South		
+ Station 113	56,749	53,294
Gulf of Anadyr	17,238	20,083
Chirikov Gulf	75,321	55,669
Average of the Bering Sea	67,240	44,340

The hydrozoan *Pantaeogon haeckeli*, polychaete larvae, and nauplii of *Eucalanus bungii* were encountered only in the neuston layer.

As in the summer of 1984, copepods dominated in the neuston layer making up 93% of total abundance. In density of organisms in the neuston layer, this area leads among others investigated in the Bering and Chukchi Seas.

In South Polygon, the hydrozoans *Aglantha digitale*, larvae of bivalves, ophiurians, eggs, copepodites and adult *Pseudocalanus minutus*, eggs of decapoda, and tunicates of *Oikopleura* and *Fritillaria* were found in the sample.

TABLE 4

Abundance of organisms (specimens/m³) in the neuston and subneuston layers in the Polygon East of the Bering Sea July 28–31, 1988.

Station Number	Neuston layer	Subneuston layer
1	225,295	109,432
2	134,079	68,397
3	30,772	45,810
4	47,273	16,692
5	53,764	2,240
Average	118,234	48,314

V. copepodites of *Calanus plumchrus*, IV-*Calanus glacialis* and, *Evadne nordmanni* of Cladocera and also juvenile *Lepas* show complete adherence to the neuston layer.

Thirty-three percent more organisms prevail in the neuston layer (Table 5). Average abundance in the region was 6,749 specimens/m³, which is 1.6 times greater than in the summer of 1984. In comparison to other marine aquatories at that time, this region was characterized by high abundance indices. In 1988, according to quantitative characteristics, it ranks third after East Polygon and Chirikov Gulf.

As copepods were the dominating group up to 80%, with hyperiids (17.6%) ranking second. The rotatorian *Synchaeta*,

TABLE 5

Abundance of organisms (specimens/m³) in the neuston and subneuston layers in Polygon South and Station 113 (south region) in the Bering Sea, August 26–29, 1988.

Station Number	Neuston layer	Subneuston layer
108	51,761	57,414
109	143,692	71,539
110	74,810	43,278
111	33,035	80,063
112	3,972	18,811
Average for polygon	61,454	54,221
113	33,226	48,664
Average for region	56,749	53,294

hydrozoan *Aglantha digitale*, pteropods *Limacina* and *Clione*, larvae of bivalves, cirripeds, and ophiurians, all adult stages of *Acartia tumida*, nauplii, first three copepodite stages of *Pseudocalanus minutus*, nauplii, IV–V copepodite stages and adult *Calanus glacialis*, IV–V copepodite stages of *Epilabidocera amphitrites*, nauplii of *Acartia longiremis* and *Eucalanus bungii*, hyperiids *Parathemisto japonica*, zoea of decapods and tunicate *Oikopleura* all predominate in the neuston layer of the Gulf of Anadyr. Absolutely predominating in the neuston layer were tintinnids, the pelagic polychaete *Tomopteris*, larvae of *Bryozoa*, nauplii of *Calanus plumchrus* and *Epilabidocera amphitrites*, and larvae (megalopa) of decapods.

In comparison to the subneuston layer, 36% more organisms predominated in the neuston layer. Average abundance in the region was 17,238 specimens/m³ (Table 6) which is almost 7 times less than in the east and 3.2 times less than in the south.

Copepods dominated in the Gulf of Anadyr similar to above-mentioned polygons, making up about 97%. In this region, a large amount of detritus formed from dying phytoplankton cells was found in zooneuston samples. A large amount of organic matter suspended near the pelagic surface layer possibly inhibited the development of neuston and was one of the reasons for low indices.

As to the Chirikov Gulf, foraminiferous, tintinnids, all stages of ontogenesis of *Oncea borealis*, I–III stages of copepodites of *Calanus glacialis*, and adult forms of *Tortanus* and *Epilabidocera* were encountered only in the neuston layer.

Similar to other regions of the Bering Sea, copepods (40%) prevailed in Chirikov Bay; however, here there were significantly more zoobenthos larvae, especially the bivalves (20%) and marine urchins (23%).

The average number of organisms in the neuston layer of Chirikov Gulf was 75,321 specimens/m³, which ranks second after the East Polygon in the Bering waters studied (Table 7).

The most northern water mass studied is the Chukchi Sea, which has a quite diverse and abundant zooneuston. The rotatorian *Synchaeta*, the hydrozoans *Rathkea*, *Obelia*, *Aglantha*, polychaete larvae, the pteropod *Clione*, larvae of bivalves, cirripeds, ophiurans, and marine urchins, all stages of ontogenesis of the copepods *Acartia longiremis*, *Pseudocalanus*

TABLE 6

Abundance (specimens/m³) of organisms in the neuston and subneuston layers of the Gulf of Anadyr of Bering Sea August 1–8, 1988.

Station Number	Neuston layer	Subneuston layer
6	76,393	80,984
7	9,259	16,335
9	3,680	5,564
11	8,748	13,053
13	43,274	54,790
15	12,023	13,133
18	5,551	4,943
19	6,164	3,948
22	18,263	12,598
24	11,061	2,192
32	22,541	22,335
35	2,330	10,418
36	4,119	2,372
41	17,916	39,399
Average for region	17,238	20,083

TABLE 7

Abundance of organisms (specimens/m³) in the neuston and subneuston layers of Chirikov Gulf in the Bering Sea, August 19–23, 1988.

Station Number	Neuston layer	Subneuston layer
83	24,246	44,624
86	24,529	15,850
89	82,185	42,832
92	269,147	73,910
100	110,104	46,180
102	30,241	174,919
104	60,120	45,317
Average	75,321	55,669

minutus, *Eutytemora pacifica*, *Eurytemora herdmani*, *Oithona similis*, eggs and nauplii of *Calanus glacialis*, nauplii of *Eucalanus bungii*, nauplii and copepodite stages of *Acartia tumida*, furcillia of euphausiids, megalops of decapods, juvenile polychaetes, and tunicates *Oikopleura* and *Fritillaria* quantitatively predominated in the neuston layer. Foraminiferous, the siphonophore *Dimophyes arctica*, gastropod larvae, I–III copepodite stages of *Eucalanus pacifica*, nauplii of *Epilabidocera anihitrites*, III–V copepodites of *Calanus plumchrus*, hyperiids, eggs, and larvae of fish were found in greater quantities in the neuston layer.

In 86% of the cases, there were more organisms predominating in the neuston layer (Table 8).

Average abundance for hydrobionts in the 0–5 cm layers was 43,464 specimens/m³, which is 1.5 times less than the average abundance of organisms in this biotope of the Bering Sea.

TABLE 8

Abundance of organisms (specimens/m³) in the neuston and subneuston layers of the Chukchi Sea, 9–15 August 1988.

Station Number	Neuston layer	Subneuston layer
45	7,522	3,300
47	67,608	21,875
49	24,767	14,447
50	45,612	28,940
52	19,139	12,120
53	51,158	14,806
55	25,198	9,522
59	19,854	9,435
61	55,572	30,052
64	64,568	24,263
66	162,169	59,902
71	44,039	26,134
74	3,626	3,887
75	17,659	18,172
Average for Sea	43,464	19,775

Similar to the Chirikov Gulf in the Bering Sea, the Chukchi Sea was dominated by copepods, bivalve larvae, and tunicates making up 50%, 26%, and 17%, correspondingly, from the total number of organisms. Besides, protozoa, rotatoria, hydrozoans, polychaete larvae, cirripeds, ophiurians, marine urchins, cladocereans, euphausiids, decapod larvae, fish eggs, and larvae were encountered.

Thus, the number of organisms in the neuston layer in comparison to the subneuston layer in the Bering Sea (East Polygon, 80%; South Polygon, 33%; Gulf of Anadyr, 38%; Chirikov Gulf, 75%) prevailed on the average in 63% of the cases; in the Chukchi Sea, 86%. The distribution of the number of organisms in the neuston and subneuston layers of the Bering and Chukchi Seas is illustrated in Fig. 1. Taking into consideration the dominance of organisms (%) in these two layers, seven regions less favorable for the development of neuston in comparison to others have been distinguished (Fig. 2).

It is known that wind and surface water circulation have a great influence on the development and distribution of neuston. According to the general scheme of surface water circulation in the Bering and Chukchi Seas, the regions pertain to zones of mixing of waters of different origin, such as: I–II—warm Pacific and Bering marine waters; III–IV—warm Pacific and cold fresh Anadyr waters; V—cold fresh Anadyr and cold Chukchi marine waters; VI—warm Pacific and Bristol waters; and VII—warm Pacific and cold Chukchi marine waters.

The data received, at first glance, do not coincide with Zaitsev's concept (1977), where it has been stated that a rich community of neuston develops on the boundaries between different water masses. Probably, the main factor here is the velocity of water currents. At small velocities a concentration of organisms occurs, initiating the development of hydrobionts;

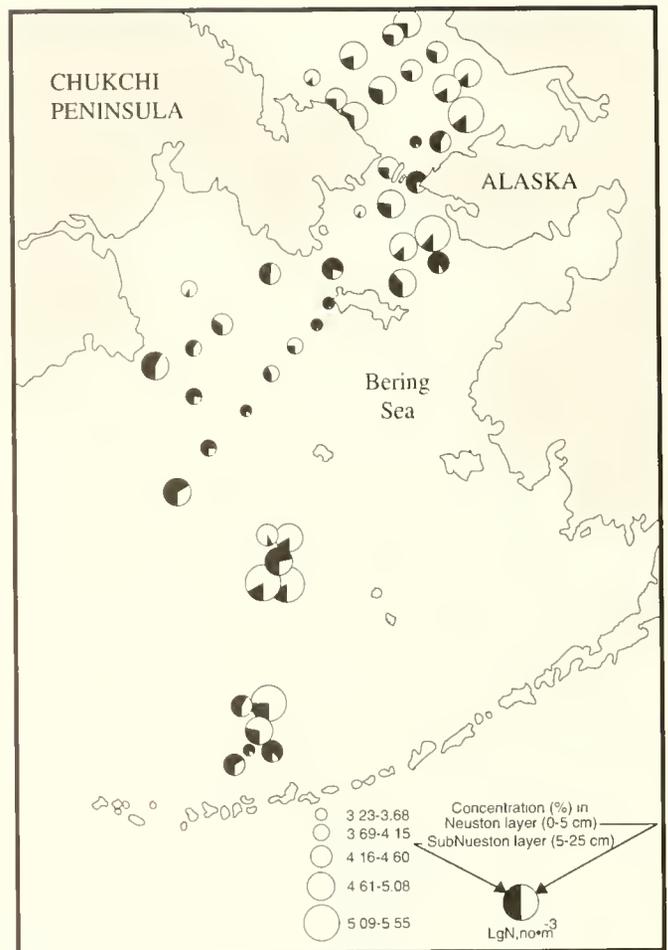


Fig. 1. Distribution of organisms in the near surface microlayers and relation to abundance in stations in the Bering and Chukchi Seas.

at greater speeds, organic matter promoting their development is carried out with the currents.

The following explanation may also hold. The regions do not coincide with the areas of convergence of heterogeneous waters but with the centers of circulation of surface currents where funnels are formed and organisms are sucked into them entering the lower layers of the pelagic zone. This explanation, probably, is closer to the truth, as the regions with a higher density of organisms in the neuston layer (Fig. 3), when compared to regions unfavorable for the development of zooneuston, confirm that they are adjacent to one another, but the former overlap with marginal regions of circulation of surface currents.

Five areas of distribution of organisms in the neuston layer of the Bering and Chukchi Seas having high abundance are distinguished: southwest of the southern region (South Polygon), southeast of the eastern region (East Polygon), the northwest of the Gulf of Anadyr, the north and east of Chirikov Gulf, and the east and north of the Chukchi Sea.

The average abundance of organisms in the neuston layer of the Bering Sea is 68,658 specimens/m³, and 43,464 specimens/m³ in the Chukchi Sea. The most diverse in number was the eastern region in the Bering Sea (East Polygon), 118,234 specimens/m³, while the lowest numbers were found in the Gulf of Anadyr, 17,238/m³.

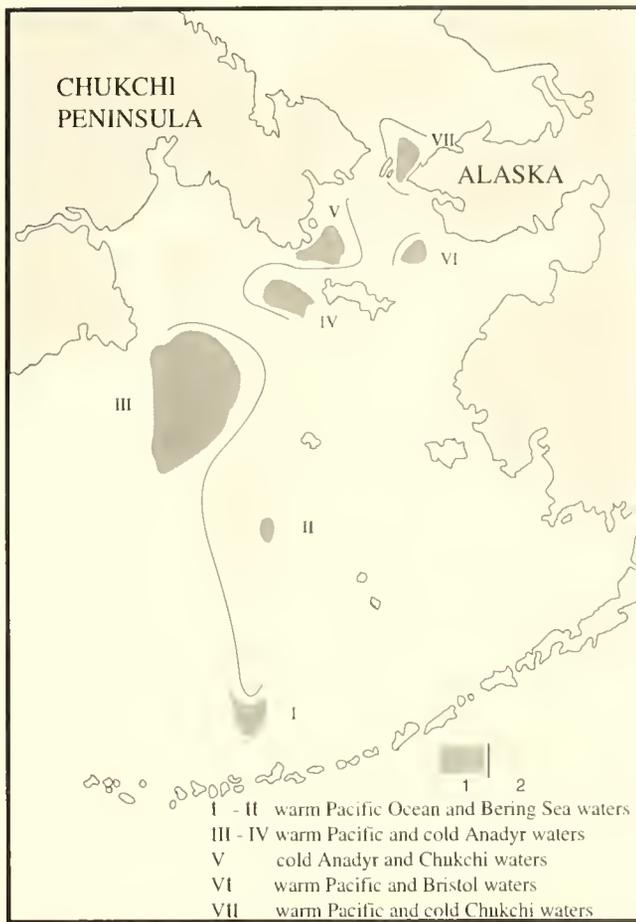


Fig. 2. Areas of absence (1) and presence (2) of aggregations of organisms in the neuston layer. Isoline marks the boundary of equal distribution of organisms in the near surface microhorizons.

On characterizing the qualitative composition of zooneuston represented by 47 taxa, it should be noted that the greatest species diversity was found in the Chukchi Sea and Chirikov Gulf (up to 38 taxa). The smallest amount of species (18) was discovered in East Polygon.

The dominating group of organisms in all regions investigated in the Bering and Chukchi Seas was made up of copepods (Fig. 4). Among the 14 species of copepods, a significant part was played by three: *Oithona similis*, *Acartia longiremis*, and *Pseudocalanus minutus*. During the summer of 1984, a similar pattern was observed, but the number of cold-loving *Pseudocalanus* organisms was more abundant than *Acartia* (the neritic, epipelagic species). But this was due to the slight heating of surface waters in comparison to that during the period of investigation. In the neuston layer, the copepods were represented by all stages of development, while the ratio of different age groups according to regions was about the same. More than half of the number of copepods pertained to earlier stages of ontogenesis (eggs, nauplii), which gives evidence for their high reproductive activity corresponding to the biological summer period.

The wide shelf in the northeast part of the Bering Sea and slight depths in the Chukchi Sea maintain favorable conditions for the existence of bottom fauna with bivalve mollusks, echinoderms, polychaetes, etc., predominating. Their larvae

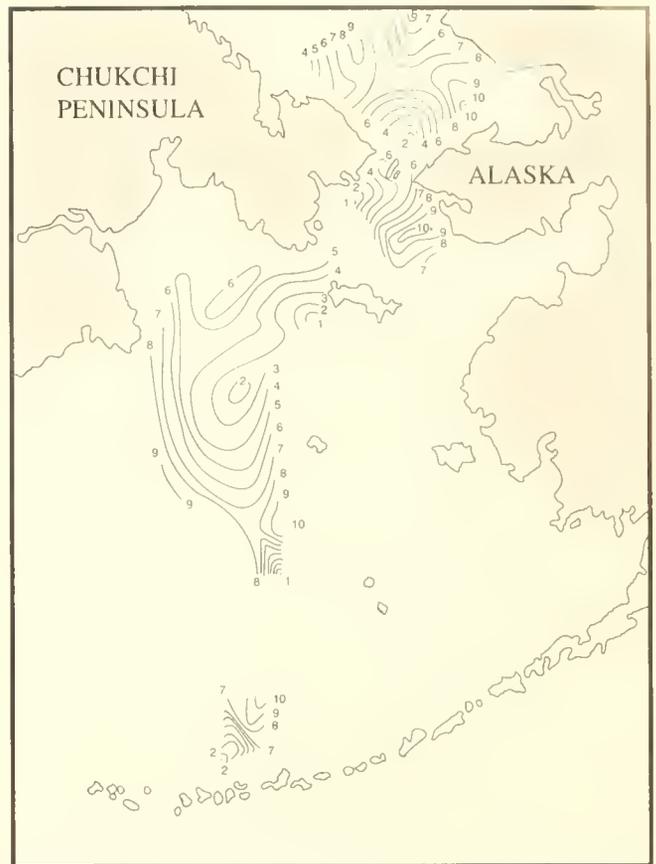


Fig. 3. Abundance (1g number/m³) of zooneuston in regions investigated in the Bering and Chukchi Seas. 1—< 3.4; 2—3.4—3.6; 3—3.6—3.8; 4— 3.8—4.0; 5—4.0—4.2; 6—4.2—4.4; 7—4.4—4.6; 8—4.6—4.8; 9—4.8—5.0; 10—> 5.0.

make up a significant part of the total number of zooneuston in the Chirikov Gulf (larvae of marine urchins, 24%; bivalve mollusks, 20%; and polychaetes, 29%). In comparing the Chukchi Sea to Chirikov Gulf, the role of bottom invertebrate was slightly less; they make up to 30% (larvae of bivalve mollusks, 26%; cirripeds, 3%; and ophiurans, 1%). In the rest of the regions of the Bering Sea, the role of sea bottom larvae is insignificant. Even in East Polygon which is partly located in the neritic zone over small depths, they are represented by polychaetes making up only tenths of a fraction of specimens/m³. Probably, larvae from these regions are carried out by currents flowing from the south to the north and northwest.

Thus, on the average, copepods in the neuston layer of the Bering Sea made up 77%; larvae of bottom invertebrates, 12%; hyperiids, 4%; tunicates, 3%; and shell infusorians, 2%.

Many taxa are common for the fauna of zooneuston of the regions investigated. When using the method of Preston (1962), it has been established that the fauna of zooneuston of the Chukchi Sea and Chirikov Gulf are identical. The index (coefficient) of differences is minimum, while the high similarity index gives evidence, first, to similar conditions of existence, and second, to the exchange of fauna between these regions (Table 9).

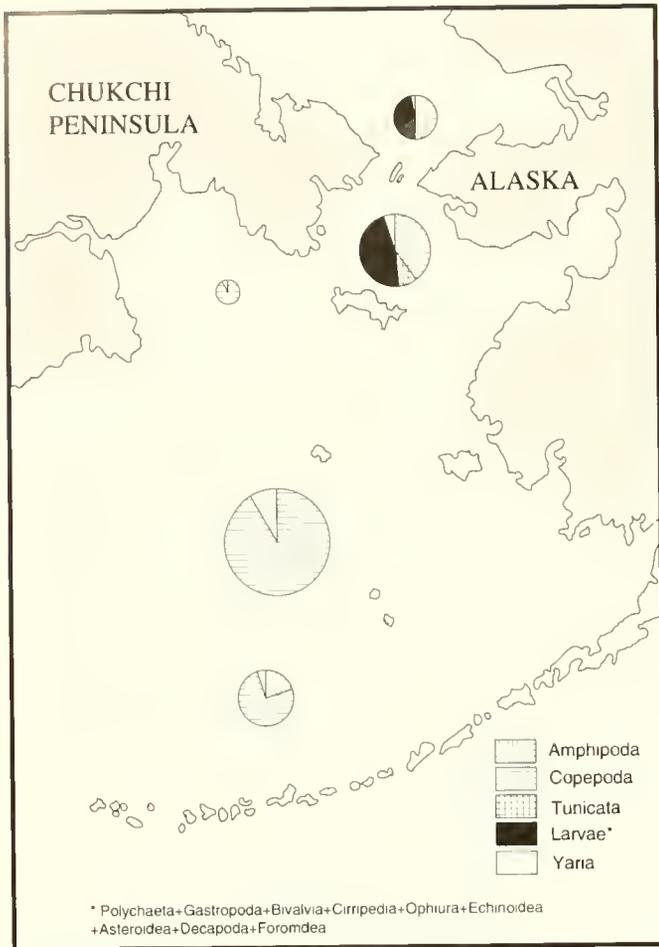


Fig. 4. Ratio between average abundance and qualitative composition of zooneuston in investigated regions of the Bering and Chukchi Seas.

TABLE 9

Coefficients of faunistic similarity and differences of zooneuston of the Bering and Chukchi Seas (according to materials collected during the summer, 1988).

Sea, region	1	2	3	4	5
	Similarity				
Chukchi Sea		0.69	0.80	0.43	0.55
Bering Sea					
Gulf of Anadyr	0.31		0.53	0.46	0.40
Chirikov Gulf	0.20	0.48		0.55	0.41
Eastern region					
(East Polygon)	0.57	0.55	0.45		0.62
Southern region					
(South Polygon)	0.45	0.77	0.59	0.38	

Differences

The indices of faunistic similarity in the other regions are high, which shows that their fauna are partly or completely isolated. The exchange of species is insignificant or there is none, while conditions for existence of zooneuston are different.

In the Bering Sea, distribution of zooplankton can be divided into five faunistic groups (Vinogradov, 1956; Brodsky, 1957): south Bering Sea, north Bering Sea, east and west neritic, as well as, deep-water Bering Sea. After confirming, with the help of literature data (Mescheryakova, 1970; Motoda & Minoda, 1974; Kolosova *et al.*, 1987), the composition of indicator species characterizing the first four groups, an analysis was carried out of their distribution in the neuston layers of the Bering and Chukchi Seas (Fig. 5). The center of south Bering Sea faunistic group was situated over the deep water part of the south and east regions of the Bering Sea, and in the way of two tongue-like intrusions entered into the Gulf of Anadyr. The center of the north Bering Sea is broken in the area. One part is found south of the Gulf of Anadyr, another in the central and northeastern part of the Chukchi Sea. The center of the west neritic group is situated in the Chirikov Gulf and Chukchi Sea. One south Bering Sea faunistic group is characteristic for the south and east regions of the Bering Sea. The main part of the east neretic and faunistic group is located in the northeast of the

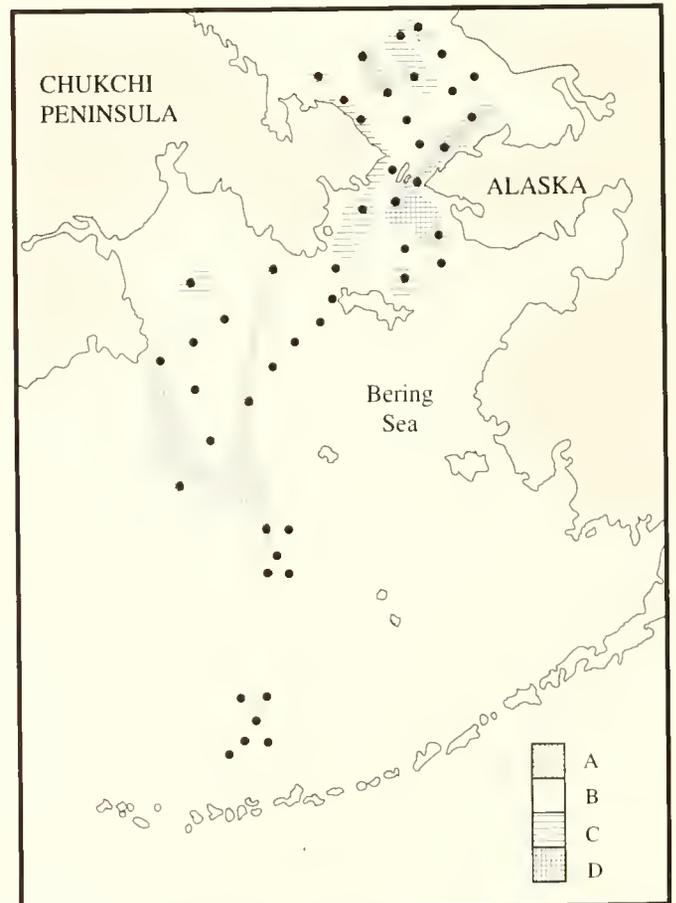


Fig. 5. Scheme of distribution (60% and more dominating) of Bering Sea faunistic groups in the neuston layer of the Bering and Chukchi Seas: A - south, B - north, C - west neritic, D - east neritic groups.

Chirikov Gulf, and through the Bering Strait near Alaskan shores enters the Chukchi Sea. The second part is found in the central region of the Chukchi Sea.

Thus, there is a mixing of three faunistic groups in the Chukchi Sea (east, west neritic, and north Bering Sea). In the Chirikov Gulf (Bering Sea), a mixing of two faunistic groups occurs (east and west neritic), and in the Gulf of Anadyr, three (west neritic, north, and south Bering Sea).

The conclusions obtained from the similarity of neuston fauna in the areas investigated according to Preston's methods (Preston, 1962) were confirmed in detail by biogeographic analysis based on quantitative as well as qualitative data.

The mosaic distribution of Bering Sea faunistic groups in the neuston layer of the Chukchi Sea confirm the complex hydrodynamics of near surface waters and their connection with the Bering Sea.

Subchapter 5.3:

Icthyoplankton

5.3.1 Larval Fish Distribution

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Introduction

Zooplankton samples are routinely taken during Shelf Transfer and Recycling Project (ISHTAR) cruises. Larval fish occurred incidentally in the samples. We decided to identify the fish and investigate the abundance and distribution of species. These results are part of the Third Joint US-USSR Bering & Chukchi Seas Expedition aboard the R/V *Akademik Korolev* from 27 July to 2 September 1988.

Materials and Methods

Ichthyoplankton were collected along with zooplankton in a 1-m circular net with 505 µm mesh. A vertical tow was made through the water column at 40 m/min. All larval fish were identified to family. Species were identified and standard length (SL) measured using vernier calipers for the Gadidae and the Pleuronectidae, teleost families containing commercially utilized species. The depth the larval fish occupied cannot be determined from this sampling technique.

Coachman and Shigaev (Subchapter 2.1, this volume) delineate three principal water masses in the northern Bering and Chukchi Seas. For the purposes of this study we are interested in two of these water masses: 1. water originating in the deep southern Bering Sea that travels in the Bering Slope Current into the Gulf of Anadyr then north through Bering Strait, herein referred to as Anadyr stream water (ASW); and 2. water that resides on the eastern central shelf of the Bering Sea characterized by lower salinity than ASW, herein referred to as Bering Shelf water (BSW). We delineated these two water masses further by the presence of certain zooplankton species. Indicator species for BSW are *Thysanoessa raschii*, *Calanus marshallae*, and *Calanus glacialis*. Indicator species for ASW are: *Thysanoessa inermis*, *Neocalanus cristatus*, *Neocalanus plumchrus*, and *Metridia* spp. Water masses were defined in order to explore the possibility of passive transport of fish larvae into or through the study area.

Chlorophyll *a* concentrations, as measured by fluorescence (Parsons *et al.*, 1984), were determined for each station (see Robie *et al.*, Subchapter 5.1.2, this volume), integrating the concentrations from discrete depths for surface to bottom or to 50 m when depths were >50 m.

Results and Discussion

Seven families: Scorpaenidae (rockfishes), Liparididae (snailfishes), Ammodytidae (sandlance), Cottidae (sculpins), Stichaeidae (pricklebacks), Gadidae (codfishes), and Pleuronectidae (flatfishes) were present. Three species of Gadidae—*Theragra chalcogramma* (walleye pollock),

Boreogadus saida (arctic cod), and *Eleginus gracilis* (saffron cod)—were identified and two species of Pleuronectidae—*Hippoglossoides elassodon* (flathead sole) and *Limanda* sp. (yellowfin sole) (Table 1) (Matarese *et al.*, 1989).

TABLE 1

Larval fishes sampled from the northern Bering and Chukchi Seas, the number of stations where each family or species was collected, the total number of each family or species in the samples, and the percent of each family and species of the total number of fish sampled during the cruise.

Taxa	Stations (N)	Larvae (N)	% Total
Liparididae	18	25	14
Ammodytidae	3	3	2
Cottidae	1	1	<1
Stichaeidae	2	2	1
Scorpaenidae	1	1	<1
Gadidae			
<i>Theragra chalcogramma</i>	26	68	40
<i>Boreogadus saida</i>	3	5	3
<i>Eleginus gracilis</i>	3	3	2
Pleuronectidae			
<i>Hippoglossoides elassodon</i>	14	56	32
<i>Limanda</i> sp.	2	8	5
TOTALS	58	172	100%

Fish larvae were found in 58 of the 90 stations sampled (Frontispiece). Abundance ranged from 1 to 29 fish per station (Fig. 1). Fish occur throughout the study area, primarily along the eastern border to the Gulf of Anadyr, in waters characterized as both ASW and BSW. Larval fish may be associated with a particular water mass, but we cannot determine this because we did not take discrete depth samples. The association of larval fish relative to phytoplankton fields as measured by chlorophyll *a* concentrations can only be discussed generally. Integrated data for each station shows an association of larval fish with chlorophyll values less than 100 mg/m³. *Theragra chalcogramma* was the most abundant and widespread of the identified species (Fig. 2). They were concentrated where BSW overlay ASW (Fig. 4), with associated chlorophyll values below 100 mg/m² (Fig. 3). Two size classes, newly hatched larvae (4–7 mm SL) and larvae 20–25 mm SL dominated the samples (Fig. 5). The larvae occurred northward of known spawning grounds and north of where known adult concentrations occur (NOAA, 1987).

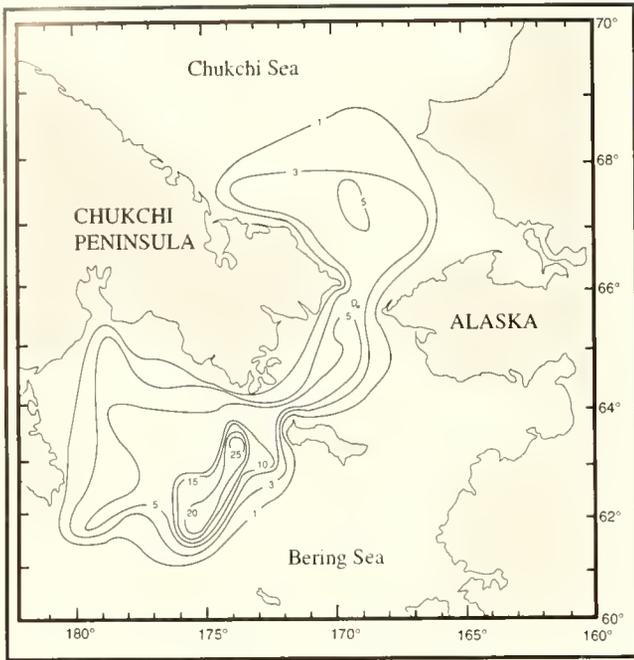


Fig. 1. Abundance and distribution of ichthyoplankton during August 1988.

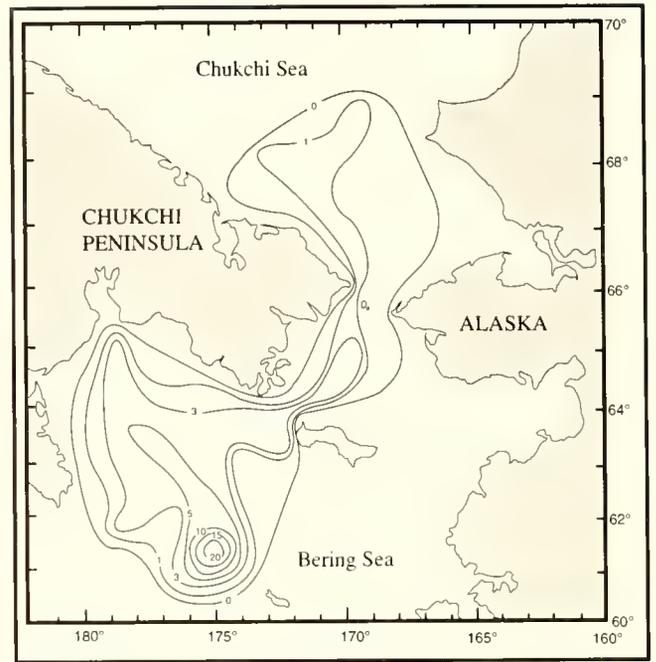


Fig. 2. Abundance and distribution of walleye pollock (*T. chalcogramma*) larvae in the northern Bering and Chukchi Seas. Abundance peaks in the northern Bering Sea. Spawning grounds are marked along the shelf break (200 m line).

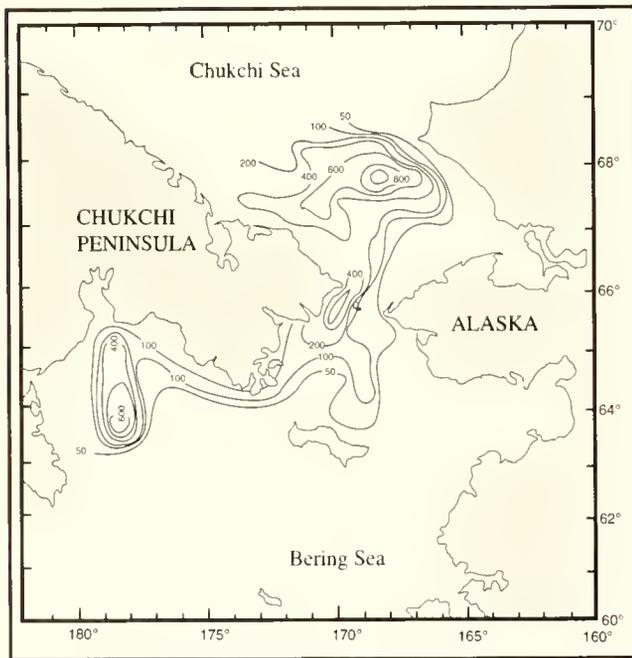


Fig. 3. Concentration of chlorophyll (mg/m^2) integrated throughout the water column (from Robie *et al.*, Subchapter 5.1.2, this volume). Larvae of *T. chalcogramma* occur where chlorophyll concentrations are $<100 \text{ mg}/\text{m}^2$.

The major spawning grounds in the Bering Sea for walleye pollock are the Korfa–Karaginskiy Shelf on the western side of the Bering Sea basin, where peak spawning times are in April and May; the southeastern shelf near Unimak Island, where peak spawning is in March and April; and the Pribilof Islands area, where the peak spawning is in April and May but extends into August; the shelf around St. Matthew Island, where peak spawning is in May and June; and the Aleutian Trough, where

peak spawning is January through March (Stepanenko, 1989). It is thought that these populations represent discrete spawning stocks (Hinckley, 1987).

Is passive transport of eggs and larvae from the known spawning grounds in Bering Slope Current a possible mechanism for the occurrence of pollock larvae in the northern Bering and Chukchi Seas? Pollock eggs have been collected from the Gulf of Anadyr between June and September, indicating advection from spawning grounds near Cape Navarin (Haryu, 1980). Low levels of larval and juvenile pollock were sampled in the Gulf of Anadyr with the highest concentrations (>10) in the area of our highest concentrations (Fig. 2) (Sobolevskiy *et al.*, 1989). Concentrations of pollock larvae in the Gulf of Anadyr can be explained by advection of eggs and larvae from known spawning areas.

Pollock larvae in the Chukchi Sea occurred in ASW suggesting advection from the south. However, spawning grounds that support the advection of larvae into the Gulf of Anadyr are too far south to be a source of larvae in the Chukchi Sea. The speed of the Bering Slope Current is $10 \text{ cm}/\text{s}$ (Kinder *et al.*, 1975; Khen, 1989). Using daily growth rates for larval pollock from the Gulf of Alaska (Yoklavich & Bailey, 1989), 5–7 mm SL larvae are approximately 4–5 days old. Adding the developmental rates for the pelagic eggs of 14 days, these larvae could be in the current for approximately 20 days. At average transport rates of $8.64 \text{ km}/\text{day}$, the larvae could cover 173 km. They would not reach the farthest stations where larvae were caught (Stations 47, 50, 69, 89, and 94; see Frontispiece), located from 300–600 km from grounds where spawning is reported to occur in July and August (Hinckley, 1987).

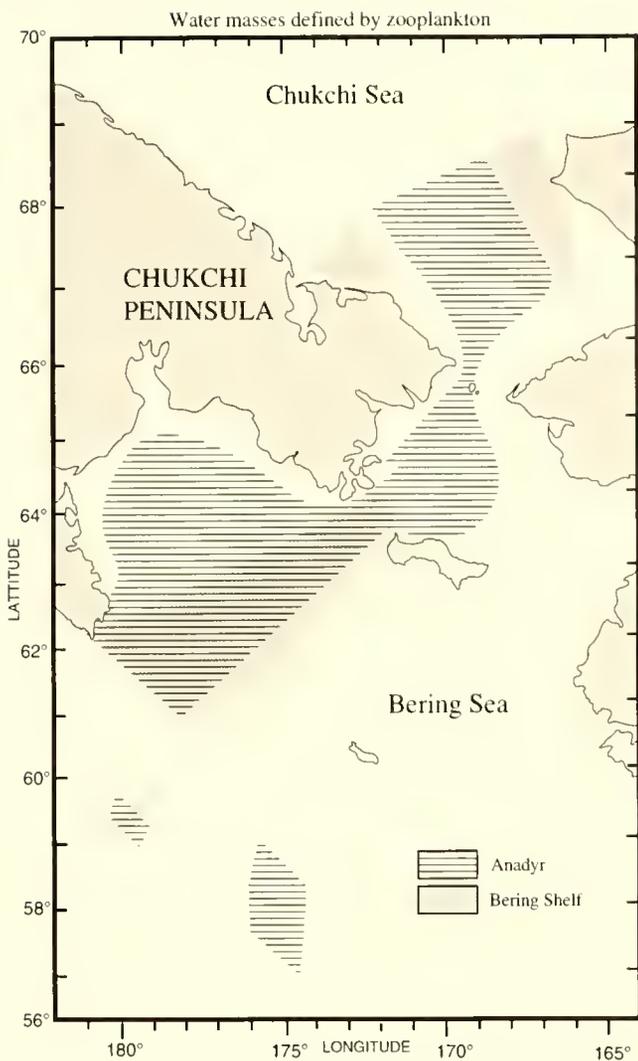


Fig. 4. Distribution of Anadyr and Bering Shelf water masses. Water masses were delineated by the species of zooplankton present in samples from 94 stations. Larvae of *T. chalcogramma* occur where shelf waters overlie oceanic waters.

The larger size range of larvae are approximately 55 days old. If we add the incubation time for eggs of 14 days, these larvae could have been transported 740 km, placing them in our study area. The original spawning stock for these fish could be the continental slope area northwest of the Pribilof Islands, where spawning takes place as late as October (Hinckley, 1987).

Two additional gadids, *B. saida* and *E. gracilis*, occurred in the Chirikov basin and Chukchi Sea where BSW overlay ASW, associated with chlorophyll values of 200–600 mg/m². Two size modes were present, newly hatched larvae (5 mm SL) and larger larvae (20 mm SL). Both species occur within the known spawning areas and the area of adult distributions (NOAA, 1987).

The flatfishes area represented principally by two species. *Hippoglossoides elassodon* concentrate at the eastern edge of the Gulf of Anadyr where BSW overlay ASW associated with relatively low integrated chlorophyll values (100 mg/m³). The samples are dominated by new hatched larvae (5 mm SL) and a few larger larvae (15 mm SL). The newly hatched larvae are

Theragra Chalcogramma

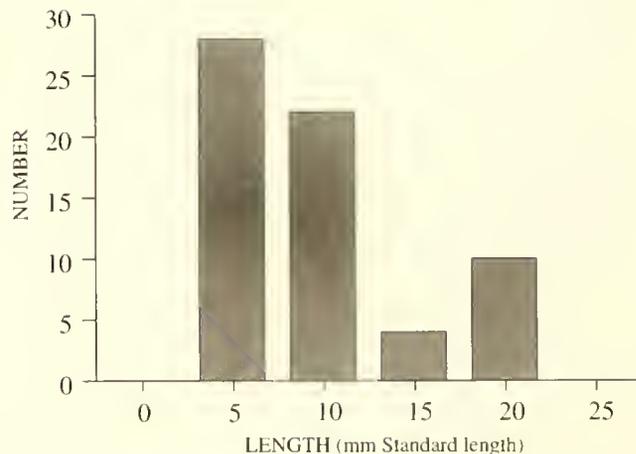


Fig. 5. Size frequency histogram of *T. chalcogramma* larvae. Two size groups occur, new hatched larvae (4–7 mm SL) and older larvae (20–25 mm SL).

present north of reported spawning grounds and much later in the season than major spawning (winter–spring) (NOAA, 1987). Again either larval transport into the area in Anadyr waters and/or a later more northerly spawning population can account for the presence of these larvae.

Limanda sp. is probably the yellowfin sole, *L. aspera*. Positive identification could not be made due to the occurrence of *L. proboscidea* in the study area, for which there is not larval description. *Limanda* sp. occurs in the Chukchi Sea in middle shelf water associated with relatively low chlorophyll values. Larvae range from 5 to 15 mm SL and occur in known spawning areas and during the spawning season.

Conclusions

1. Larval fish susceptible to capture in a 1-m, bridled plankton net were primarily commercially important species. Walleye pollock (40% of the total larval fish) and flathead sole (38% of the total larval fish) were dominant species. This study is a preliminary evaluation of the species composition and distribution of larval fishes. The number of larval fish underestimates the abundance due to patchy distributions and the potential ability of larval fish to avoid the net we used.

2. The presence of larvae in the study area could be accounted for in most cases by known spawning stocks of the species in the area or by advective transport from known spawning regions. However, for *T. chalcogramma* and *H. elassodon*, some of the newly hatched larvae were far north of known spawning areas, suggesting the possibility of as yet unknown spawning stocks.

3. The results indicate a distribution of larval fishes that warrants further investigation with the appropriate gear, sampling both larval and adult populations. We plan to investigate the possibility of a northern population of spawning walleye pollock in the area north of St. Lawrence Island.

Subchapter 5.4:

Modeling

5.4.1 Complex Ecological Evaluation of Planktonic Communities of the Pelagic Zone

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Introduction

Population–biocenotic effects of anthropogenic impacts of the marine environment, the detection of which is necessary to characterize the ecosystem stability level, are reflected in the structural and functional characteristics of its communities. However, natural communities also can cause the reconstruction of the processes of the functioning and structure of the ecosystem biotic component. At the current level of knowledge in this field, it is difficult to distinguish between the results of anthropogenic impact and natural variability. It is only possible to solve this problem in the course of long-term observations on the basis of data on the background levels of the structural and functional characteristics (Izrael & Tsyban, 1989).

Structural characteristics include evaluation of the species composition, numbers, and biomass of different systematic dimensional and trophic groups, as well as spatial and temporal variability of these parameters. Functional characteristics include the energy flux through communities, which are formed at the expense of productive and destructive processes, as well as trophic relations between the components of communities.

A great body of data characterizing the structure and functional processes of the basic elements of plankton communities was determined on comprehensive ecological expeditions in the Bering Sea (Izrael & Tsyban, 1990) organized by the Natural Environment and Climate Monitoring Laboratory in June 1981 and jointly with American specialists in 1984. These data have formed the basis for estimation of the integral characteristics of the status of the plankton communities inhabiting the epipelagic in the Bering Sea, carried out on the basis of the analysis of trophic relations between their elements. Calculations of the parameters of the production–destruction processes of zooplankton present an important stage in this work.

Materials and Methods

Our work is based on the data obtained during the comprehensive ecological investigations carried out during the expedition in the Bering Sea on board the R/V *Akademik Shirshov* in June 1981 and R/V *Akademik Korolev* in July 1984 on the South, East, and West Polygons (Fig. 1). During the investigations, the basic structural characteristics of the plankton inhabiting the surface 100-m layer (numbers and biomass of

bacterioplankton; species composition, number, and biomass of phyto-, microzoo-, and mesozooplankton) and functional ones (primary and bacterial production) were determined. Results of the analysis of the data characterizing the status of individual dimensional–trophic groups of the Bering Sea plankton community and the description of the methods used in investigations have been published in the monographs (Izrael & Tsyban, 1987) and some papers (Moisyev, 1987).

The ration and production of the heterotrophic link of plankton communities was calculated in accordance with a scheme developed in the plankton laboratory of the P. P. Shirshov Oceanology Institute of the USSR Academy of Sciences (Vinogradov & Shushkina, 1987). The authors believe this to be the only acceptable method for determining the production values of heterotrophic elements of multispecies plankton communities in the ocean pelagic region, consisting of populations with an extended period of reproduction and functioning in conditions of limited food resources.

The preparations of data for the calculations consisted, first, in separating out the elements of the communities with allowance for taxonomic, dimensional, and trophic particularities of the biota. Analysis of the trophic composition of zooplankton and communities, as a whole, was carried out using the literature data describing food interrelations in the epipelagic zones of subarctic and highly productive regions of the World Ocean (Petipa, 1981; Cooney & Coyle, 1982; Vinogradov & Shushkina, 1987). The results of the analysis made it possible to isolate nine basic elements in the Bering Sea plankton (Table 1) and evaluate the relations between them from the degree of the use of different kinds of food by various consumers (Table 2). The scheme of trophic relations includes, apart from the elements, dead organic matter ($d+y$) that resulted from the vital activity of hydrobionts and could be consumed by them again. The feeding selectivity coefficient J assumed the values 1.0, 0.5, 0.2, and 0, which corresponded to the following gradations: “consume fully,” “consume partially,” “consume little,” and “do not consume at all” (Vinogradov & Shushkina, 1987). In the case when all organisms making up the consumer element (i) are able to consume all the organisms making up the prey element (j), the coefficient was given the maximum value of 1.0. The ability of one consumer to use a variety of the objects making up the prey elements for food, J was given the value 0.5 or 0.2. If there is no trophic relationship between the elements, $J = 0$.

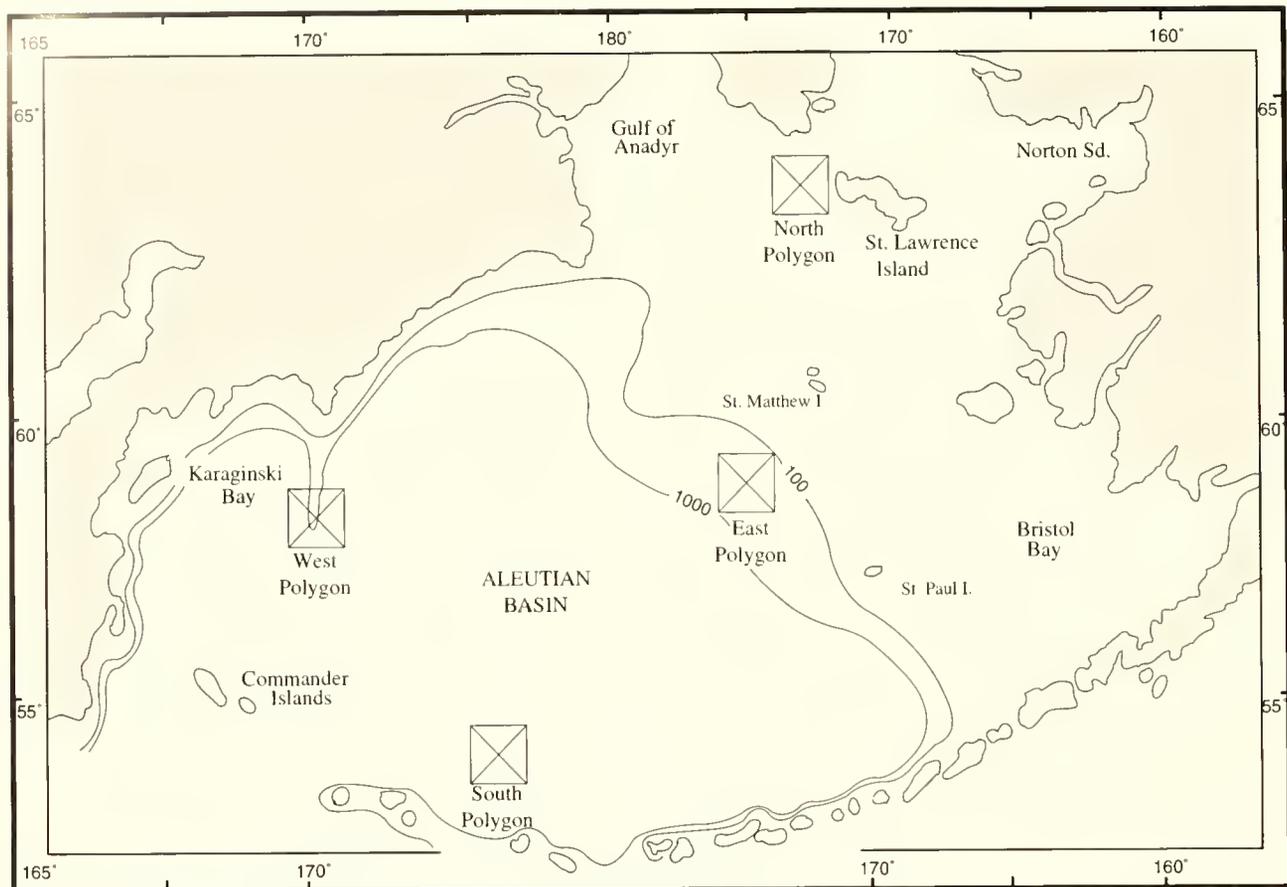


Fig. 1. Scheme of location of the polygons in the Bering Sea in June 1981 and July 1984.

TABLE 1

Elements of the plankton community, their composition and characteristics.

Group	Element	K_{max}	Assimilability	Caloric content, cal/mg wet weight	Composition of elements
Phytoplankton (p)	Small (< 15 m), (p_1)			1.0	
	Large (> 15 m), (p_2)			0.6	
Bacterioplankton (b)		0.5	1.0	1.0	
Zooplankton (z)					
Microzooplankton (a)	Zooflagellates (a_1)	0.6	0.7	1.0	
	Infusorians (a_2)	0.6	0.7	0.8	
Meso zooplankton (m)	Fine nannophage filters (f)	0.6	0.7	0.7	Copepod nauplii, copepodite stages of fine calanoid genera <i>Microcalanus</i> , <i>Pseudocalanus</i> , <i>Acartia</i> , larvae of mollusks, polychaetes, echinoderms; rotifers, appendicularians
	Small euryphages (v) (0.3-3.0 mm)	0.5	0.7	0.7	Younger copepodite of calanoid genera <i>Calanus</i> , <i>Eucalanus</i> , older copepodites of calanoid genera <i>Acartia</i> , <i>Pseudocalanus</i> , cyclopods, harpacticoids, ostracods
				0.35	Nonpredatory pteropod mollusks
	Large euryphages (g) (3.0-30.0 mm)	0.5	0.7	1.0	Older copepodites of calanoid genera <i>Calanus</i> , <i>Eucalanus</i> , <i>Euphausia</i>
Predators (s)		0.5	0.7	0.7	Decapod larvae, sideswimmers, nemertines, polychaetes
				0.35	Predatory pteropods
				0.4	Arrowworms
				0.05	Siphonophores, medusae, ctenophores

TABLE 2

Scheme of trophic relations and nutrition selectivity coefficient (J).

Consumer-element	Prey - element							
	b	a ₁	a ₂	f	v	p ₁	p ₂	d+y*
b	0	0	0	0	0	0	0	1.0
a ₁	1.0	0	0	0	0	0	0	1.0
a ₂	1.0	1.0	0.2	0	0	1.0	0.2	0.5
f	0.5	1.0	0.5	0	0	1.0	0.5	0.2
v	0.2	0.5	0.5	0.2	0.2	0.5	1.0	0.2
g	0	0	0.2	0.5	0.2	0.5	1.0	0.2
s	0	0	0.2	0.5	0.5	0	0	0

* d+y - detritus suspended (d) and dissolved (y).

The supposition that the overall ration of each element of the community [C(i)] consists of its particular rations [r_(ij)] on different food objects was used as the basis for the quantitative assessment of the trophic relations (Vinogradov & Shushkina, 1987).

The particular ration r_(ij) of the i-th consumer on the j-th prey element with the biomass B_(j) was calculated by the modified V.S. Ivlev's equation (Shushkina *et al.*, 1984):

$$r_{(ij)} = r_{(ij)}^{\max} [1 - \exp(-\xi_0 B_{(j)}) / E_{(j)}] \quad (1)$$

where E_(j) is consumption of the j-th element by all its users; $\xi_0 = 1$.

Since the value E_(j) had not been known at the moment of the calculation by the iteration method: first, the maximum tension with respect to the j-th feed,

$$K_{(j)} = \sum_i r_{(ij)}^{\max} / B_{(j)}, \quad (2)$$

and an underrated approximate value r_(ij) were calculated. Then E_(j) = $\sum_i r_{(ij)}$ was found and substituted into Equation (1) to obtain a new value r_(ij), etc., up to satisfying the equality:

$$E_{(j)} = \sum_i r_{(ij)} = \sum_i r_{(ij)}^{\max} [1 - \exp(-\xi_0 B_{(j)}) / E_{(j)}] \quad (3)$$

The value of the maximum particular ration r_(ij)^{max} was calculated by the relation:

$$r_{(ij)}^{\max} = \frac{C_i^{\max} B_j J_{ij}}{\sum_j B_j J_{ij}} \quad (4)$$

The maximum overall ration C_i^{max} was determined by the balance equation (Vinberg & Anisimov, 1966):

$$C_i^{\max} = [P_i^{\max} + R_i] / U_i \quad (5)$$

where R is the metabolic rate of the i-th element 1/U_i—the assimilability coefficient of the i-th element; and P_i^{max}—the maximum possible value of production of the i-th element was calculated by the formula:

$$P_i^{\max} = R_i \frac{K_{2i}^{\max}}{1 - K_{2i}^{\max}} \quad (6)$$

where K_{2i}^{max}—coefficient of the expenditure of food assimilated by the i-th element in growth.

The full real ration of each i-th consumer [C_i] was calculated as a sum of particular real rations:

$$C_i = \sum_j r_{(ij)}; \quad (7)$$

and production of the i-th element, except phytoplankton, as:

$$P_i = C_{(i)} U_i^{-1} - R_i \quad (8)$$

All the dimensional and trophic elements were characterized by the definite numbers N, average weight W, and biomass B. Energy value of biomass was expressed in calories on the basis of caloric content values K. It is known that its average values for copepodite plankton are equal to

0.7–0.8 cal/mg wet weight (Vinogradov & Shushkina, 1987). At the same time, the caloric content of interzonal species of Copepoda and Euphausiacea, playing an important role in the trophic chain of the Bering Sea, increased at the expense of fat inclusions up to 1.0–1.5 cal/mg wet weight (Shushkina, 1977). The bodies of an overwhelming majority of these Crustacea, found in the samples during the present investigations, contained droplets of fat. In this connection, the caloric content value of large euryphages was assumed equal to 1.0 cal/mg wet weight.

The values of the coefficient of the use of consumed food in growth, in maximum meeting food requirements of consumers K(2i max), and food assimilability 1/U(i) of each element are presented in Table 1. M. E. Vinogradov and E. A. Shushkina (1987) believe that one may use in the calculations the values of K(2i max) equal to 0.5–0.6 for elements including small animals that quickly reproduce themselves: bacteria, protozoans, and fine nannophages filters; and 0.4–0.5 for hydrobionts whose size exceeds 1.0 mm. Assimilability was assumed as a value independent of the concentration of consumed objects—it was established equal, on average, to 0.6 for plant food and 0.7 for animal food (Sushchenya, 1975). It should be noted that Japanese researchers (Ikeda & Motoda, 1978) and American ones (Dagg *et al.*, 1982) used the value of the assimilability equal to 0.7 for calculations of production of the herbivorous plankton of the Bering Sea.

The respiration rate of zooplankton was estimated with the use of the general dependence of the metabolic rate R on the weight of the body W at a water temperature of up to 20 grad, which was obtained experimentally (Shushkina *et al.*, 1984; Vinogradov & Shushkina, 1987):

$$R = 0.6W^{0.8} \quad (9)$$

where R is measured in meal/organism/day, and W in meal/organisms.

A correction for temperature allowing for Q(10)=2.2 was introduced into the values of the metabolic rate.

The respiration expenditure of the bacterioplankton and zooflagellates was determined by other methods. The calculation for the bacterioplankton was carried out with allowance for the production measured during the investigations and the efficiency of the use of assimilated food in growth, determined experimentally (Sorokin & Mamaeva, 1980): K(2)=0.33. The value of R/W for zooflagellates was assumed equal to 250%. It remained constant in all the calculations (Shushkina *et al.*, 1984).

At the productive stage of the development of plankton communities, the main course of energy is the production of photosynthesis, produced during the day under consideration. At the same time, some elements of the community are able to use the energy of autochthonous dead organic matter formed inside the community for a day and allochthonous dead organic matter introduced from outside or formed earlier, prior to the period of observations. Inclusion of dead organic matter, especially its dissolved forms, into the trophic chain of a community occurs mainly through bacterioplankton.

At the destructive stage of the development of a community, a situation may arise when the energy of autochthonous dead organic matter will not be sufficient to cover the ration of bacterioplankton. In this case, an element of self-regulation is introduced, according to the calculation scheme (Shushkina

et al., 1984; Vinogradov & Shushkina, 1987)—that is, bacteria consume, besides autochthonous organic matter, as much allochthonous organic matter as they need to meet their requirements for food in conditions of production of this element, determined experimentally, and in order that the production calculated on the above scheme corresponded to that determined experimentally (Shushkina *et al.*, 1984b). It is assumed that allochthonous organic matter consumed by other elements of the community is far less than that consumed by bacterioplankton, and it is not taken into account in the calculation scheme.

The method makes it possible not only to estimate the net production of the community [P(0)] equal to the difference between the primary production formed at the entrance into the system [P(p)] and the heterotrophic destruction of the community $D_o = \sum_{i=b}^s R_i$, but also to estimate the actual production of the community, P_{act} , which takes into account at the beginning the primary production and allochthonous organic matter arriving to the trophic chain the bacterial link:

$$P_{act} = P_p + r b x - D_o \quad (10)$$

where $r(bx)$ is the ration of allochthonous organic matter.

There following tropho-ecological characteristics of the elements and community as a whole (Vinogradov & Shushkina, 1987) are used in the work:

—the degree of the satisfaction of requirements in food of the consumer element (i):

$$S_i = c_i / c_i^{max} \quad (11)$$

—real specific production of the prey element (j):

$$\xi_j = \tau \frac{P_j - E_j}{B_j} \quad (12)$$

where $2\tau 0 = 1$ day; and the ratio of the energy assimilated by bacterioplankton and other detritophages to the total energy of detritus energy and phytoplankton assimilated by all the heterotrophic parts of the community:

$$\rho = \frac{\sum_{i=b}^f A_i(d+y)}{\sum_{i=b}^f A_i(d+y) + \sum_{i=a}^s A_{ip}} \quad (13)$$

As a criterion for determining the trophic character of waters, use was made of the ratio of the primary production level to the overall heterotrophic destruction level [$K_{3p} = P_p / D_o$] according to the following ranges of the coefficient values: $K(3p) > 2$, hypertrophic; $2 > K(3p) > 0.7$ eutrophic; and $0.7 > K(3p)$, oligotrophic water (Lebedeva, *et al.*, 1982; Vinogradov & Shushkina, 1983).

Results

The values of the structural and functional characteristics of the plankton community found in the epipelagic region of the southwestern Bering Sea at South and East Polygons consisted of 71% mesozooplankton hydrobionts; the portions of other dimensional and functional groups accounted for 10% each.

The results obtained have indicated that the community under consideration was at the destructive stage of the seasonal development and experienced a deficiency of newly formed organic matter. The amount of energy necessary to maintain the vital activity of heterotrophic elements [$D(o)$] was nearly

four times more than the energy arriving to the community as a result of photosynthesis of phytoplankton [P(p)], which determined respectively the negative values of the net production of the community [P(o)]. Its average level was $-11.8 \text{ kcal/m}^2 \text{ day}$. The average values of the coefficient of the primary production of the community [$K(3p)$] made it possible to place the waters of the study areas into the category of mesotrophic waters. It should be noted that 74% of the values of the overall heterotrophic destruction consisted of the respiration expenditure by bacterioplankton.

Energy of allochthonous organic matter arriving to the community though the bacterial link fully covered a shortage of the production of autotrophs. As a result, the actual production levels of the community [P(act)] had positive values and amounted to an average of $4.9 \text{ kcal/m}^2 \text{ day}$.

Functioning of the zooplankton elements of the community, in such a situation, was based to a great extent on the detrital food chain. The amount of the energy of dead organic matter assimilated by heterotrophic accounted, on average, for 53% of the total volume of the energy (ρ) assimilated by heterotrophs.

Only 29% of the total ration of zooplankton consisted of phytoplankton. The basis objects of its food were the following heterotrophic elements: bacterioplankton (24%) and small zooplankton (37%). The existence of the communities under conditions of a deficiency of newly formed organic matter caused a certain tension in the trophic relations, which was reflected in a comparatively low degree of satisfaction of the food requirements of zooplankton (δ): 73%, on average, for infusorians and 81% for mesozooplankton, as well as in the negative values of the rates of real production (ξ) of micro- and mesozooplankton. This indicates a tendency for an increase in biomass of these elements.

Unlike the polygons located in the southwestern deep-water region of the Bering Sea, the North Polygon was characterized by the status of the plankton communities in two kinds of water masses of different origin and having different hydrological indices, namely, the waters of the central shelf (the central and south areas of the polygon) and the waters of the Anadyr Current (the north area of the polygon) (Izrael & Tsyban, 1990). In this connection, the structural and functional characteristics of the plankton communities discovered in the region of the North Polygon differ greatly from those calculated for the community of the epipelagic regions of deep-water areas of the Bering Sea and were different inside the polygon; the characteristics of its north region differed appreciably from those in its southern part (Table 3).

In the waters of the Anadyr Current (the northern part of the North Polygon), the community was at the clearly expressed production stage of succession. Its total biomass [B(o)] was maximum over the whole water area of the sea and amounted to an average of 61.3 kcal/m^2 . The biomass of phytoplankton makes up more than two-thirds of this volume; the remaining part consisting of mesozooplankton content of the pelagic region was not significant.

The production of phytoplankton was almost four times more than the overall magnitude of destruction of organic matter. The magnitude of production of the community [P(o)]

TABLE 3

Structural and functional characteristics of the plankton community of the Bering Sea in July 1984.

Characteristics 1	Elements of the plankton (i, j) 2	POLYGONS				
		South 3	East 4	West 5	North	
					Northern part 6	Southern part 7
B_o , kcal/m ²		41.3 ± 7.3	37.9 ± 6.6	51.0 ± 1.2	61.3 ± 3.9	28.8 ± 3.2
B_i/B_o , %	p	6 ± 2	12 ± 5	11 ± 4	69 ± 2	69 ± 2
	b	8 ± 2	12 ± 4	3 ± 0.5	2 ± 0.3	9 ± 3
	a	14 ± 6	12 ± 2	9 ± 1	2 ± 0.5	6 ± 1
	m	72 ± 7	64 ± 10	77 ± 4	27 ± 1	17 ± 2
D_o , kcal/m ²		9.0 ± 1.7	17.7 ± 1.8	23.8 ± 3.3	10.8 ± 0.4	11.4 ± 1.7
R_i/D_o , %	b	59 ± 10	80 ± 2	82 ± 2	90 ± 2	91 ± 2
	a	24 ± 9	9 ± 1	8 ± 2	3 ± 1	6 ± 2
	m	17 ± 4	11 ± 2	10 ± 1	7 ± 1	3 ± 1
P_p/D_o		0.33 ± 0.13	0.22 ± 0.08	0.27 ± 0.06	3.90 ± 0.46	0.65 ± 0.18
P_o , kcal/m ² day		-7.1 ± 2.6	-13.1 ± 2.1	-15.1 ± 2.1	30.1 ± 3.2	-5.3 ± 2.3
P_{act} , kcal/m ²		0.7 ± 1.3	6.1 ± 3.4	7.9 ± 0.1	44.1 ± 3.0	7.3 ± 1.2
ρ , %		62 ± 3	61 ± 7	36 ± 6	11 ± 1	30 ± 9
E_i/C_z , %	p	24 ± 6	23 ± 4	40 ± 9	94 ± 1	78 ± 7
	b	28 ± 2	27 ± 3	16 ± 2	2 ± 1	14 ± 6
	z	37 ± 5	37 ± 5	38 ± 6	4 ± 1	5 ± 1
	d+y	11 ± 2	13 ± 2	6 ± 1	0	3 ± 1
δ , %	a	75 ± 4	72 ± 4	71 ± 4	100	98 ± 1
	m	82 ± 2	80 ± 2	82 ± 3	100	99 ± 1
ξ	p	0.62 ± 0.51	2.58 ± 2.37	0.34 ± 0.19	1.07 ± 0.29	0.12 ± 0.07
	b	0.11 ± 0.34	2.27 ± 0.65	5.27 ± 1.77	4.99 ± 1.28	3.13 ± 0.94
	a	-0.12 ± 0.09	-0.16 ± 0.09	-0.17 ± 0.10	0.36 ± 0.03	0.38 ± 0.01
	m	-0.13 ± 0.05	-0.13 ± 0.05	-0.12 ± 0.06	0.08 ± 0.01	0.10 ± 0.01

reached the average value equal to 30 kcal/m² day, which made it possible to classify the waters of the studied area as hypertrophic waters.

The degree of satisfaction of the food requirements of consumers (δ) was maximum, which was indicative of the absolute availability of food. Ninety-four percent of their total ration consisted of phytoplankton; the detrital component was practically absent [$E(i)/C(z)$]. The average value of the index (ρ), through which the role of detritus in the total volume of energy assimilated by heterotrophs, was estimated and accounted for only 11%. Consequently, the food chain of the plankton community was realized more completely in the waters of the Anadyr Current as compared to other studied areas.

In the waters of the central shelf region (the southern part of the North Polygon) the level of the overall biomass of the plankton community [$B(o)$] was very low and did not exceed 30 kcal/m². This value was two times less than that in the waters of the Anadyr Current.

While the fraction of phytoplankton remained constant in spite of the absolute reduction of the biomass of autotrophs by half, the mesozooplankton content decreased by 10%, and its biomass became three times less, and the role of bacterio- and microzooplankton increased to 9% and 6%, respectively.

The productivity of waters in the region under consideration was low and corresponded to the mesotrophic level.

The relation between the rates of the primary production and overall heterotrophic destruction pointed to the predominance of the process of destruction of organic matter over photosynthesis in the same proportion as in the deep-water southwestern region of the sea. A deficiency of the consumed organic autochthonous matter [$P(o)$] reached 5.3 kcal/m² day, but it was covered in plenty at the expensive of allochthonous organic matter [$P(alt)$]. Judging by the low production rate of phytoplankton ($P/B = 0.25/day$), the cells of algae were in an inactive state. It is felt that the major fraction of phytoplankton biomass arrived to this region from the water area of the Anadyr Current where plankton was characterized by the maximum possible production and by accumulation of the autotrophs due to the horizontal mixing of water mass.

Due to the low productivity of the shelf waters, the trophic relations inside the plankton community were tense. The degree of satisfaction of the nutritional requirements of zooplankton did not reach the maximum level, 98–99%. Apart from phytoplankton (78%), bacterioplankton (14%) and detritus made up the ration of the animals. The energy flux through the detrital chain increased up to 30% (ρ) as compared to that calculated for the Anadyr Current. In spite of the low productivity of shelf waters, the rate of actual production (ξ) of all the elements of the community was positive, which pointed to a tendency towards an increase in their biomass.

Conclusion

The results of the comparative analysis of the status of the plankton communities discovered in June 1981 and July 1984 have shown that the majority of revealed changes constituted a part of the seasonal spring–summer dynamics of the structures and functions of the pelagic communities in the basin under consideration (Geinrikh, 1959; Kun, 1975). At the same time, it is obvious that the revealed differences were determined, to a certain measure, by the interannual variability of the habitats of the communities. At the present stage of investigations, it is not possible to distinguish between them, but we believe that the seasonal variability is a determining factor; therefore, the data obtained were considered in the aspect of the seasonal variability.

The structural and functional characteristics of the Bering Sea plankton communities are described in detail in a monograph (Izrael & Tsyban, 1990).

Comparing the structure of the community populating the deep-water southwestern Bering Sea in June 1981 and July 1984, it should be noted that in the changeover from the spring to summer season, the biomass of the whole community decreased, on average, by a factor of 1.5, and, in particular in the East Polygon, by a factor of 2 (Fig. 2). A decrease in the level of the index occurred primarily at the expense of phyto- and bacterioplankton. Their biomass decreased by a factor of 2.6 and 3.0, respectively.

The character of changes in the biomass of plankton elements was not similar. Thus, at the West Polygon where the epipelagic community was, due to the geographic location, at an earlier stage of the seasonal development as compared with other sea areas (Kulikov, 1989), the biomass of microzooplankton increased by a factor of 1.7 and that of mesozooplankton, by a factor of 1.2. At the same time, a significant decrease of the mesozooplankton biomass (on average, by a factor of 1.7) was observed at South and East Polygons. As a result of the seasonal reconstruction of the structure of the community, the fraction of autotrophs reduced in July by a factor of 2 and that of zooplankton, vice versa, increased by a factor of 1.2 in all the investigated areas of the deep-water region of the Bering Sea.

In the shelf region of the northern Bering Sea, the trend of the seasonal succession in the north sharply differed from that in the south. In the south of the North Polygon, the dynamics of the structure of the shelf pelagic community had the same features as that in the deep-water regions (see Fig. 2). In contrast, in the northern area of that polygon, in the waters of the Anadyr Current, the biomass of the community increased by a factor of 1.5. This was determined by an increase in the biomass of phytoplankton by a factor of 1.6 and in that of mesozooplankton by a factor of 2.3. The relative values of the biomass of these elements changed in the same direction, but to a lesser extent. At the same time, the fraction of the biomass of microheterotrophic elements decreased, on average, by a factor of 3–5.

The character of the functions of the plankton communities in the surface waters of the Bering Sea also underwent a

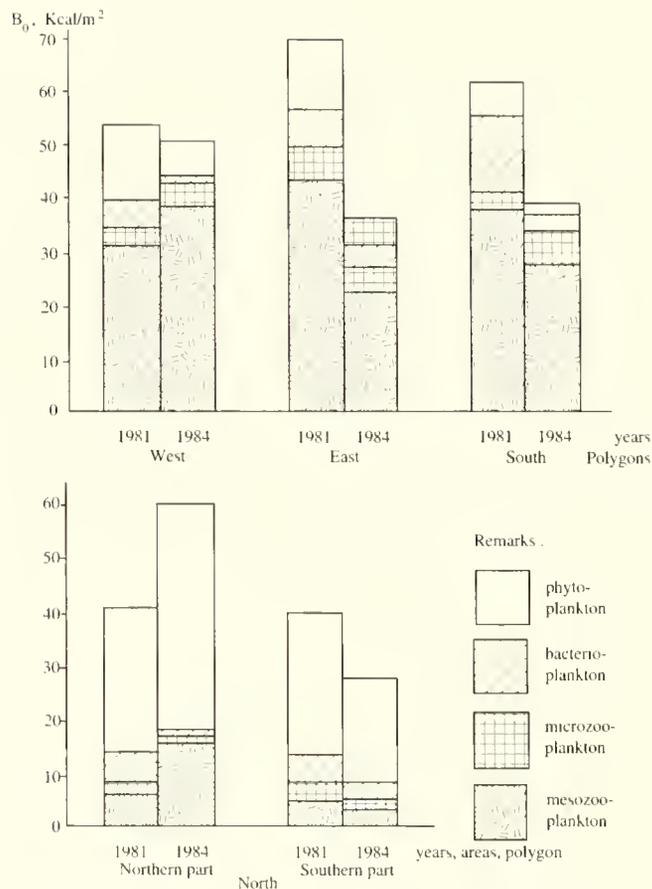


Fig. 2. Biomass of the plankton communities (B_0) and consisting elements (B) in June 1981 and July 1984.

number of significant changes in July 1984 as compared to June 1981. For instance, the levels of the overall heterotrophic destruction of organic matter in the southwestern sea (South, East, and West Polygons) increased by a factor of 2–5 and at North Polygon by a factor of 6. So sharp an increase in the rate of destruction in July was caused by a significant increase by a factor of 6–13 in the intensity of vital activity of the bacterial link of the epipelagic communities. The fraction of bacterial destruction in the total flux reached, on average, 90% in July 1984 versus 43% in June 1981.

As a result of increased expenditure of the communities on metabolism in the summer period, the balance of production–destruction processes observed in spring was disturbed in the epipelagic region of the deep-water sea areas and shelf water masses (Fig. 3). A deficiency of newly formed organic matter $[P(o)]$ in these regions amounted to an average of $12 \text{ kcal/m}^2 \text{ day}$. Attention is drawn to the fact that in spring the inflow of the energy of allochthonous organic matter to the community was small and did not produce a significant effect on the levels of the actual production $[P(\text{act})]$, and in summer its volume sharply increased and covered in plenty a shortage of organic matter produced in the community. Thus, for instance, at the West Polygon, in the most productive waters among those investigated in the deep-water sea area, the average value of the actual production of the community reached in June and July $1.1 \text{ kcal/m}^2 \text{ day}$ and $7.9 \text{ kcal/m}^2 \text{ day}$,

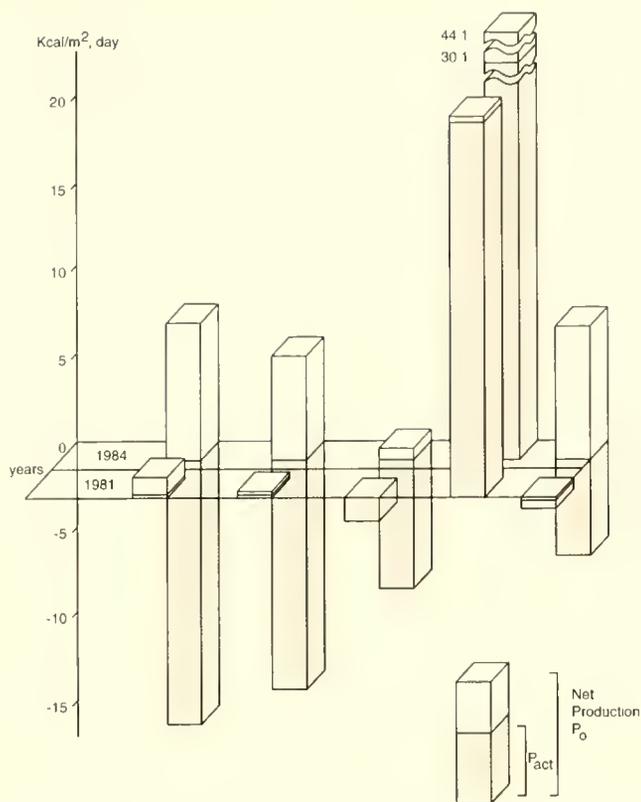


Fig. 3. Net (P_o) and actual (P_{act}) production of the plankton communities in June 1981 and July 1984.

respectively. In the waters of the Anadyr Current, the level of the net production in summer increased as compared with spring values by a factor of 1.5 and that of the actual production by a factor of two.

Intensification of destruction in summer adversely affected the efficiency of production of the autotrophic link (Fig. 4). After the changeover of the community populating the epipelagic region of the southwestern deep-water area of the Bering Sea from the spring status to the summer one, the levels of the index $K(3p)$ decreased by a factor of two to five, which is indicative of a decline in the trophic character of water, from the eutrophic level in June 1981 to the mesotrophic one in July 1984. In shelf water masses, no changes in the level of trophicity occurred, since an increase in the destruction was compensated by an increase in primary production. In the waters of the Anadyr Current, in spite of an increase in the values of the coefficient on average by a factor of three, they remained at a high level, which characterizes the waters of this region as hypertrophic.

It should be noted that during both the spring and summer seasons of the investigations, the energy flux through the detrital food chain played an important role primarily in the functions of the plankton community populating the epipelagic region of the deep-water area of the Bering Sea (Fig. 5). The levels of the values of ρ , which characterized the energy fraction of assimilated dead organic matter in the total volume of the energy assimilated by heterotrophic elements, were maximum at later stages of seasonal development of the community (at the South and East Polygons).

The trend of the seasonal succession of the Bering Sea plankton communities, accompanied by a change in the structure

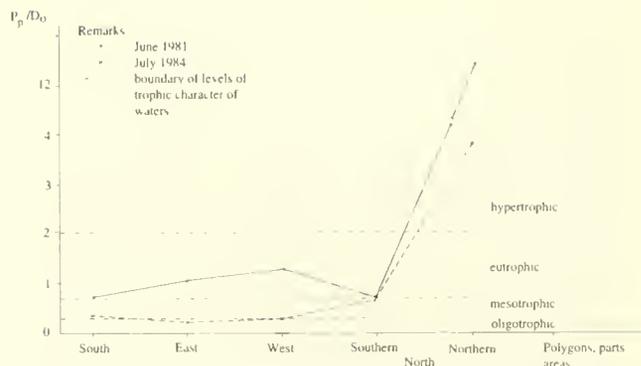


Fig. 4. Efficiency of production P_p/D_o of the plankton communities in June 1981 and July 1984. P_p - production of phytoplankton; D_o - heterotrophic destruction of the community.

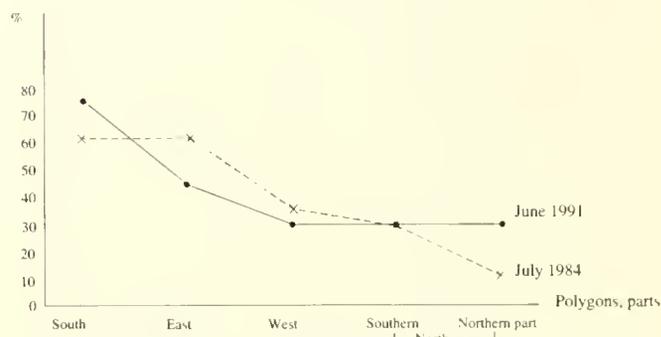


Fig. 5. Relations between level of energy assimilated by bacteria and other detritophages and level of energy of dead organic matter and phytoplankton assimilated by all heterotrophs of the plankton communities in June 1981 and July 1984.

and parameters of the processes of functioning, also included a reconstruction of trophic interrelations between the elements of the communities in the quantitative respect.

A decrease in the supplies of "primary food" in the epipelagic region of the deep-water in the summer season has led to intensification of preying of euryphages on others (Fig. 6). The fraction of animal food became predominant in the overall ration, of zooplankton elements in contrast to their spring ration, in which vegetable food predominated. A contrary tendency was observed at the North Polygon where the fraction of phytoplankton in the ration of zooplankton increased in a changeover to the summer season.

In conditions of a summer deficiency of easily assimilated food, observed in the southwestern Bering Sea, the degree of meeting nutritional requirements (δ) of micro- and mesozooplankton decreased appreciably as compared with the levels calculated for the spring season (Fig. 7). The real specific production of these elements (ξ) acquired negative values, which was indicative of the appearance of a tendency towards a decrease in their biomass (Fig. 8). At the same time, trophic tension appeared in June in the elements of phyto- and bacterioplankton and, vice versa, disappeared in July, and it became possible for the elements to increase their biomass.

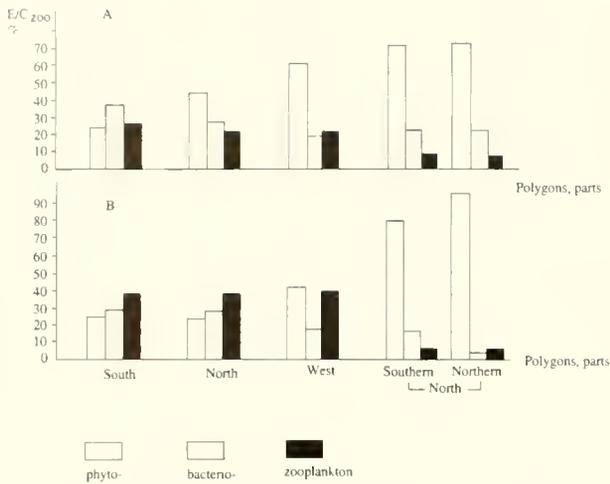


Fig. 6. Composition of the ration of zooplankton (E/C_{zoo}): A. June 1981; B. in July 1984.

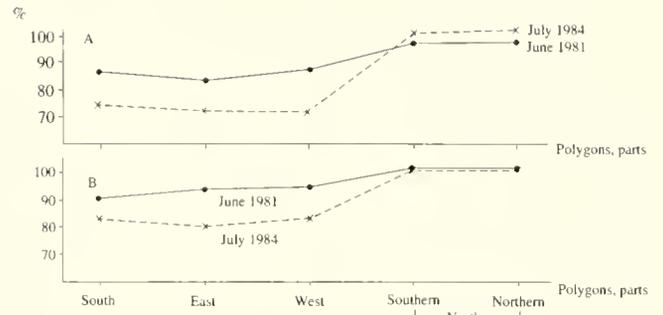


Fig. 7. The degree of satisfaction of the nutritional requirements of macrozooplankton (A) and mesozooplankton (B) in June 1981 and July 1984.

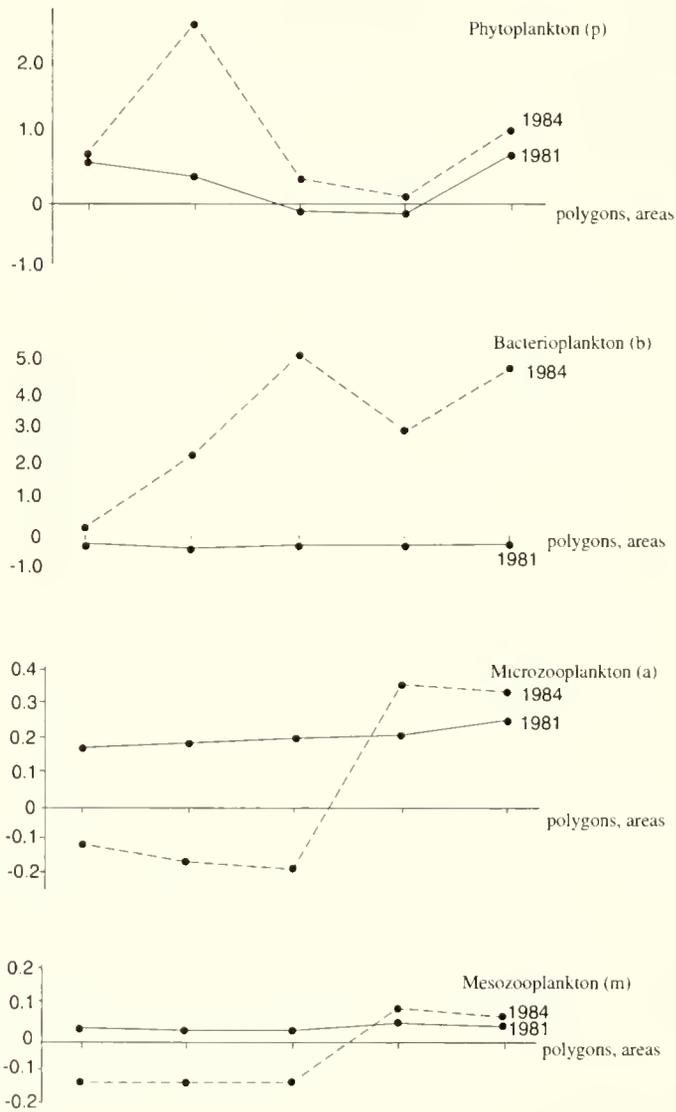


Fig. 8. Real specific production of elements (ξ_i) of the plankton communities (June 1981 and July 1984).

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Chapter 6:
PRIMARY PRODUCTION

Editors:

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6.1 Primary Production of Organic Matter

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Introduction

The Bering and Chukchi Seas are situated in the subarctic and arctic regions of the Pacific and Arctic Oceans. They are among the most productive regions of the oceans. Consequently, these areas are of great significance from the standpoint of fisheries. For example, the annual output of the sea products in the region of the Bering Sea is approximately 3 million tons, including 1 million tons of fish (Sorokin *et al.*, 1983). The results of previous research conducted in the Bering Sea showed that, from the point of view of productivity, this basin is comparable to the upwelling regions of the Pacific and Atlantic Oceans (Sorokin, 1973; Izrael & Tsyban, 1981; Korsak, 1982, 1985; Sorokin *et al.*, 1983; Tsyban, 1985; Tsyban *et al.*, 1985).

The amount of annual gross primary production in the Bering Sea is about 1–1.5% of the total primary production of the World Ocean (Sorokin *et al.*, 1983; Korsak, 1985).

The amount of organic production reaches $7 \text{ g C m}^{-2} \text{ d}^{-1}$ in some regions of the sea during the period of biological succession of the plankton community. This allows us to classify the Bering Sea as a eutrophic water basin (Sorokin, 1973; Korsak, 1982; Sorokin *et al.*, 1983; Tsyban *et al.*, 1985).

In contrast to the Bering Sea, the ecological system of the Chukchi Sea has been explored to a much lesser degree. The existing data from the literature, however, allow one to presume that the productivity of this basin is also rather high (Sorokin, 1973; Korsak, 1982). According to the classification of waters of the World Ocean, proposed by O. A. Koblents-Mishke *et al.* (1970), the Chukchi Sea is considered to be mesotrophic. The amount of net production of the region is $35\text{--}55 \text{ g C m}^{-2}$ annually (Sorokin, 1973). For the purpose of comparison, it should be noted that this amount for the Bering Sea is 90 g C m^{-2} .

The amounts of primary organic production in the Bering Sea and in the Chukchi Sea were determined during the course of the Third Joint US-USSR Bering & Chukchi Seas Expedition on the Research Vessel (R/V) *Akademik Korolev* in July–August of 1988. In contrast to the previous expeditions of 1981 and of 1984, the research conducted this time covered a much larger area of the Bering Sea, including the insufficiently studied northwestern and northern regions of the sea, the Bering Strait, and the southern part of the Chukchi Sea.

Materials and Methods

The measurements of phytoplankton primary production were performed at 23 stations in the Bering Sea and 11 stations in the Chukchi Sea during the period from July 28 through

August, 1988. The determination of phytoplankton production was conducted with the bottle method and ^{14}C modification proposed by Sorokin (Sorokin, 1973; Sorokin *et al.*, 1983). The depth of the euphotic zone was assumed to be equal to triple the Secchi disk transparency. The samples were taken with 5-l Niskin bottles from depths of 0.5, 5, 10, 15, 25, and 45 m. As a rule, incubations were started in the morning and continued for a 6-hour exposure period.

Seawater samples were incubated in a flowing seawater bath, located on the deck of the ship in conditions of natural light. Special experiments determining photosynthetic dynamics during the day were performed in order to calculate the daily production values. Radioactivity of the ^{14}C labeled phytoplankton retained on the filters and of ^{14}C isotope solutions was measured with the use of a scintillation counter, "Rack- β ," in the course of the voyage. The biomass of phytoplankton was calculated on the basis of chlorophyll concentration, with the assumption that chlorophyll accounted for 0.3% of total organic content of phytoplankton. For calculation of daily values of P/B coefficients, it was assumed that the amount of organic carbon in the biomass of seaweeds is 6%.

Results and Discussion

The third complex ecological expedition started its work at the end of July 1988 in the region called East Polygon. This area is situated in the central part of the Bering Sea, near Pearl canyon. According to the results obtained during the expeditions of 1981 and 1984, the amounts of primary organic production in this area of the sea during the middle-to-end of biological summer were $430\text{--}530 \text{ mg C m}^{-2} \text{ d}^{-1}$, and the values of P/B coefficients were 0.48–0.56 (Izrael & Tsyban, 1981; Korsak, 1982, 1985; Sorokin *et al.*, 1983; Tsyban, 1985; Tsyban *et al.*, 1985). The results of the measurements of primary production in the East Polygon during the third ecological expedition give ground to suppose that the development of phytoplankton on Stations 1–5 took place rather actively. The average values of primary production at these stations were approximately $1,300 \text{ mg C m}^{-2} \text{ d}^{-1}$, with a station-to-station range of 840 to $2,600 \text{ mg C m}^{-2} \text{ d}^{-1}$ (Tables 1, 2; Fig. 1). The value of P/B coefficient varied from 0.84 to 1.6. It is obvious that significant variations of the primary production indicate high heterogeneity of water masses in this region during the research period.

Further experiments on determination of primary organic production were done in the Gulf of Anadyr. This region is comparatively less studied, from the point of view of production biology, than the rest of the Bering Sea (Fig. 1). At the entrance to the gulf, on Stations 6 and 7, the level of primary production

TABLE 1

Primary production (mg C m⁻³ per day) at given depth for stations of the Bering Sea.

Depth (m)	Station																	
	1	2	3	4	5	6	7	12	13	29	22	83	86	89	92	96	100	102
0.5	250	1,900	780	140	64	150	15	230	95	47	260	22	520	140	5.1	82	53	40
5	90	2,250	810	85	120	146	20	240	69	34	242	28	270	82	7.7	68	41	18
10	58	1,250	390	11	48	58	11	-	-	-	-	11	83	-	3.4	-	29	5.2
15	18	280	11.0	4.3	9.6	9.2	10	36	11	9.3	31	3.6	42	19	2.1	7.4	13	4.4
25	5	3.8	4.7	0.14	1.3	1.5	0.15	2.3	1	0.47	0	0.3	2.1	0.25	0.15	0.5	0.7	0.4
P'	1,500	2,600	830	810	1,000	980	290	2,800	880	450	2,800	190	2,500	1,070	82	750	560	240
B**	1.0	2.6	0.84	1.0	0.44	0.62	0.34	0.26	3.0	-	-	0.76	3.5	1.4	0.6	3.5	1.5	0.6
P/B	1.6	1.0	1.0	0.84	2.5	1.6	0.90	-	0.28	-	-	0.37	0.91	0.71	0.14	0.21	0.37	0.4

* Integral primary production (mg C m⁻² d⁻¹)

** Integral phytoplankton biomass (g C m⁻²)

TABLE 2

Primary production (mg C m⁻³ d⁻¹) in the Bering and Chukchi Seas.

Depth (m)	Station															
	32	104	106	109	112	45	49	50	53	55	57	59	64	68	69	74
0.5	350	77	86	2.5	5.0	36	20	21	31	37	21	30	3.6	2.9	112	97
5	270	57	67	4.8	10.5	27	19	26	50	76	23	33	82	14	150	104
10	120	-	26	1.7	-	16	16	28	53	140	-	-	290	13	9	130
15	46	8.5	10	0.5	1.2	5	15	9.4	46	290	-	-	206	-	9	75
25	3.5	0.5	0.3	0.00	0.04	14	5	2.6	34	130	75	195	42	0.4	24	18
45	-	-	-	-	-	0.11	0.4	0	0.9	-	-	-	-	-	-	-
P'	3,210	680	720	38	100	420	404	390	1,400	4,700	1,070	2,400	-	-	970	2,020
B**	-	1.3	0.78	0.56	0.40	5.0	-	0.13	0.84	16	5.0	2.8	-	-	3.0	1.9
P/B	-	0.52	0.92	0.07	0.25	0.08	-	3.0	1.7	0.29	0.2	0.86	-	-	0.32	1.0

* Integral primary production (mg C m⁻² d⁻¹)

** Integral phytoplankton biomass (g C m⁻²)

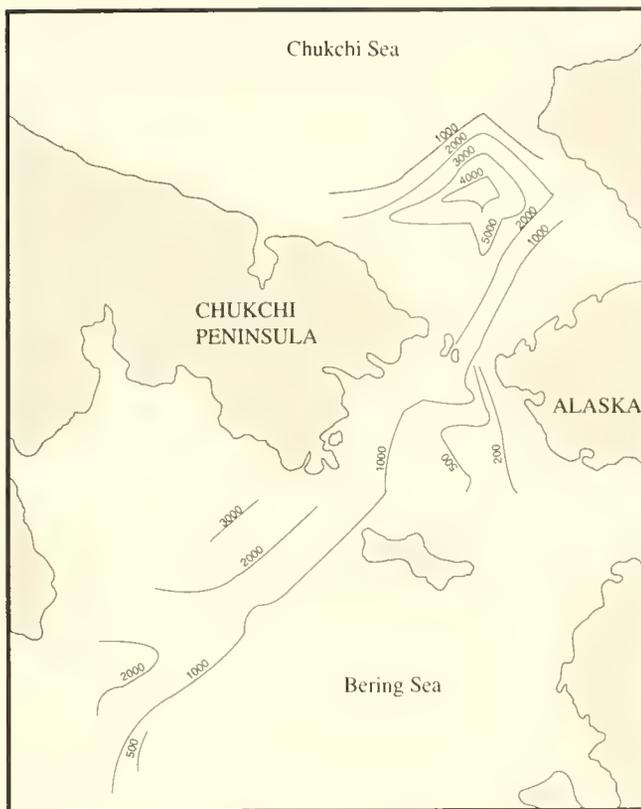


Fig. 1. Distribution of primary production in the Bering and Chukchi Seas (July–August, 1988). Values are represented in $\text{mg C/m}^2 \text{ day}$.

was 980 and 290 $\text{mg C m}^{-2} \text{ d}^{-1}$, respectively (Table 1). The level of primary production at stations located in the gulf itself varied from 470 $\text{mg C m}^{-2} \text{ d}^{-1}$ at Station 19 to 3,200 $\text{mg C m}^{-2} \text{ d}^{-1}$ at Station 32 (Table 1).

The average value of primary production in the Gulf of Anadyr was 1,850 $\text{mg C m}^{-2} \text{ d}^{-1}$, and the average value of the P/B coefficient was 0.8. It should be noted that the highest values of phytoplankton production were obtained in the western part of the gulf (Tables 1,2). In the eastern part of the gulf, the production of phytoplankton was considerably less (Fig. 1).

The research on determination of primary production of phytoplankton in the Chirikov Basin showed that in the middle of August, the value of primary production was approximately 1,800 $\text{mg C m}^{-2} \text{ d}^{-1}$ in the western part of the gulf, 600 $\text{mg C m}^{-2} \text{ d}^{-1}$ in the central part, and only 320 $\text{mg C m}^{-2} \text{ d}^{-1}$ in the eastern part of the gulf (Table 1).

It should be noted that the peculiarities of the distribution of primary organic production in the northwestern and northern regions of the Bering Sea observed during the expedition are very closely correlated with the quantity of nutrients and the quantity of phytoplankton in these regions of the sea.

Thus, according to the results obtained by the American research workers who participated in the expedition on board the R/V *Akademik Korolev*, the stations richest in nutrients and chlorophyll *a* were situated in the western part of the research area. An especially high concentration of chlorophyll *a* (55 mg Chl m^{-3}) was discovered in the Gulf of Anadyr. High productivity of the Gulf of Anadyr waters can be explained by the topographically induced rise of deep waters. These waters

are rich in nutrients and are brought into the photosynthetic zone by the transverse current along the shelf. The same current, which provides high productivity of the Gulf of Anadyr, moves further on to the north, along the eastern Soviet coast and Saint Lawrence Island into the Chirikov basin. Situated between Saint Lawrence Island and the Bering Strait, the Chirikov Basin differs significantly from the Gulf of Anadyr. Cold waters, rich with nutrients, are located along the Chukchi coast. Along the coast of Alaska, however, there are low-salinity, low-nutrient shelf waters, which result from runoff from the coast. According to the data obtained by the American specialists, the concentration of chlorophyll *a* in this area was only 1–5 mg m^{-2} at that time.

The investigations in the southern part of the Bering Sea were performed at the end of August, in the region called South Polygon. The amounts of phytoplankton production at stations in this region were comparatively small, 40–105 $\text{mg C m}^{-2} \text{ d}^{-1}$, which seems to be typical for the period of biological autumn. During the expeditions on the R/V's *Shirshov* and *Akademik Korolev*, in 1981 and 1984, this region was investigated one month earlier in the period of the middle of biological summer. Naturally, the values of primary production measured at that time were a bit higher for this region: on average, 190–320 $\text{mg C m}^{-2} \text{ d}^{-1}$ (Tsyban *et al.*, 1985). At the same time, the values of P/B coefficient were 0.11–0.71. This indicates relatively high intensity of photosynthesis, which is an important characteristic for the period of biological summer. The values of P/B coefficient during the third ecological expeditions on the stations of this region were 0.40–0.56.

Concerning vertical distribution of primary production in the Bering Sea, it should be noted that, similar to the research of 1981 and 1984, the depth of the euphotic zone during this time did not exceed 45 m (Tables 1,2). As a rule, the vertical profiles of primary production had a maximum located within the area of optimal light conditions at 5–10 m or more seldomly in the surface layer. The values of primary production below this maximum decreased monotonically (Tables 1,2).

Consider that the average of the primary production of phytoplankton at the stations in the Bering sea was about 2,200 $\text{mg C m}^{-2} \text{ d}^{-1}$, according to our data. Furthermore, according to the data obtained by V. M. Kudryatsev (Subchapter 4.1.2, this volume), the average of bacterial degradation in the photic zone of the Bering Sea during the period of our research work was 6,100 $\text{mg C m}^{-2} \text{ d}^{-1}$. The value of the P/D-coefficient, which was used as an indicator of the balance between the processes of synthesis and destruction of organic substances in the Bering Sea ecosystem, was 0.36 during the period of the end of biological summer to the beginning of biological autumn.

Besides the studies of the Bering Sea ecosystem during the course of the expedition on board the R/V *Akademik Korolev*, we performed ecological pelagic research of the eastern sector of the Arctic basin, that is, the Chukchi Sea. The average value of primary production in the southern part of this sea was 1,700 $\text{mg C m}^{-2} \text{ d}^{-1}$. This fact indicates that the productivity of this area of the Chukchi Sea is very high (Table 2). The highest rates of photosynthesis were discovered in the central part of the basin, at Station 55 (Table 2). The minimum values of phytoplankton production were obtained in the course of

measurements in the eastern part of the basin, at Station 67 (Table 2; Fig. 1). Comparatively small values of phytoplankton production, about $400 \text{ mg C m}^{-2} \text{ d}^{-1}$, were found at Stations 45, 49, and 50 (Table 2; Fig. 1).

As was shown by the oceanographic and hydrochemical research conducted by the American scientists during the expedition, high productivity of the central and western regions of the Chukchi Sea is explained by the penetration of waters rich in nutrients, from the Anadyr current into these areas. In addition, the western regions of the sea could be also influenced by the flow of more saline and nutrient-rich waters moving to the south along the coast of Siberia. Together with Anadyr water brought from the Bering Sea, the above-mentioned current can provide the rather high productivity of the Chukchi Sea. The maximum concentration of chlorophyll, according to the data obtained by the American specialists during our expedition, reached 77 mg Chl m^{-3} . Shelf waters of the Chukchi Sea along the coast of Alaska are considerably less enriched with nutrients. Correspondingly, the concentration of chlorophyll and the values of primary production are much smaller in the eastern regions of the Chukchi Sea (Table 2; Fig. 1).

Because of the somewhat greater transparency of waters in the Chukchi Sea, the depth of the euphotic zone there was correspondingly deeper. However, similar to the Bering Sea, it did not exceed 45–50 m (Tables 1, 2). The maximum values

of phytoplankton production were usually found at depths between 5 and 15 m, which is probably related to optimal light conditions. More seldom, the maximum of primary production in the Chukchi Sea was discovered in the surface layers of water (for example, on Stations 45 and 49) (Table 2; Fig. 1).

Thus, the research of primary production in the Bering Sea, conducted during the expedition on board the R/V *Akademik Korolev* in 1988, made it possible to determine the level of productivity of the central, southern, northwestern, and western regions of the Bering Sea, including the Bering Strait for the period of the end of biological summer to the beginning of biological autumn. The results obtained indicate high productivity of the Bering Sea ecosystem and great heterogeneity of water masses from the point of view of biological parameters. The data on the rates of photosynthesis in the Bering Sea ecosystem, obtained in 1988, complement and extend the results obtained in the course of expeditions in 1981 and in 1984. The results from the previous expeditions characterize the status of plankton community of the Bering Sea during the period of summer phase of the seasonal succession of plankton community, while the results of the latest expedition cover the period of biological autumn.

The results, which were obtained during the joint US–USSR ecological expedition in the Chukchi Sea, give an idea of the level of productivity of the region during the period of biological autumn.

6.2 The Importance of Primary Production and CO_2

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Introduction

The high-latitude seas are among the most productive regions of the world (Koblentz-Mishke *et al.*, 1970). This is despite the low temperatures encountered here and the severely reduced sunlight during the winter. The cold may even aid in the transfer of energy to higher trophic levels since this reduces metabolic requirements and losses through respiration (Pomeroy & Deibel, 1986). The Bering Sea has been the focus of recent investigation by a team of scientists from the USSR and the USA (Whitledge *et al.*, 1988). The data reported here is a continuation of the effort begun in 1984 to characterize the oceanography of the Bering Sea with respect to the importance of phytoplankton primary production. High production rates and biomass values have been reported throughout the Bering Sea (Koike *et al.*, 1982; Sambrotto *et al.*, 1984, 1986; Whitledge

et al., 1988). In the present study, the investigations extended into the Chukchi Sea and areas of limited access.

An important function of phytoplankton production is the transfer of energy through food webs, which may ultimately result in higher levels of production of commercially important species. The Bering Sea is important in the production of finfish and shellfish (Hood & Kelly, 1974). It is the largest source of Pacific pollock, amounting to about 1.1 million metric tons (Washburn & Weller, 1986). This rich resource must be managed to sustain the populations, and this entails assessing the available food resources.

Global climate change has come to the forefront of public attention with the international public, private, and scientific sectors becoming concerned about the possible consequences. Among the major unknowns in the global climate research is the function of ocean systems. Potentially, the oceans could

serve as a very large reservoir for storage of anthropogenic CO₂. The physical, chemical, and biological mechanisms still are not well understood. It has been suggested that the capacity of the oceans to store CO₂ may have been overestimated (Brewer *et al.*, 1989). However, much research still needs to be conducted before an accurate understanding of the role of the oceans emerges. The Bering Sea ecosystem may be an important area for storing carbon, both by burial in the sediments and via transport to areas of deep-water formation.

Materials and Methods

Primary productivity measurements were carried out at 30 of the 113 stations occupied (Fig. 1). Standard ¹⁴C methods using liquid scintillation counting were employed on samples from two depths. One sample was collected near the surface, the other from the subthermocline layer. The latter from the light absorption maxima if one was identified by a SeaTek *in situ* beam transmissometer. Samples were collected with 8-l Niskin samplers and samples from each layer were homogenized in a 20-l carboy prior to subsampling. Triplicate subsamples were incubated with 2.5 μCi NaH¹⁴CO₃ at each of eight light intensities from 0.25 to 200 μEin m⁻²s⁻¹. Fluorescent lamps were used as the light source. Additional samples were kept in total darkness and at ambient, sea-surface, natural light. Incubations took place in water-cooled chambers at near-ambient sea-surface temperature. After 1-h incubations, samples were filtered through 0.4 μm pore Gelman metricel filters. Filters were acidified in vials with 0.5 ml 1.0 N HCl and counted in Ecolume scintillation cocktail (ICN Biomedicals, Inc.).

Primary production rates were calculated and normalized to chlorophyll *a* concentrations (Strickland & Parsons, 1972). Alkalinity and total CO₂ concentrations were estimated by titration (Strickland & Parsons, 1972). Chlorophyll was determined fluorometrically by G. Holmes and W. Robie at the time of sampling (Strickland & Parsons, 1972). Photosynthesis versus light intensity (P-I) parameters were estimated with a hyperbolic tangent function (Jassby & Platt, 1976) and with a

function incorporating photoinhibition (Platt *et al.*, 1980). The best fit model was determined from the sum of squares obtained by using nonlinear least-squares regression (Systat, Inc.).

Incident sea-surface light intensity was monitored continuously with a photosynthetically active radiation (PAR) sensor (Li-Cor LI-192S) mounted on a post removed from most light interferences and connected to a data logger (Li-Cor LI-1000). Subsurface light was measured and the extinction coefficients calculated at each station with a LI-185 quantum meter equipped with a LI-192S sensor (Li-Cor).

The incident light, extinction coefficients, chlorophyll versus depth distribution, and P-I parameters were used in a numerical model to calculate integral production through the water column throughout the day. The program was written in Fortran 77 (Lahey Computer Systems) and could also be used to calculate seasonal and annual estimates of production.

Results

Figure 2 shows incident surface light intensity (as photon flux density). The maximum values ranged from about 350 to 1,900 μEin m⁻²s⁻¹. Storms were common near the Aleutians and the Polar Front, which accounted for some of the PAR variability.

The areal primary production throughout the Bering and Chukchi Seas was relatively high, with a mean of 1.8 g C m⁻²d⁻¹. The maximum value estimated was 15.3 g C m⁻²d⁻¹, while the low value was 0.174 g C m⁻²d⁻¹.

The distribution of primary production had several peaks throughout the region, especially in shallow waters on the shelf. Not all the shelf area was productive, however. Some of the lowest values recorded during this cruise occurred south of

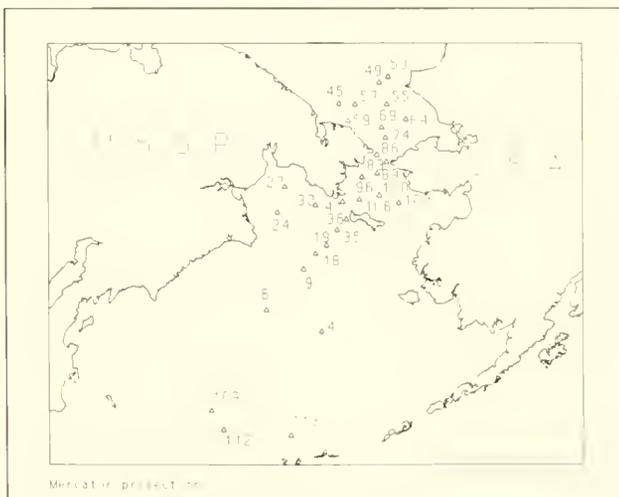


Fig. 1. Locations of stations where primary productivity was measured.

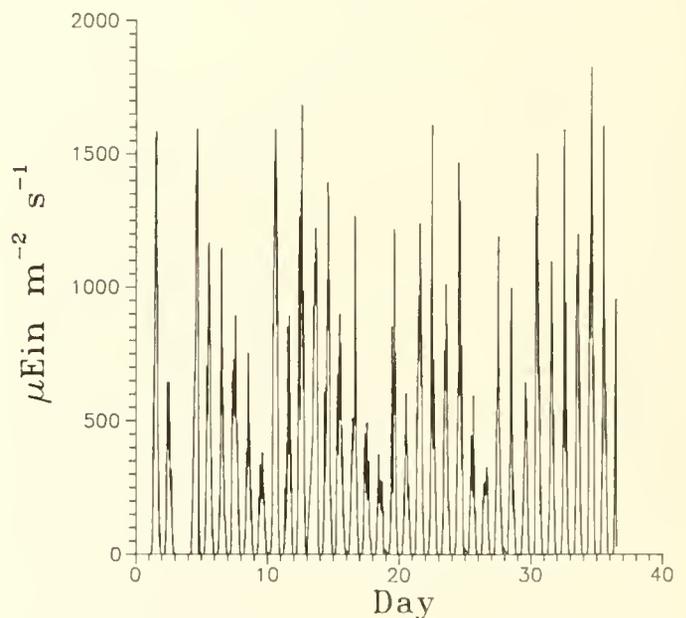


Fig. 2. Photon flux density (15 min means) measurements taken during the cruise, July–August, 1988.

St. Lawrence Island. The massive changes in the production rates from south to north are most obvious in the three-dimensional representation shown in Fig. 3. The highest value ($15 \text{ g C m}^{-2} \text{ d}^{-1}$) was found at Station 36 near St. Lawrence Island. There were also secondary peaks at Station 55 in the center of the Chukchi Sea ($5.4 \text{ g C m}^{-2} \text{ d}^{-1}$), Station 69 in the Chirikov basin ($4.4 \text{ g C m}^{-2} \text{ d}^{-1}$), and Station 24 in the Gulf of Anadyr ($3.6 \text{ g C m}^{-2} \text{ d}^{-1}$). A further breakdown of the data (Table 1) shows the values at each station with means for various regions.

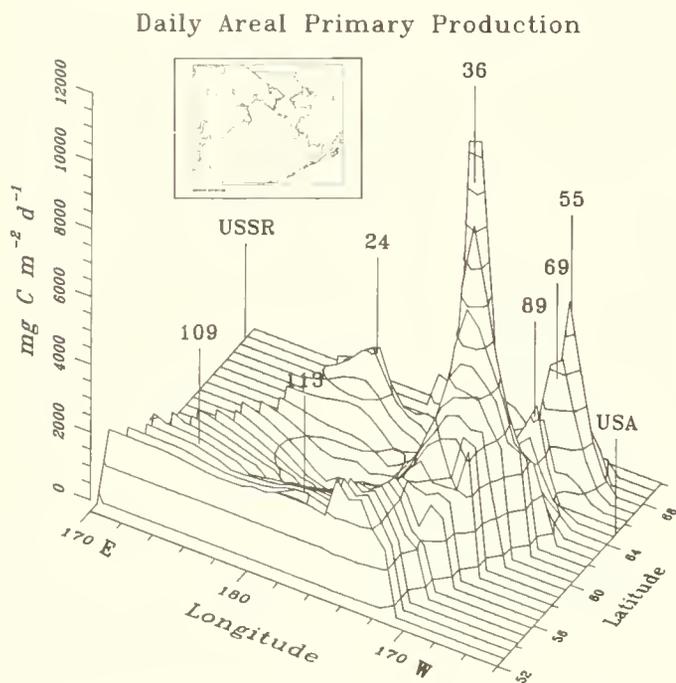


Fig. 3. Three-dimensional plot of primary productivity estimated during this study. Horizontal contour intervals are $1000 \text{ mg C m}^{-2} \text{ d}^{-1}$. The numbers of selected stations are shown for orientation. Inset shows limits of the contoured region.

Much of the primary production was subsurface, with significant amounts below the thermocline in nutrient-rich waters. The importance of subsurface production is shown in Fig. 4. The peak in Fig. 4 is about $300 \text{ mg C m}^{-3} \text{ hr}^{-1}$ at a depth of 31 m. The high carbon assimilation rates are not necessarily coincident with high chlorophyll *a* values as shown in Fig. 5. The major subsurface production peak at 63.5°N is in a region where chlorophyll values were only about 1 mg m^{-3} . In another area at 67°N there was a peak in chlorophyll that was not associated with a production maximum. The productivity peak, however, is associated with a nutricline as evidenced by the $\text{NO}_3 + \text{NO}_2$ contours shown in the lower panel of Fig. 5.

The P-I parameters were relatively uniform over the study area as shown by the P_{max} values in Figs. 6a and 6b. The values were generally less than $10 \text{ mg C (mg Chl)}^{-1} \text{ hr}^{-1}$, although some exceptional values were higher. Surface P_{max} values were also generally higher than those from the deeper samples.

Predictive modeling of primary production throughout the season based on calculated solar irradiance (Brock, 1981), but without taking account of ice cover, is shown in Fig. 7.

Table 1

Areal productivity in various regions on a daily and hourly basis. The means for each region are presented ± 1 standard deviation.

Region	Station	$\text{mg C m}^{-2} \text{ d}^{-1}$	$\text{mg C m}^{-2} \text{ hr}^{-1}$
Bering Shelf	4	918.33	91.81
	6	105.63	11.02
	9	744.33	60.38
	18	1,222.98	111.71
	19	751.85	82.53
	35	483.13	56.93
	Mean	704.37 ± 381	69.1 ± 34.95
(Station 36)	36	15,252.19	1596.61
Bering Deep	109	1,885.09	256.12
	112	1,769.59	140.0
	113	2,041.39	273.99
	Mean	$1,898.7 \pm 136$	223.4 ± 72.8
Gulf of Anadyr	24	3,599.01	405.45
	27	548.11	71.99
	32	1,698.07	173.52
	Mean	$1,948.4 \pm 1540$	216.9 ± 170.9
Anadyr Strait	41	1,722.97	175.39
Bering Strait	83	206.92	24.9
	86	1,417.18	164.8
	Mean	812.04	94.85
Chukchi Sea	45	503.55	72.66
	49	1,222.03	127.40
	50	375.61	51.03
	55	5,450.28	396.71
	57	264.88	32.71
	59	1,949.28	302.77
	64	150.64	18.41
	69	4,444.64	521.93
	74	241.8	32.32
Mean	$1,622 \pm 1987$	172.9 ± 186.8	
Chirikov Basin	89	3,163.37	346.09
	96	760.05	81.91
	100	604.25	89.6
	102	143.0	23.76
	106	494.46	39.73
	Mean	$1,033 \pm 1212$	116.2 ± 131.5

The notable points here are that the baseline of the graph slopes downward from south to north, but the peaks of production increased from south to north. This may be related to interactions of limiting light and nutrients, or possibly the temperature gradient.

In relation to the international interest in global climate change, the importance of the Bering Sea was also evaluated by estimating the ΣCO_2 at all primary productivity stations (Table 2). Estimates of ΣCO_2 flux through the Bering Straits was calculated from the total transport of about $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$

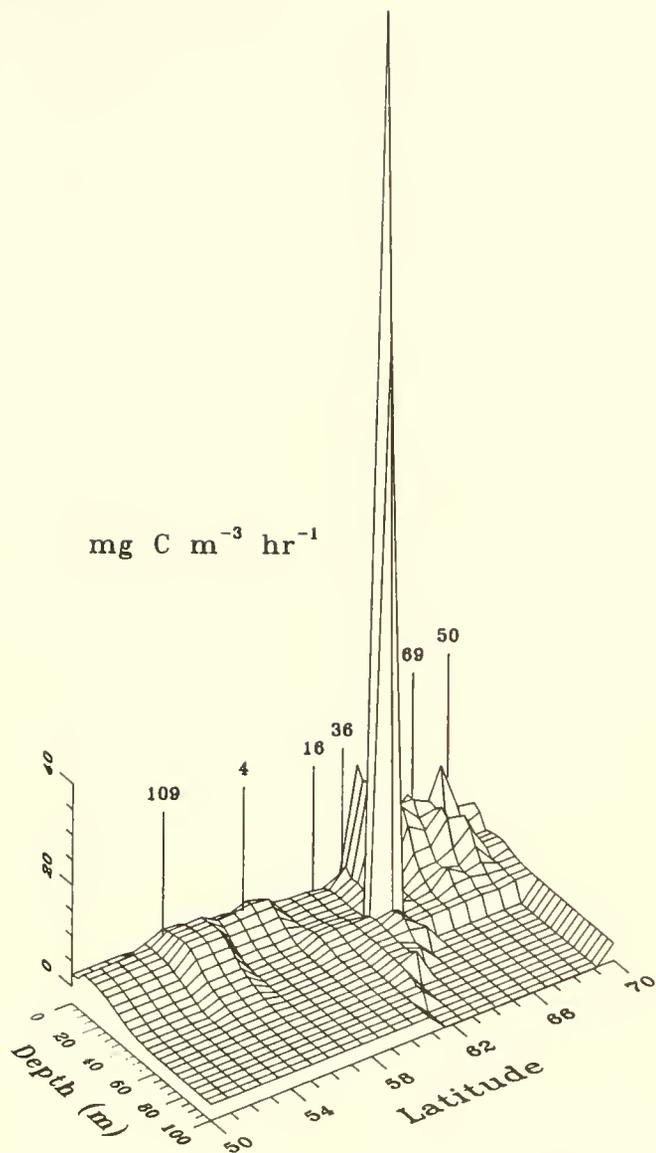


Fig. 4. Three-dimensional plot of primary productivity rates estimated along a transect from the Aleutian Islands to the Chukchi Sea. The major peak at Station 36 reaches $300 \text{ mg C m}^{-3} \text{ h}^{-1}$ at a depth of 31 m. Selected station numbers are indicated for orientation.

(Favorite, 1974). Instantaneous shipboard measurements were close to this value, although a realistic estimate of the mean flux might be closer to 0.5–0.8 Sv (Coachman, personal communication). Transport of CO_2 was calculated from the average of surface and thermocline estimates of ΣCO_2 and the 1 Sv transport. This comes to 35.3×10^{12} moles C yr^{-1} on the eastern side of the strait and 32.8×10^{12} moles C yr^{-1} on the western side. The combined east and west side transport would then be 0.82×10^9 metric tons C per year. This provides an estimate of the flux of dissolved CO_2 but does not account for particulate flux.

The present study cannot derive a value for the total particulate flux but can estimate phytoplankton biomass and, therefore, phytoplankton particulate carbon flux. During the

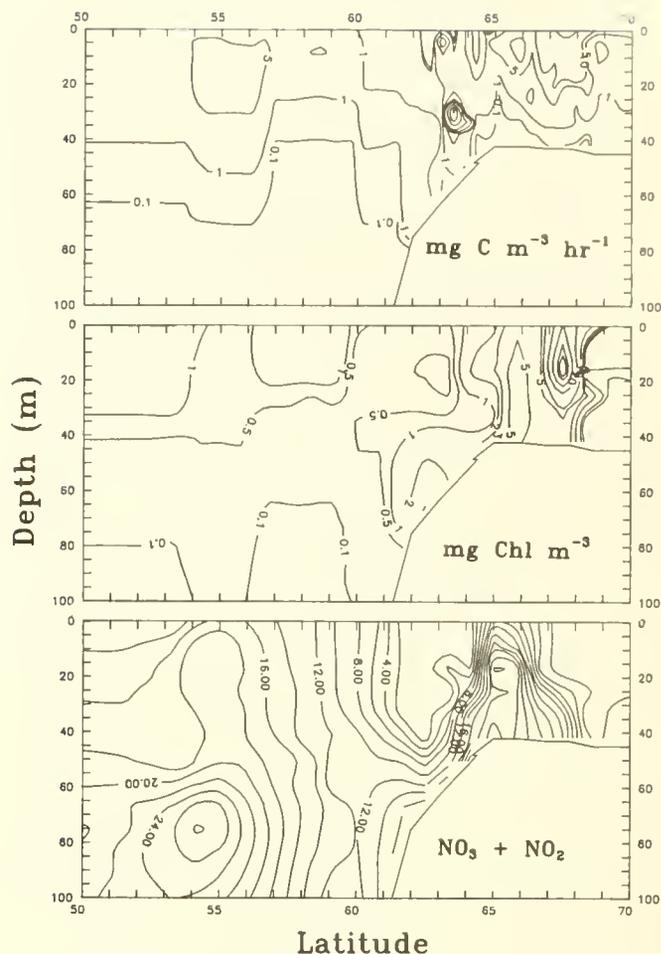


Fig. 5. Contour plots of primary productivity, chlorophyll *a*, and nitrate plus nitrite concentrations along a transect from the Aleutian Islands to the Chukchi Sea.

cruise we occupied transects on either side of the Diomed Islands. The measured chlorophyll concentrations averaged $5.72 \text{ g Chl m}^{-3}$ on the western side and 1.1 g Chl m^{-3} on the eastern side. Taking the mean chlorophyll concentration for both sides and multiplying by the approximately 1 Sv transport results in an estimated annual particulate phytoplankton flux. Assuming a C/Chl ratio of 30, and that the chlorophyll concentrations remain unchanged seasonally, then the annual flux would amount to 3.2×10^9 metric tons C per year. This is about 0.4% of the estimated dissolved carbon flux. Other particulate material, either detritus or living, could contribute significantly to the total particulate carbon flux. Therefore, the relative magnitude of particulate versus dissolved transport will need to be investigated further.

Another aspect to consider is how much carbon is fixed by primary production regionally. For example, in the region north of the Bering Strait, the cruise track covered approximately $85,320 \text{ km}^2$. The average rate of primary production in the Chukchi was $1.6 \text{ g C m}^{-2} \text{ d}^{-1}$ (Table 2). Assuming a 60-day growing season, the southern Chukchi would fix roughly 8.2×10^6 metric tons of carbon. A similar calculation for the Chirikov basin obtains a seasonal production of about

3.12×10^6 metric tons. The area of the Bering Sea is $2.268 \times 10^6 \text{ km}^2$ (Sverdrup *et al.*, 1942). The mean productivity rate for the entire Bering Sea (excluding Station 36) amounts to $1.4 \text{ g C m}^{-2} \text{ d}^{-1}$, or 0.19×10^9 metric tons during the growing season.

Discussion

Oceanographers have become more aware of the importance of primary production in the Bering Sea since the charts of Koblenz-Mishke *et al.* (1970) were published. More recent estimates of the magnitude of primary production range

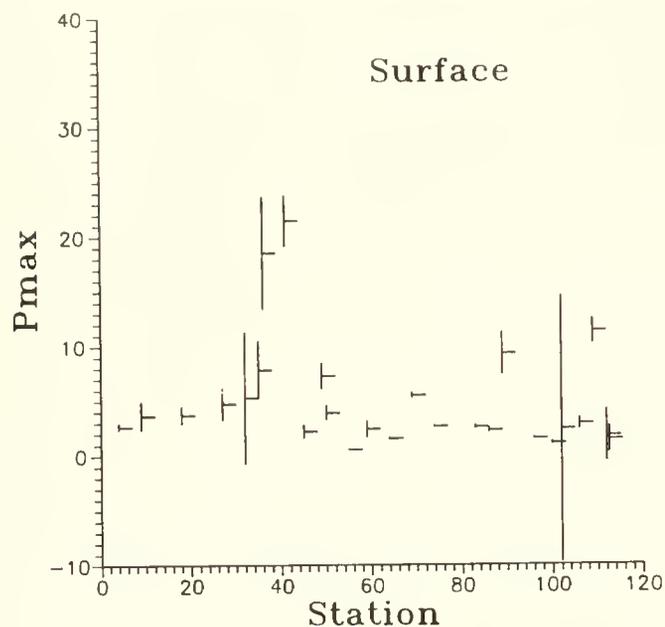


Fig. 6a. P_{max} values for surface samples obtained during the summer of 1988.

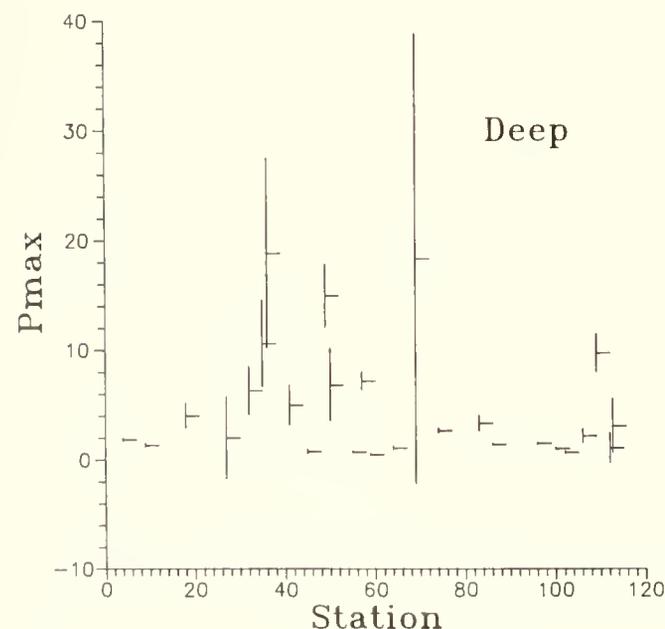


Fig. 6b. P_{max} values for samples from below the thermocline, and in the deep chlorophyll-maximum layer when one existed.

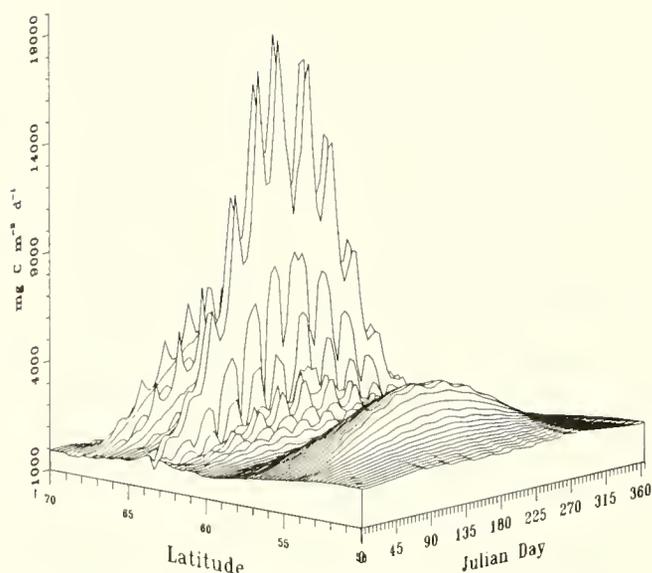


Fig. 7. Results from numerical model simulating production through an entire year, based on summer P-I values, and neglecting ice-cover.

Table 2

ΣCO_2 during Summer 1988 in the Bering and Chukchi Seas, for samples from the surface and a deeper layer below the thermocline.

Region	Station	ΣCO_2 (mM)	
		Surface	Sub-Thermocline
Bering Sea and Gulf of Anadyr	6	2.124	2.185
	9	2.014	---
	18	2.027	2.024
	19	2.014	2.024
	24	2.049	2.264
	27	2.061	2.202
	32	2.052	2.021
	35	2.052	2.021
	36	2.027	2.027
	Chukchi Sea	41	2.037
45		1.609	2.208
49		2.043	2.115
50		2.090	2.068
55		1.910	1.990
57		1.950	2.170
59		1.620	2.060
64		2.070	2.130
Bering Strait	83	2.231	2.250
	86	1.997	2.160
Chirikov basin	89	2.052	2.090
	96	2.210	2.220
	100	2.010	2.220
	102	2.102	2.190
	106	2.010	2.130

to the grams of $C\ m^{-2}\ d^{-1}$ (Whitledge *et al.*, 1988). Fisheries scientists were aware long before that this was a region of rich productivity (Hood & Kelly, 1974; Washburn & Weller, 1986).

The present study adds new data to this knowledge base. It also confirms the patterns seen in the 1984 cruise. First, the regions of upwelling and associated high production were again seen, thus verifying that this is a continuing phenomenon. Second is the large expanse of the deep production maximum. The tighter grid spacing of stations in the present data set allowed a clearer picture about the extent of these phenomena and showed that they were localized in the region of the northern Bering Shelf and the Chukchi Sea.

Figure 5 shows the productivity, chlorophyll, and $NO_3 + NO_2$ concentrations along a north-south transect. The patterns show that the highest production occurred where there was upwelling of nutrient rich water. This tongue of water broke through to the surface between 64° and $65^\circ N$. Furthermore, P_{max} was generally lower in deep water than in the surface waters at the same location. At Station 36 ($63^\circ 25' N$, $172^\circ 10' W$), however, the P_{max} values were nearly identical in surface and deep waters. These values were also higher than at most of the other stations (Fig. 6). The subsurface position of the primary productivity peak indicated that the phytoplankton were possibly nutrient-limited in the surface waters. At stations where upwelling appeared most intense and nutrient concentrations were greater, the productivity rates were high. However high, these rates were still not as great as in areas where the water column was stratified. The magnitude of vertical currents in the upwelling regions transport the phytoplankton from high light to low light and back. This circulation takes place at time scales that do not allow physiological adaptation. Cellular levels of chlorophyll and photosynthetic enzymes cannot be adjusted as rapidly as changes in light intensity.

In the Chukchi Sea, the productivity maximum (between 67° and $68^\circ N$) was generally in the surface waters. Chlorophyll concentrations there were also high, with a maximum centered around 15 meters in depth. The contribution to total water column production was greater at the surface than at the chlorophyll maximum. This was due to the shading of the deeper populations. This was not so at Station 36, however, where surface chlorophyll concentrations were below $2\ mg\ Chl\ m^{-3}$.

Overall, the primary productivity of the Bering and Chukchi Seas was controlled by hydrographic conditions. There were high photosynthetic rates near the Aleutian Islands ($1.9\ g\ C\ m^{-2}\ d^{-1}$), but not nearly the magnitude of those found at higher latitudes (15 at Station 36). On the continental shelf, there appeared to be a decline in production ($0.7\ g\ m^{-2}\ d^{-1}$) and a lower nutrient regime in the surface waters. This is indicative that the populations there were nutrient-limited. The nutrient stress was alleviated further north on the continental shelf. Nutrient enrichment on the continental shelf was due to upwelling and served to stimulate production. In the region of the Bering Strait, topographic conditions led to turbulence and enhanced mixing of the water column (including the phytoplankton). The instability reduced production to some extent ($1.4\ g\ m^{-2}\ d^{-1}$). In the Chirikov basin and the Chukchi

Sea, the stability of the water column was greater while nutrient concentrations remained high. This combined effect produced high photosynthetic rates ($1-1.6\ g\ m^{-2}\ d^{-1}$), especially in the central portion of the area ($5.4\ g\ m^{-2}\ d^{-1}$).

It was clear from the data that the source of nutrients was the deep Bering Sea water. This water mass upwelled onto the continental shelf (see Coachman & Shigaev, Subchapter 2.1, this volume). The northward flow then provided a source of new nutrients and a standing stock of phytoplankton to the Chukchi Sea and Arctic Ocean. There also appeared to be a northern source of nutrients for the production maximum in the Chukchi Sea (see Coachman & Shigaev, Subchapter 2.1, this volume). The origin of these nutrients is uncertain, but they may be from the region near Wrangel Island and flow off the Siberian coast. Some of these nutrients may have come from the Bering Sea and be recirculating around the basin from the previous year.

The distribution of production, interestingly, nearly matches the northern distributions of historical whaling data (Nasu, 1974). The regions of high primary production also match historical data of high benthic biomass (Alton, 1974). Recently, the link between phytoplankton production and high benthic metabolism was shown by Grebmeier *et al.* (1988, 1989) for the Bering and Chukchi Seas. Although food webs in oceanic systems are difficult to quantify, the case of the Bering and Chukchi Seas seems fairly clear. A major pathway is for phytoplankton to sink to the bottom where they serve as a carbon source for a detrital food web. This food web ultimately feeds pollock and large mammals such as walrus (*Odobenus rosmarus*) and the gray whale (*Eschrichtius gibbosus*). Grebmeier *et al.* (1989) have implicated interannual variability of phytoplankton production as the causative agent for interannual variation in oxygen consumption rates in Bering Sea water. Another major pathway is more typical of pelagic systems, and that is through zooplankton. The relative importance of these two pathways was not studied, but it seems that in the northern Bering and Chukchi Seas, a large proportion must go through the benthic pathway.

The importance of the Bering Sea phytoplankton does not end with food webs alone. The biology and chemistry of the Bering Sea might serve as major modulators of atmospheric CO_2 . The present study shows that about 166 metric tons of C are taken up by phytoplankton a year. Much of this is, of course, remineralized (Grebmeier *et al.*, 1989), but a fair fraction is buried in the sediments.

A second mechanism of isolating carbon from the atmosphere is also possible. There are two major sources for the formation of bottom water in the oceans, the Antarctic, and the Norwegian Sea. Prior studies have shown that there is a transport of about 15 Sv into the Bering Sea from the North Pacific (Favorite, 1974). Most of that flow returns to the North Pacific. Still, about 1 Sv passes through the Bering Strait into the Arctic Ocean (Favorite, 1974) where circulation could bring it to the North Atlantic. Since much of the flow would be in deeper layers and under the ice cap, little of the CO_2 would be transferred back to the atmosphere. With the appropriate temperature and salinity, this water could form North Atlantic bottom water. An interesting thought here is that during the

winter, polynyas form in the Bering Sea near St. Lawrence Island allowing surface water to supercool. Extremely cold and highly saline waters have been found southwest of St. Lawrence Island (Takenouti & Ohtani, 1974). Such cooling reaches the bottom in the northern Bering Sea where the shelf region is generally shallow (Ohtani, 1969). The cold water would have a higher loading of CO₂. Walsh *et al.* (1985) have shown that much of the production on the shelf may be transported off the shelf. The off-shelf transport to deeper water in the Bering Sea could act as a sink for carbon. Similar transports occur off the shelves in the Arctic Ocean. The winter is also when strengthened flows are expected to occur due to meteorological forcing. Thus there would be an increased transport of water and CO₂ through the Bering Strait. The winter flows could supply source water for deep water mass formation. These water masses could form either in the North Atlantic or

in the North Pacific via outflow along the Kamchatka Peninsula. A salient point here is that in the Atlantic, the southward transport of CO₂ is only 0.26 gigaton of C per year (Brewer *et al.*, 1989). This is a relatively small quantity in comparison to the annual production of CO₂ (about 5.5 gigaton). Thus, magnitude of the net Atlantic transport, while relatively small, is of the same order as the estimated Bering Strait northward transport (0.82 gigaton). Certainly not all the carbon in the Bering Sea flux finds its way to the Norwegian Sea, but it could be a significant contribution. Thus, the quantity of carbon stored in the North Atlantic bottom water may be in good part due to the flow from the Bering Sea. Additional storage of carbon may result from transport of particulate carbon to the deep basins of the Bering Sea.

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6.3 Intensity of Biosedimentation Processes

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Introduction

Marine organisms play an important part in the sedimentation processes. The influence of biotic processes upon sedimentation provides evidence of active participation of marine organisms in the biological accumulation (concentration) of chemical substances. They are also important in the subsequent transfer of these substances through organic products (organism remains, feces, etc.) or by the organisms themselves to the deep layers of the ocean and the bottom. The biotic processes directly or indirectly determine transformation and distribution of essentially all the elements in the sea. Changes occur in the physical and chemical form of the elements during these transformations. The organisms may accumulate essential elements as well as useless and even detrimental ones. The chemical substances are circulated from the external environment into the organisms and back by typical routes. These processes thereby form relatively closed biogeochemical cycles whose rates vary for different substances.

The influence of marine organisms on geochemical mobility may be broken into biological accumulation and sedimentation stages (Lisitsyn, 1983).

The essential regularity of these processes can be used to develop methods of determining the biosedimentation rates on the basis of vertical distribution of the elements differing from each other in their biogeochemical activity. With this in mind, it is logical to use natural radionuclides as tracers. Their concentration can be measured in the medium with a highly sensitive radiometric apparatus (McKee *et al.*, 1984).

Materials and Methods

From the middle of the sixties there began an intensive study of the distribution in the ocean of the two genetically connected natural radionuclides, ²³⁸Uranium and ²³⁴Thorium. ²³⁴Thorium is the product of ²³⁸U α -decay. This process of radioactive decay is the main source of ²³⁴Th in the sea. As shown previously, these isotopes display a shift in the radiochemical balance in ocean surface-water (Bhat *et al.*, 1969; Matsumoto, 1975). This shift is due to biological accumulation and biosorption of Th by planktonic organisms and suspended organic particles, which are then removed from the surface layer as a result of sedimentation.

The bioaccumulation factors of Th for different types of plankton organisms in open ocean range from 10⁴ to 2 × 10⁵ (Barinov *et al.*, 1967). The average values of accumulation factors for Th in suspended organic particles are the same order of magnitude (Cherry & Shannon, 1974).

²³⁸Uranium is relatively evenly distributed in the oceanic waters, where its concentration is about 3 μ g/l. Furthermore, the accumulation factors in plankton and detritus are some 3 to 5 orders of magnitude lower than those of thorium.

Thus, the shift in the radioactive balance is in fact determined by the changes in the concentrations of ²³⁴Th due to its transfer in the process of biosedimentation. Knowing the vertical profile of these radionuclides, it is possible to calculate the sedimentation rate of the suspended organic matter (Polikarpov *et al.*, 1976, 1980).

²³⁴Thorium balance in a single volume of seawater is described by equation:

$$\frac{dN_{Th}}{dt} = \lambda_U \cdot N_U - [\lambda_{Th} + k \cdot P] \cdot N_{Th} \quad (1)$$

where

- N_{Th} — ²³⁴Th atoms concentration in sea medium;
- N_U — ²³⁸U atoms concentration in sea medium;
- λ_{Th} — ²³⁴Th radioactive decay constant;
- λ_U — ²³⁸U radioactive decay constant;
- k — factor of ²³⁴Th accumulation in suspended organic substance;
- P — rate of biosedimentation removal of suspended organic substance from single water volume.

The general solution of differential equation (1) in relation to N_{Th} is as follows:

$$N_{Th(t)} = N_{U(0)} \cdot \lambda_U \cdot \left[\frac{e^{-\lambda_U \cdot t}}{(\lambda_{Th} + k \cdot P) - \lambda_U} + \frac{e^{-(\lambda_{Th} + k \cdot P) \cdot t}}{\lambda_U - (\lambda_{Th} + k \cdot P)} \right] + N_{Th(0)} \cdot e^{-(\lambda_{Th} + k \cdot P) \cdot t} \quad (2)$$

where $N_{U(0)}$ and $N_{Th(0)}$ are ²³⁸U and ²³⁴Th concentrations respectively, at times zero.

Transforming equation (2) with regard for small value λ_U and $N_U = \text{constant}$ to the results in:

$$N_{Th(t)} = \frac{\lambda_U \cdot N_U}{\lambda_{Th} + k \cdot P} + \left[N_{Th(0)} - \frac{\lambda_U \cdot N_U}{\lambda_{Th} + k \cdot P} \right] \cdot e^{-(\lambda_{Th} + k \cdot P) \cdot t} \quad (3)$$

For steady state conditions ($dN_{Th}/dt = 0$), the biosedimentation rate is determined by equation (1):

$$P = \frac{N_U \cdot \lambda_U - N_{Th} \cdot \lambda_{Th}}{k \cdot N_{Th}} \quad (4)$$

Introducing specific activities of ²³⁸U and ²³⁴Th in seawater,

$$C_U = N_U \cdot \lambda_U \quad \text{and} \quad C_{Th} = N_{Th} \cdot \lambda_{Th} \quad (4a)$$

and specific activity of Th in the particulate organic matter:

$$C_{Th}^P = N_{Th} \cdot \lambda_{Th} \cdot k \quad (4b)$$

we obtain the equation to calculate the biosedimentation rate:

$$P = \frac{(C_U - C_{Th}) \cdot \lambda_{Th}}{C_{Th}^P} \quad (5)$$

The residence time of ²³⁴Th, T_{Th} in the upper layers of water is inversely proportional to the rate of the biosedimental removal of this isotope (Coale & Bruland, 1987):

$$T_{Th} = \frac{C_{Th}}{(C_U - C_{Th}) \cdot \lambda_{Th}} \quad (6)$$

The flux from the surface water layer at depth H is determined as follows:

$$F_{(0,H)} = \int_{z=0}^H P_z \cdot dH. \quad (7)$$

During the Third US–USSR Joint Research Expedition in July–August 1988 experiments were carried out at 8 stations in the Bering Sea and at 3 stations in the Chukchi Sea. These measurements included the vertical profiles of ²³⁸U and ²³⁴Th and the concentration ²³⁴Th in particulate organic matter (POM). These data were then used to calculate biosedimentation parameters in the region.

The ²³⁸U concentrations in seawater were calculated based on the close correlation of ²³⁸U with salinity (Turekian & Chan, 1971; Ku *et al.*, 1977):

$$C_U = 0.07081 \cdot S \quad (8)$$

where C_U = specific activity of ²³⁸U (dpm l^{-1}); S = salinity (‰).

²³⁴Thorium concentrations were determined separately in filtered seawater and in POM. The POM samples were collected at 3–4 depths within the upper 100-m layer. The water (about 1 m^3) was forced by a vibrating immersion pump through a “Midiya” filtration unit. The filters were FPP-15-1.5, which retained suspended particles larger than μ 0.5 m (Vakulovsky, 1986). The following procedure was used to determine ²³⁴Th concentration in the filtered water. In plastic tanks cosedimentation of Th(4+) with Fe(3+)-hydroxide was performed on 100 l of water. The precipitate was isolated by paper filtration, dried, and redissolved in 50–100 ml 8N HCl. This solution was then brought to a volume of 150 ml with 8N HCl. Thorium was isolated by passing the solution through glass columns packed with cation-exchange resin, Dowex in (H⁺) form. The resin was ashed at 450–500°C. The ash residue was placed in a scintillation vial, dissolved in about 1 ml of 0.5N HCl, and then 5–10 ml of scintillation cocktail was added. The β -activity of the sample was measured by liquid scintillation counting in a “Rack β -121, Wallac LKB.” The radiochemical purity of the ²³⁴Th was checked by double measurement of activity, once immediately after isolation and then again 24 days later.

The filters with the POM were dried at 60°C. The dry weight of the particulate matter and its concentration in water were determined by the difference in weight before and after filtration. The filters were then ashed in a muffle furnace at 450–500°C and the weight of the ash residue (with correction for ashing of the filter itself) was determined. The ash residue was dissolved in a HCl and HNO₃ mixture (3:1 ratio) then evaporated in a sand bath. The resulting dry residue was re-dissolved in 8M HCl. Any insoluble residue (silicates) was isolated by means of centrifugation. The supernatant was collected. Then 7 ml of 8M HCl was added to the remaining precipitate, mixed, and centrifuged again. The supernatant was again collected and added to the first collection. The procedure was repeated three times. The combined supernatant liquid was brought to a volume of 150 ml with 8M HCl. The ²³⁴Th was then determined as described above for the seawater samples.

Results and Discussion

The calculation of ^{238}U concentration in seawater was based on salinity data obtained by American and Soviet specialists during the expedition. The calculated results of ^{238}U concentrations and measured ^{234}Th content in water and particulates are shown in Tables 1 and 2.

Data analysis points to high spatial homogeneity of ^{238}U within the Bering Sea. The average concentrations of ^{238}U in the Bering Sea was 2.31 ± 0.01 dpm l^{-1} . Near the surface the content varied from 2.19 in the Gulf of Anadyr to 2.35 dpm l^{-1} in the open waters of the Bering Sea. The vertical profile of ^{238}U showed a slight increase in concentration with depth. The maximum concentration gradient (in the Gulf of Anadyr) did not exceed 0.0002 dpm l^{-1} .

In the Chukchi Sea, the ^{238}U concentration varied over a broader range, from 1.73 to 2.39 dpm l^{-1} , and averaged 2.26 ± 0.11 dpm l^{-1} . Only in the western part of the Chukchi Sea, however, were vertical gradients of ^{238}U concentrations evident and also considerable differences from the average concentration for the sea. This was due to a thin (5–10 m) low-salinity water

layer near the surface. Still, as a whole, in the central part of the Chukchi Sea ^{238}U concentrations were close to the average values for the Bering Sea.

The ^{234}Th vertical profile in the upper layers of the sea is closely correlated with not only the hydrological parameters but also with the rates of the biosedimentation processes. This relationship determines the balance (R) between ^{238}U and ^{234}Th in the euphotic layer:

$$R = \frac{C_{Th}}{C_U} \quad (9)$$

In contrast to ^{238}U , it should be noted that a considerable part of ^{234}Th , in layers with high suspended loads, is in the POM. Because of this, the ratio of particulate to dissolved forms of ^{234}Th varied considerably from region to region.

In the Bering Sea, the total content of ^{234}Th in water and in POM in the upper 100 m layer was in the range of 0.54–1.58 dpm l^{-1} . The dissolved and particulate ^{234}Th concentrations averaged 0.44 ± 0.03 and 0.40 ± 0.05 dpm l^{-1} , respectively. The R value averaged 0.43 in the Bering Sea.

TABLE 1

Concentrations of ^{238}U and ^{234}Th in seawater and POM of the Bering Sea.

Date	Station	Latitude Longitude	Depth (m)	C_U (dpm/l)	C_{Th} (dpm/l)		Total
					Dissolved	Particulate	
29 Jul 88	3	57°06'N 175°05'W	0	2.84	0.38	0.29	0.67
			20	2.32	0.33	0.37	0.83
			40	2.33	0.28	0.66	0.94
			80	2.34	0.31	0.31	0.62
02 Aug 88	7	60°28'N 177°50'W	0	2.33	0.61	0.56	1.17
			40	2.32			1.22
			80	2.35			1.20
			120	2.35			0.76
04 Aug 88	22	63°00'N 176°00'W	0	2.23			1.04
			20	2.23			1.35
			40	2.30			1.50
			80	2.36			0.99
06 Aug 88	35	63°00'N 173°00'W	0	2.19			1.12
			20	2.23			1.23
			40	2.27			1.07
			60	2.30			1.43
20 Aug 88	89	65°14'N 169°21'W	0	2.25	88.66	0.22	0.88
			20	2.29	0.39	0.25	0.64
			40	2.30	0.54	0.25	0.79
22 Aug 88	100	64°23'N 169°09'W	0	2.25	0.27	0.27	0.54
			15	2.27	0.59	0.16	0.85
			30	2.32	0.99	0.33	1.32
27 Aug 88	110	53°59'N 176°00'W	0	2.36	0.38	0.61	0.99
			20	2.35	0.29	0.30	0.59
			50	2.36	0.62	0.44	1.06
			170	2.38	0.59	0.32	0.91
29 Aug 88	113	53°11'N 177°18'W	0	2.33	0.39	0.39	0.78
			20	2.34	0.26	0.39	0.67
			70	2.36	0.58	1.00	1.58

In the Chukchi Sea, the ^{234}Th concentration (dissolved + suspended) was lower (0.81 ± 0.08 dpm l^{-1}) than that in the Bering Sea. The dissolved ^{234}Th concentration (0.45 ± 0.06 dpm l^{-1}) was the same as in the Bering Sea while the particulate ^{234}Th content was lower, amounting to 0.35 ± 0.04 dpm l^{-1} . The value of R in the Chukchi Sea averaged 0.36.

The average value of accumulation factor of ^{234}Th by particulates in the Bering Sea was 574 ± 63 dpm g^{-1} of dry weight, and 650 ± 280 dpm g^{-1} of dry weight in the Chukchi Sea.

It is evident that there were considerable variations of C_{Th}^{p} within relatively homogeneous water masses and with depth at any given station (Table 3). On one hand, it can be due to the differences in the composition of the suspended matter, in particular the organic matter. This is because the Th accumulation factor in organic matter is some orders of magnitude higher than in inorganic matter (Cherry & Shannon, 1974; Polikarpov *et al.*, 1976). On the other hand, with highly intensive sedimentation processes, the accumulation factors depend on the length of time the particles remain in suspension.

TABLE 2

Results of determinations of ^{238}U and ^{234}Th concentrations in seawater and suspended particulates of the Chukchi Sea.

Date	Station	Latitude Longitude	Depth (m)	C_{U} (dpm/l)	C_{Th} (dpm/l)		
					Dissolved	Particulate	Total
09 Aug 88	45	67°44'N 172°50'W	0	1.73	0.71	0.38	1.09
			20	2.38	0.72	0.31	1.03
			40	2.39	0.46	0.50	0.96
12 Aug 88	55	67°45'N 163°26'W	0	2.30	0.52	0.49	1.01
			20	2.32	0.38	0.35	0.73
			40	2.32	0.42	0.25	0.67
14 Aug 88	69	66°55'N 168°50'W	0	2.30	0.45	0.45	0.90
			15	2.30	0.23	0.11	0.34
			35	2.30	0.20	0.35	0.55

TABLE 3

POM and ^{234}Th concentrations in particulate matter of the Bering and Chukchi Seas.

Station	Depth (m)	Particulate organic matter (mg dry wt/m ³)	^{234}Th activity in solution (dpm/l)	^{234}Th activity in particulate organic matter (dpm/g dry wt)
3	0	1,800	391	217
	20	704	387	550
	40	767	622	811
	80	1,365	491	360
7	0	1,545	487	315
	45	0	130	2,850
45	20	1,380	1,173	850
	40	623	336	540
	55	0	1,250	575
55	20	2,776	411	148
	40	1,490	209	140
	69	0	1,140	593
69	15	1,690	150	89
	35	1,815	485	267
	89	0	439	206
89	20	1,846	591	320
	40	1,090	310	284
	100	0	477	430
100	15	1,040	514	494
	30	910	592	650
	110	0	774	636
110	20	1,700	410	241
	50	1,140	935	820
	170	630	542	860
113	0	725	716	988
	20	586	381	650

Our calculations showed that in the Bering and Chukchi Seas the correlation factor between C_{Th}^P and the residence time of ^{234}Th , T_{Th} in various water layers was high, $r = 0.86$ ($n = 26$).

The data gathered for ^{238}U and ^{234}Th concentrations in seawater made it possible to estimate the following biosedimentation parameters:

- rate of biosedimentation at specific depths;
- the POM concentrations; and
- the residence time of POM in the water column.

These results are presented in Tables 4 and 5, and in Fig. 1. The biosedimentation parameters varied considerably within the region studied. This was due both to the specific hydrodynamic conditions found and to the structural and functional features of the ecological systems under study.

In the Bering Sea, the biosedimentation rate was 46.5 ± 5.3 mg dry weight $m^{-3} d^{-1}$ with an average POM concentration of 0.98 ± 0.04 mg dry weight m^{-3} . The average residence time of POM in the water column was about one month (29.7 ± 2.9 days).

Within the Bering Sea, different regions had highly varied biosedimentation rates. In the Gulf of Anadyr, the biosedimentation parameters had the lowest values. The rate of biosedimentation ranged from 12.0 to 30.0 mg dry wt $m^{-3} d^{-1}$. POM concentration averaged 0.86 ± 0.05 g dry wt m^{-3} ($n = 9$) and, as a rule, did not exceed 1.0 g dry wt m^{-3} . The residence time of POM ranged from 16.5 to 26.1 days at 80–120 m depth, and up to 53.3–65.2 days in the euphotic zone.

In the region north of St. Lawrence Island, the biosedimentation parameters featured a relative evenness in their vertical profiles. The biosedimentation rate amounted to 110.4 mg dry wt $m^{-3} d^{-1}$ at some depths and high concentrations of POM, more than 1.0 g dry wt m^{-3} , were found throughout the water column. These are approximately the same values observed in the open sea. However, in this region significant changes in the vertical profiles of the biosedimentation parameters were noted. The maximum rates of POM removal were noted above the thermocline at 20-m depth.

TABLE 4

Biosedimentation parameters in the Bering Sea.

Station	Depth (m)	Biosedimentation Rate (mg d.w. $m^{-3} d^{-1}$)	Particulate Organic Matter (g d.w. m^{-3})	Residence Time (days)
3	0	76.0	1.12	14.8
	20	56.1	1.09	19.4
	40	43.8	1.03	23.5
	80	97.8	1.23	12.6
7	0	25.5	0.89	35.1
	40	22.2	0.86	38.6
	80	24.5	0.89	36.3
	120	70.0	1.16	16.5
22	0	29.7	0.90	30.4
	20	13.5	0.72	53.3
	40	10.4	0.68	65.2
	80	40.6	1.02	25.1
35	0	22.7	0.83	36.1
	20	18.5	0.79	42.8
	40	29.4	0.91	31.0
	60	12.6	0.72	57.2
89	0	45.2	1.01	22.3
	20	87.5	1.18	13.5
	40	60.3	1.10	18.2
100	0	110.4	1.22	11.0
	15	50.0	1.04	20.8
	30	17.4	0.80	45.9
110	0	40.0	1.01	25.3
	20	107.3	1.25	11.7
	50	34.5	0.98	28.4
	170	50.2	1.08	21.5
113	0	56.5	1.06	18.7
	20	85.8	1.20	13.8
	70	9.6	0.67	70.5

In the Chukchi Sea, the biosedimentation rate and particulate concentration were considerably higher values than those in the Bering Sea and averaged 85.0 ± 22.1 mg dry wt $m^{-3} d^{-1}$ and 1.28 ± 0.06 g dry wt m^{-3} , respectively. Maximum biosedimentation rates for this region occurred below the thermocline. The residence time of the POM in the water column averaged 23 ± 5 days in the Chukchi Sea. The vertical POM profile showed an increased concentration in the 15–40 m layer as compared with the surface waters. The high values of POM and high rates of biosedimentation were evidently due to the phytoplankton bloom observed during the investigation. The bloom achieved red tide proportions at certain stations in the Chukchi Sea. The POM concentrations as a whole matched the spatial distributions of the average biosedimentation rates (Table 6).

The values of suspended organic matter for the regions investigated, as a whole, repeated the regularities of spatial distribution exhibited by the average biosedimentation rates (Table 6).

In the Bering Sea, the minimum biosedimentation rates from the upper 40-m layer were observed in the Gulf of Anadyr,

670–950 mg dry wt $m^{-2} d^{-1}$. The POM fluxes were much higher in the shallow northern Bering Sea, 1,630–2,800 mg dry wt $m^{-2} d^{-1}$, and in the open sea, 2,320–3,130 mg dry wt $m^{-2} d^{-1}$. The average values of the biosedimentation parameters for the upper layer (0–40 m) of the Bering Sea were as follows: the POM flux was 1940 ± 410 mg dry wt $m^{-2} d^{-1}$, the POM concentration was 52.6 ± 2.4 g dry wt m^{-2} , and the residence time of POM was 19.5 ± 7.4 days.

It should be noted that biosedimentation rates vary considerably in different parts of the sea. Near the coasts of the Chukchi Peninsula and Alaska, the sedimentation fluxes from the euphotic layer were the same as in the open and “prestrait” Bering Sea. In the central part of the Chukchi Sea, where the phytoplankton bloom was most intense, the POM flux increased to 5.9 g dry wt $m^{-2} d^{-1}$.

This assessment of biosedimentation in the Bering and Chukchi Seas points to the high intensity of these processes. This is related to high productivity of the region—principally, to the high rate of organic matter formation in the subarctic and arctic zones of the World Ocean in summer.

TABLE 5

Biosedimentation parameters in the Chukchi Sea.

Station	Depth (m)	Biosedimentation Rate (mg d.w. $m^{-3} d^{-1}$)	Particulate Organic Matter (g d.w. m^{-3})	Residence Time (days)
45	0	14.6	0.86	59.2
	20	48.3	1.28	26.3
	40	56.0	1.31	23.3
55	0	45.3	1.23	27.2
	20	83.2	1.39	16.0
	40	95.5	1.35	14.1
69	0	56.5	1.26	22.4
	15	239.8	1.44	6.0
	35	125.8	1.37	10.9

TABLE 6

The average values of the biosedimentation parameters for the upper layer (0-40 m) of the Bering and Chukchi Seas.

Station	Bering Sea		Residence Time (days)
	Flux of POM (mg d.w. m ⁻² d ⁻¹)	POM Concentration (g d.w. m ⁻²)	
3	2,319	43.4	18.7
7	948	35	36.9
22	671	30.2	45.0
35	891	33.2	37.2
89	2,805	44.7	15.9
100*	1,626	30.0	18.4
110	3,133	46.7	14.9
113	2,834	44.4	15.7
mean	1,940 ± 410	39.7 ± 2.5	26.3 ± 4.9

Station	Chukchi Sea		Residence Time (days)
	Flux of POM (mg d.w. m ⁻² d ⁻¹)	POM Concentration (g d.w. m ⁻²)	
45	1,712	56.9	33.2
55	3,073	52.4	17.0
69**	5,878	48.5	8.3
mean	3,550 ± 250	52.5 ± 2.4	19.5 ± 7.4

* 0-30 m layer

** 0-35 m layer

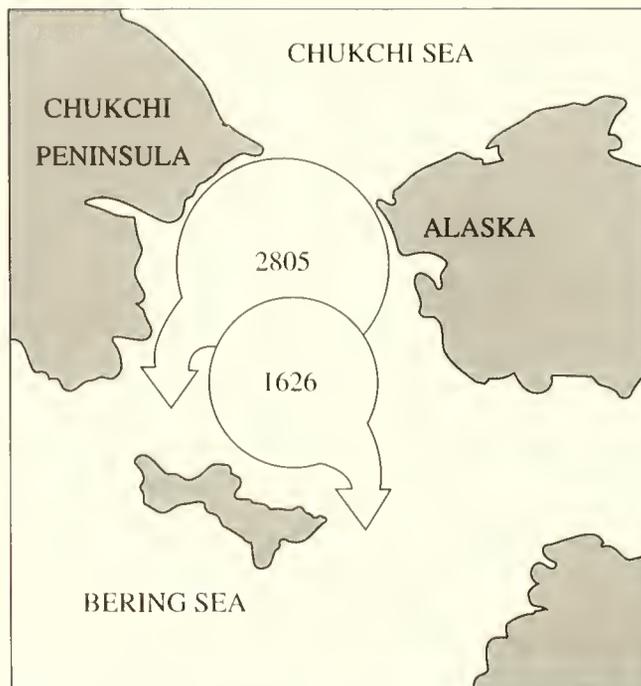


Fig. 1b. The biosedimental fluxes of the POM (mg d.w. m⁻² d⁻¹) from the upper layer (0-40 m) of the Bering Sea

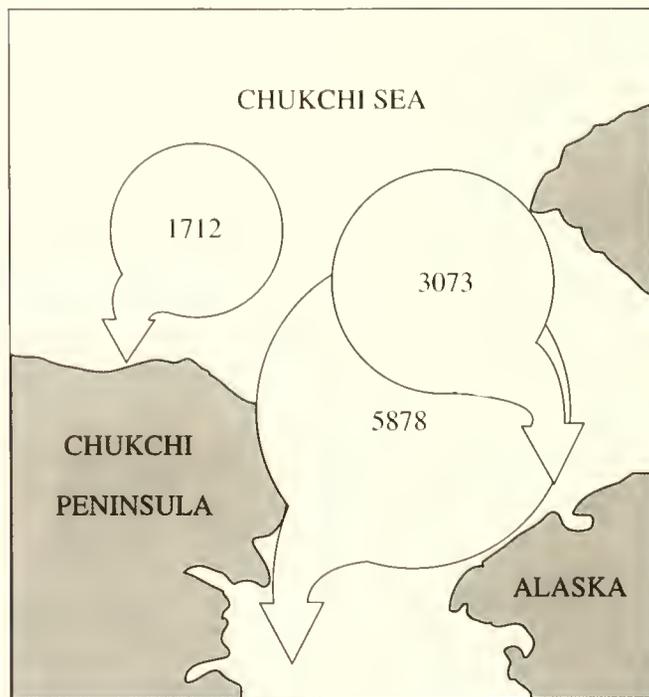


Fig. 1c. The biosedimental fluxes of the POM (mg d.w. m⁻² d⁻¹) from the upper layer (0-40 m) of the Chukchi Sea

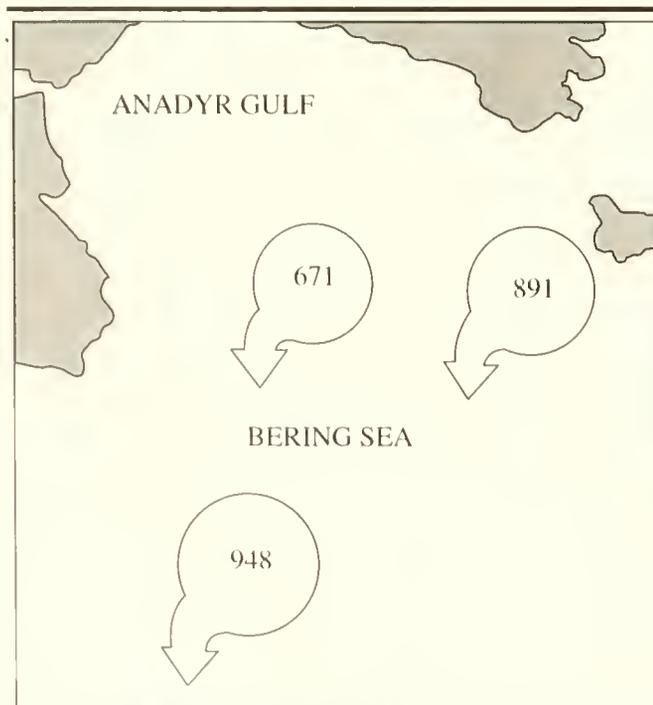


Fig. 1a. The biosedimental fluxes of the POM (mg d.w. m⁻² d⁻¹) from the upper layer (0-40 m) of the Bering Sea

6.4 Humic Acids

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Introduction

The bulk of the dissolved organic matter in natural waters, which is resistant to biochemical degradation, consists of brown, heterogeneous polymers known as humic acids (HA's). These substances account for about 30–60% of the total dissolved organic carbon (DOC) in seawater (Stuermer & Payne, 1975; Paxeus, 1985).

In oceanic areas unaffected by freshwater runoff, humic acids are mostly a by-product of algal cell degradation (Harvey *et al.*, 1988). The concentration of humic acids in seawater is, therefore, related to primary productivity of a region. Recent investigations (Carder *et al.*, 1986, 1989) have shown that phytoplankton and marine humus are only weakly covariant. However, this lack of correspondence is perhaps due to significantly longer residence times for marine humic substances (Bordovski & Ivanenkov, 1979) relative to the algal population that produced it and the quite variable flushing and mixing rates for different regions. For this reason pools of marine humus could be indicators of past primary productivity that is not manifested in the present values of productivity and chlorophyll content of the area under consideration. Especially significant correlations between these two parameters could be expected in the highly productive regions such as the Bering and Chukchi Seas.

Materials and Methods

Collection and Extraction of Seawater

Seawater was collected at depths from 0–20 m with a pumping system "Midiya" (Glebov *et al.*, Subchapter 6.3, this volume). Seawater was pumped through the system of parallel filters (0.5 μ m pore size membrane) to remove particulate matter, and the filtrate collected in 10–12 plastic vessels (35 liter capacity). When each vessel was full, 70 ml of concentrated HCl was added to it. The acidified seawater (pH 2) was passed through two 1.5 \times 15-cm glass columns containing 50 cm³ of Amberlite XAD-2 resin at a flow rate of 2 l/h per column. Each column extracted 200–250 l of seawater in each 48 h. Prior to use, the resin was cleaned as described by Gomez-Belinchon *et al.* (1988).

Isolation of the Extracted Humic Acids

Columns were first rinsed with 5–6 l of distilled water to remove salts. The collected HA's were eluted with 500 ml of concentrated NH₃ solution. To prepare the columns for reuse, they were then eluted with acetone (500 ml), ethanol (800 ml), and distilled water (8–9 l). The regenerated resin was then used

to extract the next portion of seawater. The ammonia eluent was concentrated to dryness in a rotary evaporator. The crude HA's were dried in a desiccator over P₂O₅.

Sampling Procedure for Fluorometric Analysis

The samples of natural water were taken with a 5-l Niskin bottle from the standard depths within the photic zone (Table 1). The samples were stored in 100–200 ml glass bottles at about -5°C.

Apparatus

Infrared (IR) spectra were recorded on an UR-20 instrument (GDR).

Ultraviolet (UV) spectra were recorded on a Hitachi spectrophotometer, model 100-60. Quartz cells with 1 cm path length were used.

Fluorescence spectra (excitation and emission spectra) were recorded on Jasco spectrofluorimeter, model SP 240. Excitation and emission spectra were collected with 10-nm slit widths for both monochromators. Spectra were not corrected for wavelength dependence of monochromator throughout or PMT response. For all fluorescence measurements, 1-cm path length quartz cells were used.

Chemicals

All chemicals were of analytical grade.

Preparation of the Standards

An aliquot amount of the dried HA (~20 mg) was weighed and redissolved in distilled water (~20 ml). The aqueous HA solution was filtered to remove insoluble residue and added with distilled water to 25 ml. The insoluble residue was dried and weighed. Concentration of the stock solution of HA's was determined by subtraction of the weight of the dry residue from the initial aliquot amount of the HA samples.

Calibration Curve Technique

The prepared stock solutions were used to plot the calibration curves. Standard solutions were excited at 315 nm and emission spectra were recorded from 350 to 500 nm. The relative intensity of the standard solution was registered at the maximum of emission spectra and plotted against the concentration. The plot of relative intensity versus the concentration showed a linear relationship from at least 0.1 ppm up to 20 ppm. This straight line relationship was valid for all of the standard curves. Obtained calibration curves were used for evaluating the concentration of humic acids in the seawater samples.

TABLE 1

Concentration (mg/l) of humic acids in the Bering and Chukchi Seas.

Bering Sea											
Depth (m)	Stations										
	2	41	89	100	102	110	111	112	113		
0	0.3	0.3	1.9	0.8	0.8	0.6	0.5	0.6	0.4		
5	0.9	0.5	0.9	0.7	0.9	1.2	0.3	0.6	1.0		
10	1.0	0.8	1.4	0.7	0.9	0.4	0.3	0.7	0.6		
15	0.9	0.3	1.2	0.7	0.9	0.4	1.2	0.7	0.5		
25	2.5	0.3	1.3	0.8	0.8	0.6	0.5	0.5	0.4		
45	-	0.4	0.9	0.7	1.0	0.5	0.8	0.5	0.4		

Gulf of Anadyr								
Depth (m)	Station							
	15	19	22	23	26	27	28	29
0	0.1	0.2	0.2	0.1	1.0	0.8	0.1	0.1
5	0.1	0.1	0.1	0.1	1.0	0.4	0.2	0.1
10	0.1	0.2	0.2	0.2	0.9	0.7	0.1	0.2
15	0.1	0.3	0.3	0.1	0.5	0.5	0.1	0.1
25	0.1	0.3	0.5	0.4	0.8	0.7	0.2	0.2
45	0.2	0.7	-	-	0.8	1.4	0.3	0.1

Bering Strait				
Depth (m)	Stations			
	76	77	80	83
0	2.0	2.5	1.5	2.7
5	1.8	1.9	1.7	1.4
10	1.4	2.0	1.5	1.6
15	1.6	2.7	1.3	1.6
25	2.1	1.8	1.7	3.1
45	2.3	2.0	1.2	3.0

Chukchi Sea												
Depth (m)	Stations											
	45	49	50	53	55	57	59	61	63	69	74	75
0	0.2	0.5	1.3	3.5	0.4	1.0	0.6	0.3	1.3	0.2	0.7	0.8
5	0.4	0.6	0.4	1.0	0.4	0.3	0.6	3.1	0.5	0.4	0.5	0.6
10	0.8	0.8	0.3	1.0	0.8	0.3	0.8	0.6	0.8	1.1	1.1	0.9
15	0.8	0.4	0.3	0.7	0.8	0.4	1.8	1.1	0.5	1.1	3.1	1.8
25	0.4	0.5	0.6	0.5	0.5	0.6	2.0	1.1	0.7	1.5	3.1	1.6
45	.07	0.6	1.1	0.5	1.4	0.6	1.6	0.5	2.5	1.2	1.8	1.2

Results and Discussion

Three samples of HA's were isolated from seawater that was collected at Stations (50+53) and (69+74) in the Chukchi Sea and at Station 112 in the Bering Sea. They were characterized by the elemental analysis and spectroscopic studies.

Elemental Analysis

The results of elemental analysis of the HA samples are summarized in Table 2.

TABLE 2

Elemental analysis of Humic Acids.

Sample	Station	%C	%H	%O	%S	%Ash
HA-1	50+53	36.0	9.6	52.1	1.3	1.0
HA-2	69+74	35.4	9.8	51.2	1.6	2.1
HA-3	112	36.9	8.0	53.1	N.D.	2.0

As can be seen from Table 2, the humic materials are characterized by the high oxygen content (51–53%), which is typical for marine HA in general (Brown, 1987; Alberts *et al.*, 1988). The presence of sulphur may indicate the presence of lignosulphonic acids (more or less biochemically degraded), which are one of the precursors of humic acids. As a whole, the humic materials isolated from the rather different environments show many similarities in elemental composition.

Spectroscopic Studies

The IR spectra of the HA studied are rather similar (Fig. 1). The broad band at about $3,400\text{ cm}^{-1}$ and the inflection at about $2,600\text{ cm}^{-1}$ are attributed to O–H stretching. The bands at $2,990\text{ cm}^{-1}$ and $2,970\text{ cm}^{-1}$ are due to C–H stretching. Carbonyl stretching gives rise to bands at $1,620\text{ cm}^{-1}$ (conjugated C=O). Signals from aromatic nuclei (skeletal vibrations) probably both contribute to the latter band and are also responsible for the band at $1,470\text{ cm}^{-1}$. The complex band at about $1,120\text{ cm}^{-1}$ presumably is due to C–O stretching of phenols and alcohols. A fairly well defined band at 980 cm^{-1} is primarily attributed to aromatic C–H in-plane deformation.

Finally, it should be pointed out that obtained IR spectra exhibited strong similarities in general appearance with those obtained by Paxeus (1985) and Dereppe *et al.* (1980).

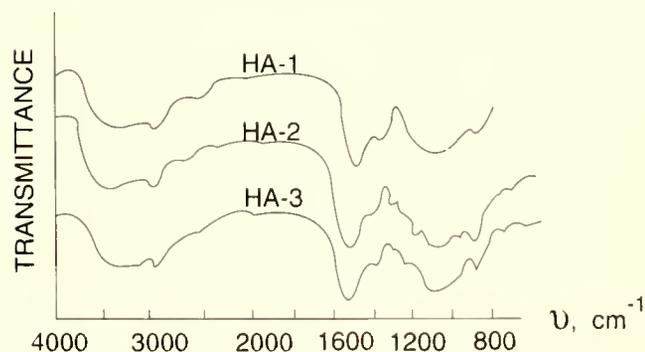


Fig. 1. IR-spectra of the isolated samples of humic acid.

Ultraviolet and Fluorescence Spectra

The UV spectra of the HA samples are shown in Fig. 2. The spectra of aqueous solutions of HA do not exhibit characteristic bands except for the shoulders at 210–230 nm.

The fluorescence spectra of the HA samples are shown in Fig. 3. The spectra show one broad band in the excitation spectrum (310–330 nm) as well as in the emission spectrum (400–420 nm). The fluorescence spectra of the HA agree with those obtained by Hayase and Tsubota (1983) and Cabaniss and Shuman (1987).

The pH-dependence of fluorescence intensity of the HA is complex (Fig. 4). Fluorescence intensity is the highest at pH values of 4–5. Decreases in the pH from 4 to 2 are followed by a fall in fluorescence intensity by 5–10%. Raising the pH value to 7.0–7.5 leads to a decrease in the intensity by 15–20%. Further increase in pH value does not affect the fluorescence intensity.

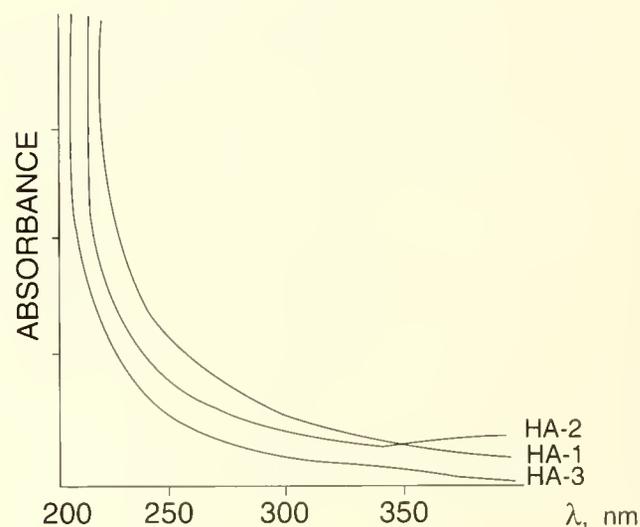


Fig. 2. UV-spectra of the isolated samples of humic acids.

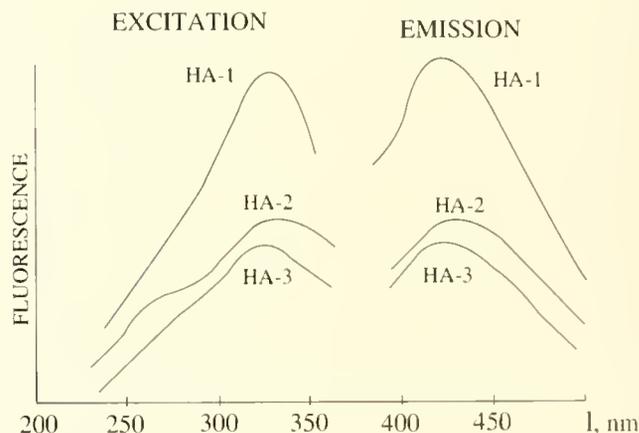


Fig. 3. Fluorescence spectra of the isolated HA samples.

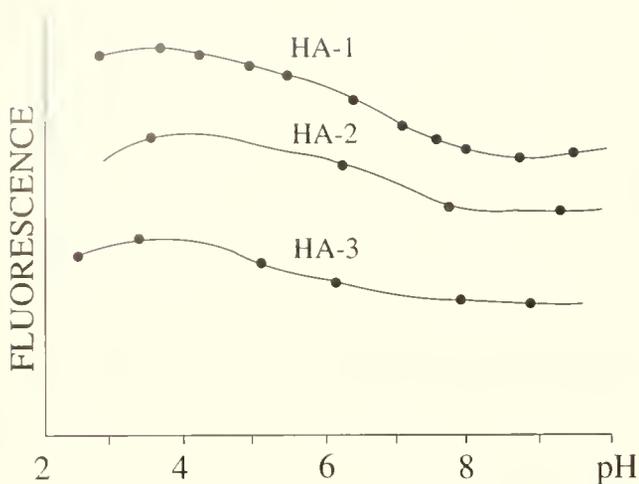


Fig. 4. pH-dependence of fluorescence intensity of the isolated HA samples.

Calibration Curves for the Isolated HA Samples

The equations for the calibration curves were determined by linear least-squares fit. They are presented below.

$$I(1) = (30.0 \pm 0.3) \times C(1) + (16.0 \pm 0.2)$$

$$I(2) = (44.4 \pm 0.2) \times C(2) + (16.2 \pm 0.2)$$

$$I(3) = (45.6 \pm 0.2) \times C(3) + (16.0 \pm 0.2)$$

Where I is the fluorescence intensity in relative units, C is concentration of HA in ppm, and the standard deviation (SD) for the method is 0.25 ppm ($p = 0.05$ and $N = 6$).

It is clear from the given equations that both samples from the Chukchi Sea show practically the same calibration curves. This fact is very important. It leads to the conclusion that an HA sample isolated from a local area could be used as a standard for the whole basin. At least, this conclusion could be drawn for moderately sized regions such as the Chukchi Sea.

Fluorimetric Determination of Humic Acids in the Seawater Samples

Humic acid concentration in the seawater samples was determined as described in Pershina (1987) using calibration curve technique. The data are summarized in Table 2 and shown in Fig. 5.

In considering the current results, the following main items could be pointed out. The highest concentration of HA's ($75\text{--}80 \text{ g m}^{-2}$ or $1.8\text{--}2.2 \text{ ppm}$) was detected in the region of the Bering Strait (Stations 76, 77, and 83) and adjacent edge of the Chukchi Sea (Station 74). High concentration of HA ($60\text{--}70 \text{ g m}^{-2}$ or $1.6\text{--}1.7 \text{ ppm}$) was found in the northern edge of the Bering Sea Shelf (Station 89) and in the southern part of the Chukchi Sea (Station 69). Relatively high contents of humic substances ($30\text{--}50 \text{ g m}^{-2}$ or $1.0\text{--}1.4 \text{ ppm}$) were observed in practically the whole area of the Chukchi Sea except for the northwestern region adjacent to the East Siberian Sea (Station 45) (16 g m^{-2} or 0.4 ppm).

These results from the Chukchi Sea agree with the previous study on the DOC distribution in Alaskan polar, subpolar, and estuarine waters (Loder, 1971; Hood & Reeburgh, 1974). In this study, the average concentration of DOC in the surface

water of the Bering Strait and Chukchi Sea was 1.25 ppm near the surface and 0.85 ppm in the bottom water. In the present study the concentration of HA's in the surface water of the Bering Strait was 2.6 ppm and 1.8 ppm in the bottom water. Taking into consideration that HA's consist of $40\text{--}50\%$ of carbon, the results from this study agree with the Loder's data on DOC distribution.

The local HA maxima ($30\text{--}40 \text{ g m}^{-2}$ or $0.6\text{--}0.8 \text{ ppm}$) were found at Stations 26 and 27 (the Gulf of Anadyr), and Stations 100 and 102 (the Bering Sea Shelf). Other areas of the Bering Sea and the Gulf of Anadyr that were studied were characterized by an average value of HA concentration $20\text{--}22 \text{ g m}^{-2}$ or $0.3\text{--}0.5 \text{ ppm}$.

The distribution described here of HA was compared with the distribution of nutrients, chlorophyll a , and primary production in the same regions (Grebmeier, Subchapter 7.1; Korsak, Subchapter 6.1; Whittleage, Subchapter 3.1; Zeeman, Subchapter 6.2, this volume). Direct correlation between the parameters was not found. However, the comparison did point out that the highest HA concentration was found between the two maxima in primary production at Stations 36 and 53 (Zeeman, Subchapter 6.2, this volume) and behind the front of chlorophyll a in the Chukchi Sea (Whittleage, Subchapter 6.2; Grebmeier, Subchapter 7.1, this volume).

To explain the observed relationships between distribution of primary production, chlorophyll a and HA, the following factors should be taken into consideration. First, the HA pool can be considered as a by-product of primary productivity. It is synthesized as a result of decay of newly produced organic matter and dead algal cells. However, there are great differences in the half-lives of humus relative to the algal population which produced it. When a phytoplankton bloom is transported offshore or northward and is grazed and degraded, the synthesis and accumulation of HA's goes on. This creates a lag between primary production and the HA concentration. Recent studies

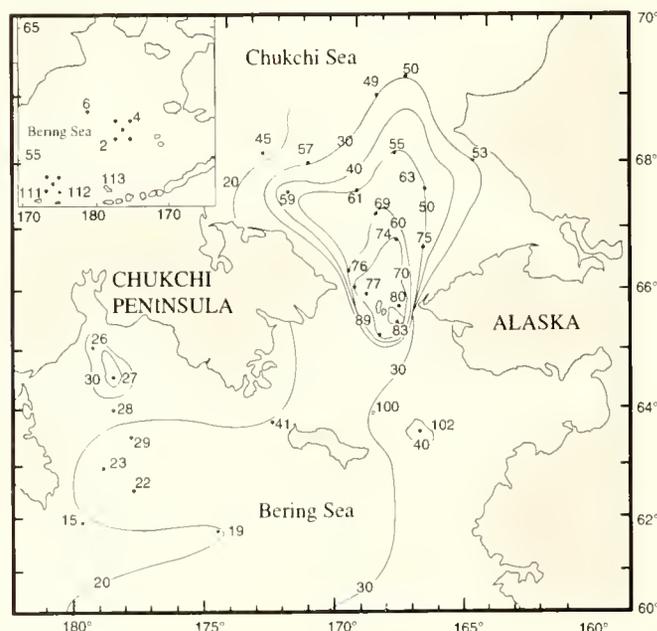


Fig. 5. Depth-integrated distribution of humic acids (g m^{-2}).

on the effects of HA's on remote sensing of ocean chlorophyll (Carder *et al.*, 1986, 1989) have shown that the lag time could be one or two months.

Second, the accumulation and distribution of HA's is dependent to a great extent on the mixing and flushing rates for the region. A reduction in the flushing or mixing rates should allow degradation products to accumulate relative to a well flushed environment. Therefore a bay or stagnant gyre should have more HA per unit of chlorophyll or newly produced organic matter than would a recently upwelled phytoplankton bloom.

While considering the present results (Fig. 4) it should be stressed that the highest HA concentration is found in the region of the Bering Strait. According to Coachman (1986) the water passing through the strait has three major components. In the west, the flow is dominated by cold, saline water from the Gulf of Anadyr. In the east, the flow consists of warmer coastal water dominated by the Yukon River discharge. South of St. Lawrence Island, a third water mass is formed of modified shelf water. The Bering Shelf–Anadyr water in the west and the Alaskan Coastal–Yukon River water in the east maintain their identity during passage through the strait.

The nutrient-laden western Bering Strait flow is associated with a large standing crop of phytoplankton (Sambrotto *et al.*, 1984). It could be one of the main factors contributing to the local HA maximum. In addition, constant inflow of the

degradation products from the highly productive waters could promote the synthesis and accumulation of HA's in the strait region as well. These sources include the Gulf of Anadyr, the Bering Sea Shelf, and the coast of Alaska. The lag of HA's behind the chlorophyll distribution and primary production value could be responsible for the observed HA maximum in the southern Chukchi Sea.

The local HA maximum at Stations 26 and 27 in the Gulf of Anadyr and at Station 102 on the Bering Sea Shelf appears to be connected with the freshwater discharges of the Anadyr River and the Yukon River.

The results showing the high HA distribution in the Chukchi and Bering Seas could be considered as the confirmation of high productivity in the region.

Taking into consideration the long half-lives of HA's, the HA concentration may be used, in a limited sense, as a quasi-conservative water mass property. Humic acid pools may be interpreted as a measure of primary productivity of a region over the previous one or two months. For this approach to be useful, a better understanding of degradation rates from dead algal cells and newly produced organic matter to HA's is required. In addition, we need to understand the effects of flushing, mixing, and photolysis on the degradation products. Even without these more intense studies, a certain degree of accuracy can be expected from empirical studies of primary productivity and HA's.

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Chapter 7:

**BENTHIC PROCESSES &
BOTTOM FAUNA**

Editors:

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7.1 Benthic Processes on the Shallow Continental Shelf

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Introduction

Participation in the Third Joint US-USSR Bering & Chukchi Seas Expedition from 24 July to 3 September 1988 extended studies of pelagic–benthic coupling and benthic carbon cycling in the northern Bering and Chukchi Seas (Grebmeier *et al.*, 1988; 1989; Grebmeier & McRoy, 1989) into Soviet waters previously inaccessible to US scientists. Scientific studies included benthic community structure and biomass, faunal bioturbation, benthic carbon cycling, and carbon accumulation in the sediments. In addition, data were collected and analyzed in cooperation with L. Cooper and M. DeNiro (University of California, Santa Barbara) to investigate a new technique for studying multiyear variation in water mass movement in polar seas using stable oxygen isotope measurements of tunicate cellulose and bottom seawater (Grebmeier *et al.*, 1990).

The shelf of the northern Bering and Chukchi Seas is shallow (30–70 m) and normally ice-covered from November to May. Northerly-flowing currents transport Pacific Ocean water through Bering Strait into the Chukchi Sea and Arctic Ocean (Fig. 1). Three major water masses develop during the open-water season, each having different salinity, nutrient, and phytoplankton dynamics (Walsh *et al.*, 1989). The high nutrient load (20–33 $\mu\text{M NO}_3^-$ -N) of the subsurface Anadyr Water provides a continuous source of nutrients for high primary production in the water column on the west side of the shelf from the Gulf of Anadyr to north of Bering Strait, but nutrient depletion limits production along the Alaska coastline after the spring bloom.

Past studies have shown a direct relationship between the particulate organic matter flux to the benthos and planktonic production in the surface waters of the ocean (Eppley & Peterson, 1979; Deuser *et al.*, 1981; Davies & Payne, 1984). The quantity and quality of freshly produced or consolidated organic carbon reaching the benthos is influenced by many factors, such as mixed layer and water column depth, zooplankton grazing, and bacterial decomposition in the water column (Parsons *et al.*, 1977). Supply of organic matter to the benthos is a major factor influencing benthic community structure, biomass, and metabolism (Mills, 1975; Graf *et al.*, 1982; Jørgensen, 1983; Smith *et al.*, 1983; Smetacek, 1984; Wassman, 1984; Grebmeier *et al.*, 1988, 1989; Grebmeier & McRoy, 1989). Sediment oxygen uptake rates provide information on aerobic utilization of carbon in sediments and have been shown to increase with elevated carbon fluxes to the sediments (Hargrave, 1973; Davies, 1975). Recent studies using shipboard sediment oxygen uptake experiments in the shallow shelf of the northern Bering and Chukchi Seas show

the value of this measurement in delineating areas of high organic carbon flux to the benthos, which are coincident with areas of high water column production, benthic faunal biomass, and sediment carbon remineralization (Blackburn, 1987; Grebmeier & McRoy, 1989). These total sediment oxygen uptake rates are used as an indicator of food supply to the benthos.

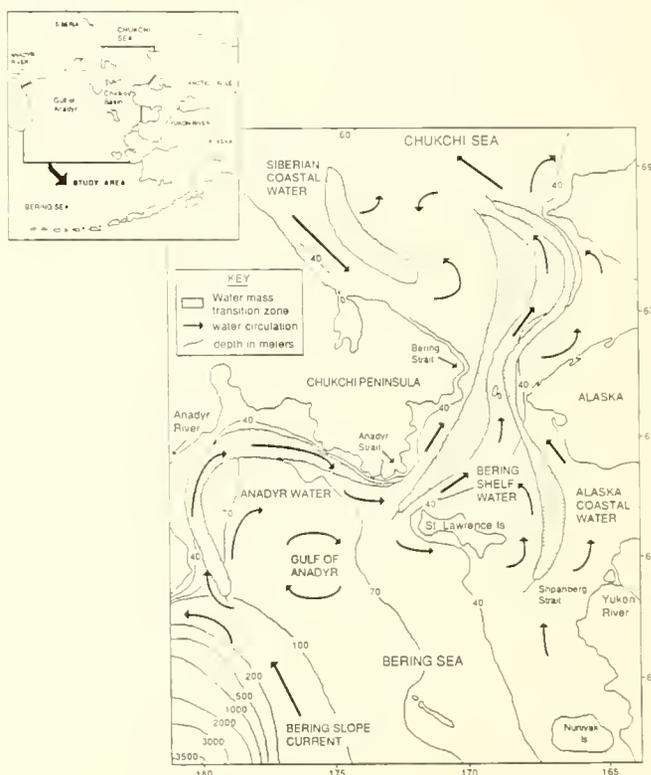


Fig. 1. Study area in the northern Bering and Chukchi Seas showing local water circulations, water masses, and bathymetry (modified from Coachman *et al.*, 1975; Walsh *et al.*, 1989).

Marine benthic systems in polar regions can exhibit high abundance and biomass in spite of cold temperatures and only seasonal pulses of particulate organic matter to the benthos (White, 1977; Stoker, 1978; Petersen & Curtis, 1980; Grebmeier, 1987; Grebmeier & McRoy, 1989). High latitude shelves have a higher percentage of water column production reaching the benthos compared to both tropical and temperate regions, supporting larger benthic populations (Petersen & Curtis, 1980). In early spring, food supply to the benthos in the northern Bering and Chukchi Seas consists of ice algal cells, water column phytoplankton, and cells resuspended from the

bottom with older detrital material. The work of Coyle and Cooney (1988) indicates that a large portion of the eastern Bering Sea ice-edge bloom is ungrazed by zooplankton and sinks directly to the benthos. These workers also found that a separate zooplankton community on the middle shelf of the southeastern Bering Sea did not graze a significant proportion of the spring carbon production (Cooney & Coyle, 1982). Here again, a large percentage of the organic carbon settles to the benthos to support a rich benthic community (Feder *et al.*, 1980; Feder & Jewett, 1981; Walsh & McRoy, 1986). Likewise, in the northern Bering and Chukchi Seas, a significant portion of the high carbon production in the Bering Shelf and Anadyr waters reaches the benthos, supporting a high benthic biomass of infaunal invertebrates and high sediment carbon mineralization (Grebmeier *et al.*, 1988, 1989; Grebmeier & McRoy, 1989; Walsh *et al.*, 1989). Although sediment grain size composition is the dominant factor in determining benthic community composition on the continental shelf of the Bering and Chukchi Seas (Stoker, 1978; Grebmeier *et al.*, 1989), food supply is the major factor influencing benthic biomass (Grebmeier *et al.*, 1988; Grebmeier & McRoy, 1989).

Carbon/nitrogen ratios in surface sediments can provide an indication of the quality of organic material arriving at the sea bottom, although water column nutrient concentration, zooplankton grazing, and bacterial degradation can influence these values (Parsons *et al.*, 1977; Valiela, 1984). Past work has used surface sediment C/N values to separate areas of high and low particulate organic carbon loss to the benthos (Walsh *et al.*, 1981). Grebmeier *et al.* (1988) used C/N ratios, in combination with sediment respiration rates, to investigate the quality and quantity of organic material available to benthic populations in the northern Bering and Chukchi Seas. Low surface sediment C/N ratios (5–7 wt./wt.) suggest a higher quality, nitrogen-rich organic material deposition to the benthos under the highly productive Bering Shelf–Anadyr water (280 g C m⁻² yr⁻¹; Walsh *et al.*, 1989), compared with lower quality, higher C/N ratios (8–14 wt./wt.), indicative of less labile, more refractory marine and terrestrial organic matter in the sediment under the less productive Alaska Coastal water (60 g C m⁻² yr⁻¹; Walsh *et al.*, 1989). In the southeastern Bering Sea, variations in the cross-shelf distributions of C/N ratios in surface sediments have been attributed to different proportions of detritus (Walsh *et al.*, 1981; Walsh & McRoy, 1986).

Lead-210 (²¹⁰Pb; half-life = 22.3 yr) is a particle-reactive, naturally-occurring radionuclide produced during the ²³⁸Uranium decay series. Since ²²²Rn is a nonreactive, noble gas, some escapes to the atmosphere before it decays to ²¹⁰Pb, which is then washed out of the atmosphere via precipitation, forming a measurable flux of ²¹⁰Pb in excess of that produced solely from ²²²Rn decay within the water column and sediments. Lead-210 rapidly adsorbs onto particulate matter and descends to the bottom sediments. It has been used successfully in both freshwater and marine systems to quantify physical and biogeochemical processes on time scales of months to decades (Krishnaswami *et al.*, 1980; Walsh, 1988). In sedimentary studies, measures of excess ²¹⁰Pb (²¹⁰Pb-ex) in sediments provide an indicator of sediment accumulation, since ²¹⁰Pb concentrations in excess of that supported by decay in the

sediments alone indicate accumulation of allocthonous materials. Used coincidentally with organic carbon measurements in the sediment, ²¹⁰Pb-ex can provide information on sedimentation and accumulation rates of organic carbon in the environment.

Stable oxygen isotope composition is normally expressed as ¹⁸O/¹⁶O ratios in the standard δ notation: $\delta^{18}\text{O} = (R^{\text{standard}}/R^{\text{sample}}) \times 10^3 \text{‰}$, where $R = {}^{18}\text{O}/{}^{16}\text{O}$ and standard is standard mean ocean water (SMOW). The stable oxygen isotope composition of seawater ($\delta^{18}\text{O}$) varies temporally and spatially in regions of the ocean, such as on shallow continental shelves influenced by freshwater input, which is depleted in the heavier oxygen isotope (¹⁸O), relative to the lighter oxygen isotope (¹⁶O), particularly at high latitudes where fractionation is intensified (Ferronsky & Polyakov, 1982). Stable oxygen isotope variability in surface marine waters has been used to study oceanic circulation, and when combined with salinity and temperature data—water contributions from rivers, evaporated surface ocean waters, melting glaciers, and melting sea ice, can be separated and water types characterized (Epstein & Mayeda, 1953; Redfield & Friedman, 1969; Tan & Strain, 1980; Bédard *et al.*, 1981; Ferronsky & Polyakov, 1982). Salinity is the predominant factor determining seawater density and water mass characteristics in the northern Bering and Chukchi Seas (Coachman *et al.*, 1975). There is a known relationship between ¹⁸O content and salinity in ocean waters, with similar processes influencing both salinity and ¹⁸O content in tandem (Epstein & Mayeda, 1953; Ferronsky & Polyakov, 1982). Thus, the major water masses in our study should be distinguishable by both $\delta^{18}\text{O}$ values and salinity concentrations. However, the salinity– $\delta^{18}\text{O}$ relationship can become decoupled when multiple freshwater sources of differing $\delta^{18}\text{O}$ values mix with saline water, leading to different $\delta^{18}\text{O}$ values but similar salinities for the mixtures. Another deviation from the salinity– $\delta^{18}\text{O}$ relationship can occur when sea ice forms and the resultant brine injection increases the underlying waters' salinities but does not significantly change $\delta^{18}\text{O}$ values over the whole water column, although sea ice itself is affected (Redfield & Friedman, 1969; Vetshteyn *et al.*, 1974; Ferronsky & Polyakov, 1982). Thus ¹⁸O data can allow tracing of known water mass distributions in polar seas despite changes in salinity over the winter period.

Oxygen removed from seawater by organisms reflects oceanic circulation processes in many circumstances. The oxygen isotope composition of cellulose is directly related to the oxygen isotope composition of water available to submerged aquatic plants and to members of the marine urochordate class Ascidiacea (tunicates), which synthesize cellulose (Epstein *et al.*, 1977; DeNiro & Epstein, 1979, 1981). DeNiro and Epstein (1981) observed that aquatic plant and tunicate cellulose $\delta^{18}\text{O}$ values were $27 \pm 3 \text{‰}$ more positive than the $\delta^{18}\text{O}$ values of the growth media. No significant temperature effects on isotopic fractionation were observed during cellulose synthesis in freshwater plants (DeNiro & Epstein, 1981) or during the carbonyl exchange reactions prior to cellulose synthesis that may govern the fractionation observed (Sternberg & DeNiro, 1983). Although tunicates have not been cultured under

different temperature regimes, the similar, consistent differences between the $\delta^{18}\text{O}$ values of water and tunicate cellulose for tropical and temperate animals that lived at temperatures differing by as much as 15°C (DeNiro & Epstein, 1981) suggest that, as in plants, there is no significant temperature effect on oxygen isotope fractionation in tunicate cellulose.

Material and Methods

Stable Oxygen Isotope Composition-Seawater and Tunicates

Bottom seawater for stable oxygen isotope analyses were subsampled in 20-ml vials, capped, sealed with Parafilm, and returned to the laboratory. Oxygen isotope ratios of water samples were determined by equilibrating 1.0-ml water samples with approximately $300\ \mu$ moles of carbon dioxide for 48 hours, purifying the equilibrated carbon dioxide cryogenically, analyzing the CO_2 mass spectrometrically, and using mass balance considerations to calculate the original oxygen isotope composition of the water (Epstein & Mayeda, 1953).

Tunicates were collected from both a 0.1-m^2 van Veen grab (weighted with 32 kg of lead for enhanced penetration) and otter trawl. Animals were sorted, keyed to species or lowest taxon possible, and frozen in Whirl-pak bags. In the laboratory, tunicates were freeze-dried and the body wall of solitary animals dissected out for cellulose extraction. In the case of colonial ascidians, a section of the outer region of the animal was excised for extraction. Cellulose was extracted using a sodium chlorite-acetic acid oxidation procedure (Wise, 1944). Oxygen isotope ratios of cellulose were determined by pyrolyzing vacuum-dried and sealed samples in the presence of HgCl_2 at 520°C for 5 hours to form CO , CO_2 and HCl . CO was disproportionated to CO_2 and C by electrical discharge. HCl was removed by reaction with isoquinoline (Epstein *et al.*, 1977). The CO_2 was then analyzed mass spectrometrically.

Sediment Oxygen Uptake Rates

Sediment samples for respiration experiments were collected using a HAPS 0.0133 m^2 benthic corer or a box corer. A shipboard core incubation technique for benthic metabolism was used, following methods of Grebmeier and McRoy (1989), which are based on experimental techniques of Pamatmat (1971), Newrkla (1983), and Patching and Raine (1983). Subsamples for core incubations were collected with 13-cm diameter, 26-cm long acrylic cores (8-mm thick walls). Average sediment depths were 10–15 cm, with the remainder of the core barrel enclosing bottom water. Overlying bottom water was carefully siphoned off and replaced with bottom water collected with a Niskin bottle at the beginning of the experiment. The cores were sealed with air-tight lids. Battery-operated stirrer blades inside the core barrel mixed the water to reduce oxygen gradient formation without disturbing the sediments (Newrkla, 1983). Control laboratory experiments showed no disturbance of sediment surfaces during stirring nor leakage of oxygen through the container walls (Grebmeier & McRoy, 1989). Cores were maintained in the dark at *in situ* bottom temperatures for 8–10 hours. This experimental duration has been determined to be adequate for measurable depletion of oxygen (average 25%) in the chambers for similar sediments (Grebmeier &

McRoy, 1989). Duplicate 60-ml water samples were collected at the beginning of the experiment from the bottom water Niskin bottle and at the end of the experiment from the sediment cores for determination of dissolved oxygen content by Winkler titration. After completion of the experiment, sediment cores were washed through 1-mm stainless steel screens. Animals were preserved in 10% seawater formalin, buffered with hexamethyltetramine, stored in plastic Whirl-pak bags, and saved for laboratory analyses (i.e., identification, abundance counts, and biomass weights).

Benthic Faunal Abundance and Biomass

Quantitative benthic samples were taken with the 0.1 m^2 van Veen grab. Previous work in the Bering Sea (Feder *et al.*, 1973; Grebmeier, 1987) indicates that 4 grab samples per station are adequate to account for natural statistical variability at each station. Each sample was washed through 1-mm stainless steel screens and animals subsequently preserved in 10% seawater formalin, buffered with hexamethyltetramine, stored in plastic Whirl-pak bags, and saved for laboratory analyses. Animals were keyed to family level, abundance was recorded, then they were blotted dry and weighed to determine wet-weight biomass. Wet-weight values were converted to organic carbon biomass using previously verified conversion values (Stoker, 1978; Grebmeier, 1987). The carbon conversions enable comparison of biomass between stations by reducing the influence of the calcium carbonate tests of mollusks and echinoids on total biomass. Log-transformed abundance data were analyzed using a numerical clustering program to group stations according to faunal similarities (Feder *et al.*, 1985; Grebmeier *et al.*, 1989).

Sediment Characteristics

Surface sediment subsamples were taken from the van Veen or Haps/box corer for total organic carbon and nitrogen determinations at each station. Samples were dried at 105°C overnight and homogenized with a mortar and pestle. One-gram subsamples of surface sediment (0–1 cm) were acidified with 2 ml of 1 N HCl and redried at 105°C overnight to obtain carbonate-free sediments, and then rehomogenized. Carbon and nitrogen contents were measured on a CHN analyzer. In addition, sediment subcores were collected at representative stations in each of the main basins, sectioned shipboard into 1–2 cm intervals, frozen, and returned to the laboratory. The concentration of ^{210}Pb was measured by gamma-spectrometry using low-background, high resolution, germanium detectors equipped with a Nuclear Data Model 990 microprocessor system programmed to record gamma spectra in 4,096 channels. Samples were dried at 105°C overnight, homogenized, and then packed in 90-cm^3 aluminum cans or 15-cm^3 plastic Petri dishes, depending on the amount of material available. The detectors were calibrated for the respective geometries with a certified mixed standard and the calibration procedures are described elsewhere (Olsen *et al.*, 1989). The low-energy (46.5 keV) ^{210}Pb gamma-ray was analyzed using a planar intrinsic-germanium detector and correction for self-absorption (Cutshall *et al.*, 1983). This technique allows for direct counting of radioactivity without leaching or radioactive

separation and allows for the simultaneous determination of both the total ^{210}Pb and the ^{214}Pb -supported level. Excess ^{210}Pb was calculated by subtracting the ^{214}Pb -supported level from the total ^{210}Pb activity.

Results and Discussion

Stable Oxygen Isotopes of Seawater and Tunicate Cellulose

During August 1988, the stable oxygen isotope ($\delta^{18}\text{O}$) signature values were determined for the major water masses in the northern Bering Sea (Fig. 2). In the northwestern section of the study area, the Anadyr Current (a bifurcation of the Bering Slope Current further south) travels clockwise in the Gulf of Anadyr. Most of this high nutrient, saline water exits northward through Anadyr Strait (Fig. 1), but some of this Anadyr water travels southeast of St. Lawrence Island (Coachman *et al.*, 1975; Walsh *et al.*, 1989). The $\delta^{18}\text{O}$ value for deep Bering Sea water was -0.8‰ , while Bering Slope Current water and Anadyr water were -1.2 to -1.3‰ and -1.4 to -1.5‰ , respectively, showing the early stages of freshwater dilution as deep Bering Sea water is advected up onto the shelf (Fig. 2). The cold pool in the Gulf of Anadyr, southwest of St. Lawrence Island, had a $\delta^{18}\text{O}$ value of -2.0‰ and the Alaska Coastal water to the east had the most depleted $\delta^{18}\text{O}$ values (-3.0 to -5.0‰). This west to east depletion of ^{18}O in bottom seawater parallels the west to east decreasing gradient in salinity occurring across the shelf in spring/summer due to freshwater dilution of Bering Sea water (Coachman *et al.*, 1975; Schumacher *et al.*, 1983).

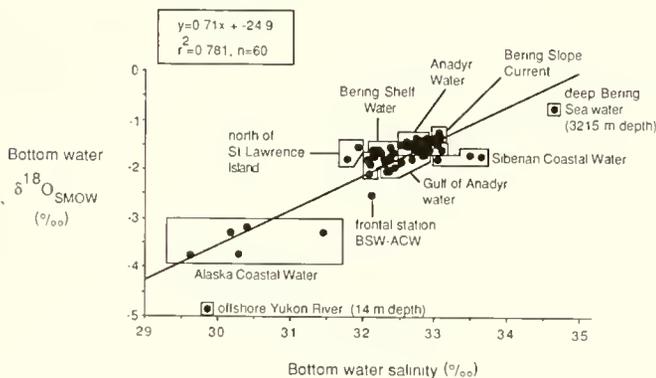


Fig. 2. Relation between bottom water ^{18}O values and salinity for stations occupied in the northern Bering and Chukchi Seas in 1987 and 1988. Water masses are defined by both salinity and location (Grebmeier *et al.*, 1990).

The Bering Shelf water (BSW) is formed south of St. Lawrence Island in the summer as a mixture of water from the Bering Sea moving northward, mixing with the less saline cold pool of resident water formed in the polynya south of St. Lawrence Island over winter, but it is the least understood water mass in the northern Bering Sea (Coachman *et al.*, 1975). $\delta^{18}\text{O}$ values for BSW north of St. Lawrence Island in August range from -1.6 to -2.1‰ (Fig. 2). The resident cold pool measured in the central Gulf of Anadyr southwest of St. Lawrence Island in August 1988 was composed of less

saline water (32.4‰) with a $\delta^{18}\text{O}$ of -2.0‰ . Coachman *et al.* (1975) propose that this cold pool results from less saline water off the Alaska coast being advected into the area between St. Matthew and St. Lawrence Islands. It is subsequently cooled and salinated in the winter and then is isolated from surrounding shelf waters in the summer, although some mixing occurs along its boundary with northward flowing water from the southeast Bering Sea Shelf to form the modified Bering Shelf water advected north of St. Lawrence Island in the summer.

A significant correlation was found between the stable oxygen isotope composition of bottom seawater and salinity in the study area, enabling determination of $\delta^{18}\text{O}$ values for the major water masses in the region dependent on freshwater dilution of the most saline Bering Sea basin core water as it moves onto the shelf (Fig. 2). The water most depleted in ^{18}O was found offshore of the Yukon River (Figs. 2,3), with intermediate concentrations found in Bering Shelf water. The

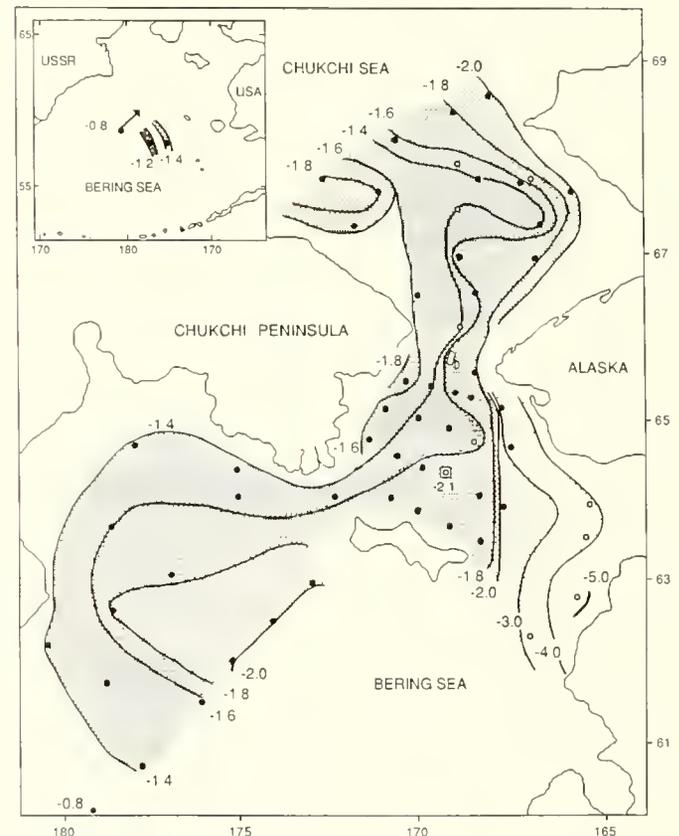


Fig. 3. Distribution of bottom waters $\delta^{18}\text{O}$ values for stations occupied during the 1988 R/V *Akademik Korolev* cruise 47 (●) and the 1987 R/V *Thomas Thompson* cruise 214 (○). Isotope ration units: (Grebmeier *et al.*, 1990).

waters most enriched in ^{18}O were found to the west in high salinity Anadyr water. In addition, the $\delta^{18}\text{O}$ -salinity dilution line shows the influence of brine rejection during ice formation enhancing salinity of the southeast-flowing Siberian Coastal water in the Chukchi Sea, even though the $\delta^{18}\text{O}$ remained constant in relation to the northwest-flowing Bering Shelf-Anadyr water, indicating the Siberian Coastal water sampled probably originated from south of Bering Strait.

The stable oxygen isotope composition of tunicate cellulose and its relationship to the water mass the animal grows in was studied for the first time in a polar system during the 1988 field season in the major water masses of the northern Bering and Chukchi Seas. The $\delta^{18}\text{O}$ values in the major water masses were mirrored in the $\delta^{18}\text{O}$ values of the cellulose in the benthic tunicates living in/on the underlying sediments (Figs. 3,4). Our objective was to test for possible short- and long-term signals for water mass location in this region. By measuring the ^{18}O content of cellulose in tunicates, which are immobile as adults, we found evidence that these animals provide a long-term indication (over a 1–3-yr. lifespan) of water mass location during the growing season, presumably during the ice-free summer months (Fig. 4). Due to oxygen isotope fractionation during cellulose synthesis, the $\delta^{18}\text{O}$ values of tunicate cellulose

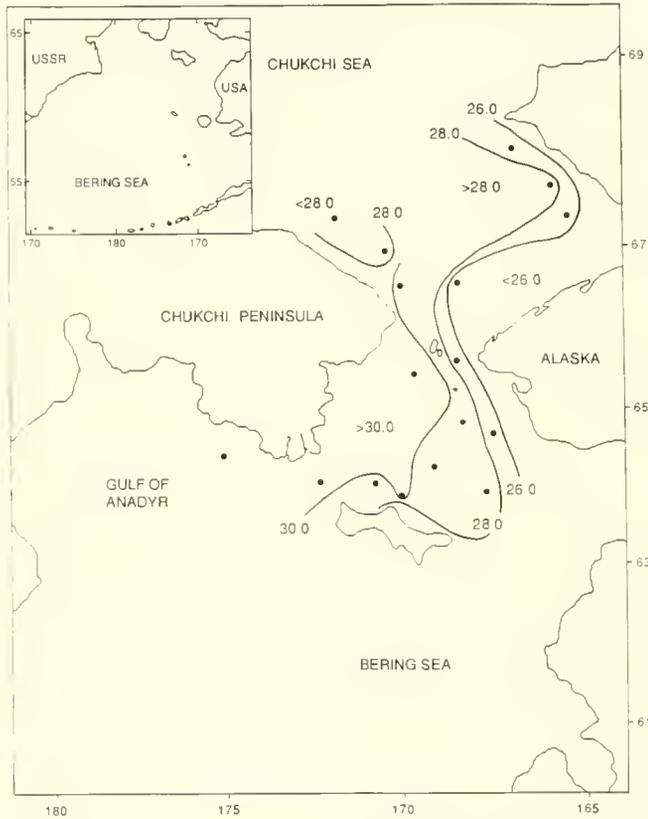


Fig. 4. Distribution of tunicate cellulose $\delta^{18}\text{O}$ values for stations occupied during R/V *Akademik Korolev* cruise 47 (●) and R/V *Alpha Helix* cruise 113 (∗) in 1988. Isotope ratio units: ‰₀₀ (Grebmeier *et al.*, 1990).

are positive, but the relative $\sim 27\text{‰}$ enrichment in ^{18}O is consistent with differences between each water mass. This signal was also observed in tunicates underlying the Siberian Coastal water.

Sediment Oxygen Uptake Rates

The high nutrient load of the Anadyr water provides a continuous source of nutrients for high primary production in the water column during the open-water season on the west side of the shelf from the Gulf of Anadyr to north of Bering Strait, but nutrient depletion limits production along the Alaska coastline after the spring bloom (Fig. 5; Walsh *et al.*, 1989).

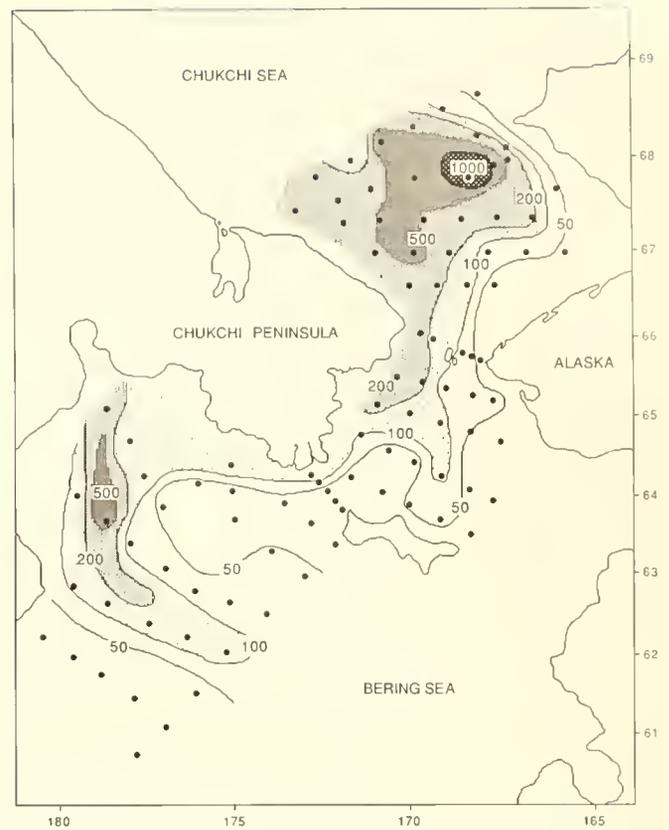


Fig. 5. Depth-integrated distribution of chlorophyll *a* (mg m^{-2}) during August 1988 (after Walsh *et al.*, 1989).

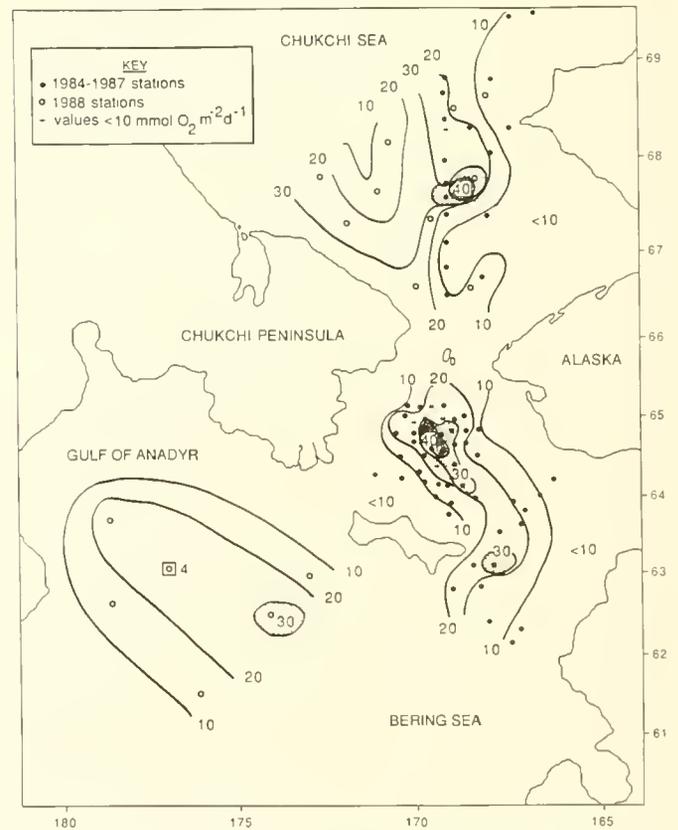


Fig. 6. Distribution of sediment oxygen uptake rates ($\text{mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$) for 1984–1986 (from Grebmeier & McRoy, 1989) and 1988 (this study).

The distribution of sediment oxygen uptake rates measured in the Bering and Chukchi Seas in 1988 (Fig. 6) is similar to water column chlorophyll *a* concentrations (Fig. 5). It further indicates the extension of a high sediment respiration zone, which can be used as an indicator of food supply to the benthos, to the west of the previously known zone in US waters (Grebmeier & McRoy, 1989).

The highest benthic respiration rates in the southern Chukchi Sea occurred in the central region where a similar value was measured in 1985 (~35 mmol O₂ m⁻² d⁻¹; Fig. 6). In contrast to the sediment regimes under Alaska Coastal water, sediment uptake rates in Siberian Coastal water and offshore Bering Shelf-Anadyr water had high respiration rates, indicating enhanced food supply to the benthos. Only a limited number of sediment respiration measurements were made in the Gulf of Anadyr, with values ranging from 10 to 40 mmol O₂ m⁻² d⁻¹. Further sampling is necessary to determine realistically organic carbon supply to the various regions of the gulf.

Benthic Macrofaunal Biomass and Community Structure

The highest benthic macrofaunal biomass for the study area was recorded in the southern Chukchi Sea in 1988 and was coincident with the location of highest macrofaunal biomass measured in the previous 1984–86 study period (~30–60 g C m⁻²; Fig. 7). The extension of this high biomass zone to the west, both under Siberian Coastal water and Anadyr–Bering Shelf water, suggests a major depositional regime for high quality organic matter to support the high secondary productivity in the underlying benthos. This western region of the Chukchi Sea contrasts greatly with the nearshore Alaskan waters, where benthic biomass normally remained below 10 g C m⁻². Ampeliscid and isaeid amphipods and tellinid and nuculid bivalves dominated the benthic fauna in the offshore region of the southern Chukchi Sea (Fig. 8). Benthic regions closer to the Alaska coastline were characterized by a mixture of communities, including tellinid and nuculid bivalves, echiurids, brittle stars, phoxocephalid, isaeid and ampeliscid amphipods, maldanid and oweniid polychaetes, and styelid tunicates. The variability in benthic community composition indicates the heterogeneity of the sediments underlying the Alaska Coastal water (Grebmeier *et al.*, 1989).

The highest biomass in the northern Bering Sea, north of St. Lawrence Island, was observed in the central basin, with lowest values once again along the Alaskan coast (Fig. 7; Grebmeier *et al.*, 1989). Ampeliscid and isaeid amphipods and tellinid bivalves dominated sandy sediments in this central region. Brittle stars and sea urchins were common in Anadyr Strait. A variety of benthic fauna characterized the region under Alaska Coastal water, which included ampeliscid and isaeid amphipods, tellinid and nuculid bivalves, echinarachnid sand dollars, and echiurids.

The Gulf of Anadyr is characterized by two major faunal populations. The inner gulf is composed of a high biomass (10–40 g C m⁻²) of tellinid and nuculid bivalves and capitellid and scalibregmid polychaetes. These animals are deposit feeders, indicative of the fine-grained sediment structure in

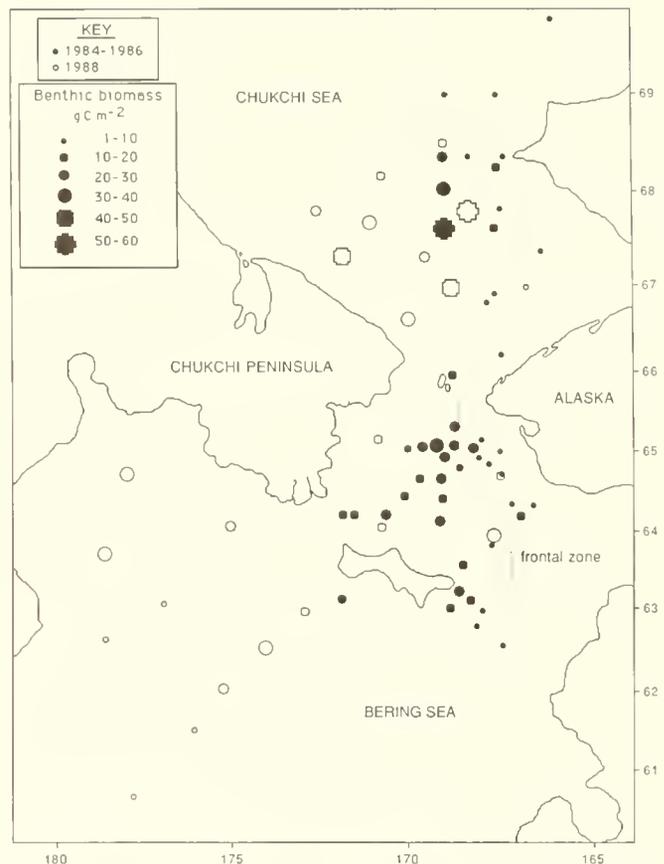


Fig. 7. Distribution of macrofaunal benthic biomass (g C m⁻²) for 1984–1986 (from Grebmeier *et al.*, 1988) and 1988.

this region. The outer gulf is composed of a more variable biomass (1–40 g C m⁻²) of nuculanid and nuculid bivalves and capitellid and scalibregmid polychaetes.

The area of high organic carbon supply to the benthos, indicated by high sediment respiration rates (Fig. 6), supports a rich benthic biomass of amphipods and bivalves (Figs. 7,8), which in turn support the dominant benthic-feeding marine mammals in the region, the California gray whale (*Eschrichtius gibbosus*) and Pacific walrus (*Odobenus ros marus*). Sediment oxygen uptake rates and benthic biomass show a strong pelagic–benthic coupling north of St. Lawrence Island into the southern Chukchi Sea, with the lowest apparent food supply to the benthos occurring in the low biomass regions underlying the Alaska Coastal water (Figs. 6,7). Sediment respiration and benthic biomass data were collected concurrently in the Gulf of Anadyr for the first time in 1988. The results support a high organic carbon flux to the benthos in the shallow nearshore Siberian waters and offshore regions southwest of St. Lawrence Island, with lower values in the central Gulf of Anadyr and deeper slope regions (Figs. 6,7). The increased benthic biomass and sediment respiration on the shelf in the eastern part of the Gulf of Anadyr is in an area affected by the St. Lawrence Island polynya (SLIP) in the winter/spring (Arctic Ocean Sciences Board, 1989), which indicates the region may be exposed to an additional carbon supply from enhanced open-water polynya primary production in the late winter–early spring.

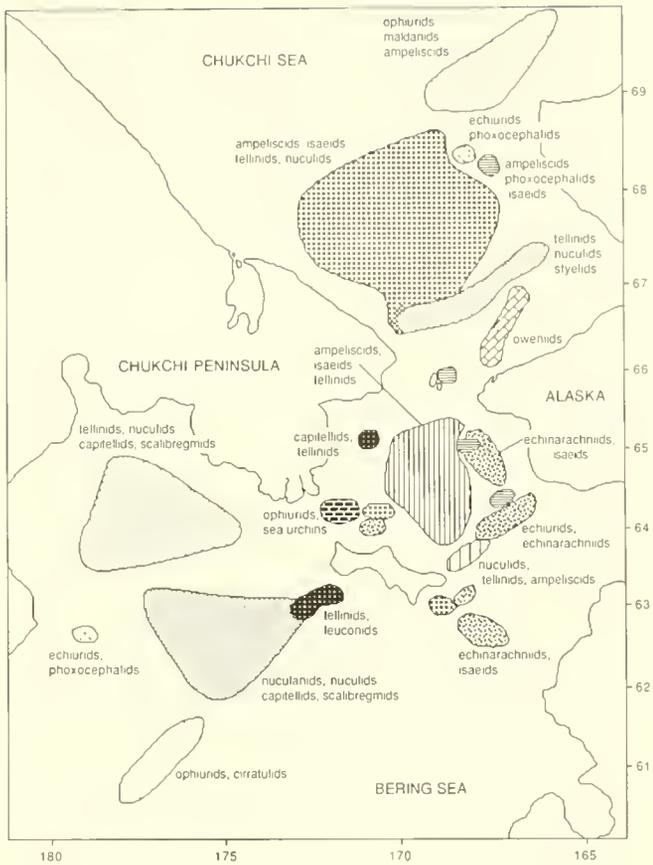


Fig. 8. Distribution of benthic communities based on data from 1984–1986 (from Grebmeier *et al.*, 1989) and 1988.

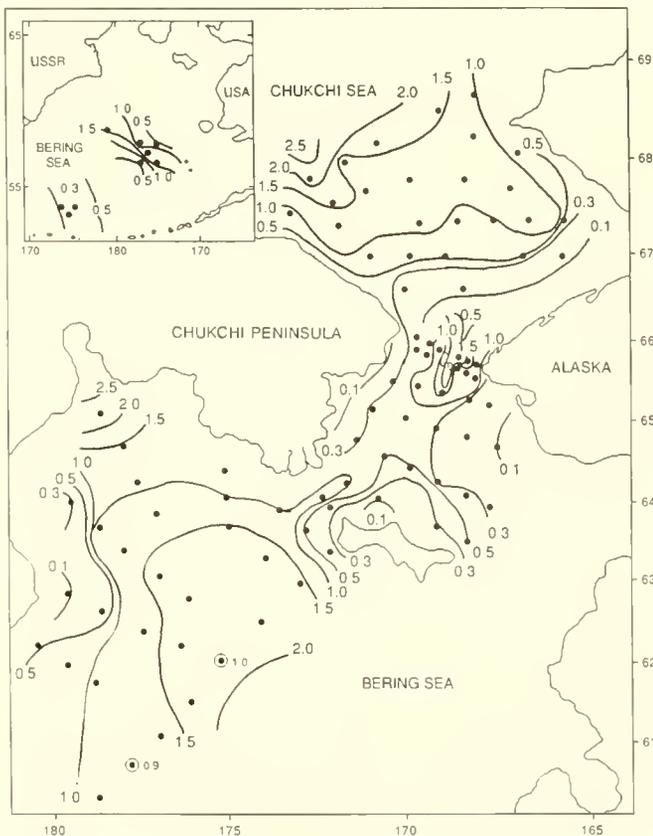


Fig. 9. Distribution of total organic carbon (%) in surface sediments during August 1988.

Total Organic Carbon and Nitrogen in Surface Sediments

Both the quantity and quality of organic matter reaching the benthos influences benthic standing stock and sediment respiration (Grebmeier *et al.*, 1988; Grebmeier & McRoy, 1989). Total organic carbon (TOC) in surface sediments was highest in the Gulf of Anadyr and the western region of the Chukchi Sea (Fig. 9), indicating a higher proportion of silt and clay in these sediments. The lowest TOC occurred in sediments under the Alaska Coastal Water (Fig. 9). The region north of St. Lawrence Island to Bering Strait has relatively low total organic carbon accumulating in the sediments due to the increased current speeds in this region. Fine sands characterize this sediment domain (Grebmeier *et al.*, 1989). In addition, the general shape of the TOC isolines follow the bathymetrically-steered currents (Fig. 1). This is consistent with previous findings that indicate the influence of hydrodynamics on organic carbon loading and sediment composition, which in turn influences benthic population community structure and biomass in this region (Grebmeier *et al.*, 1988, 1989).

High quality organic carbon settles to the benthos in these shallow waters, as evidenced by the low C/N values in sediments under the highly productive Gulf of Anadyr and Bering Shelf–Anadyr waters (Fig. 10). In contrast, highest C/N ratios (lowest quality material) occur in sediments underlying the outer shelf sediments in the Gulf of Anadyr and Alaska Coastal water in both the northern Bering and Chukchi Seas (Fig. 10). A similar pattern was observed between 1984 and 1986 to the east of the

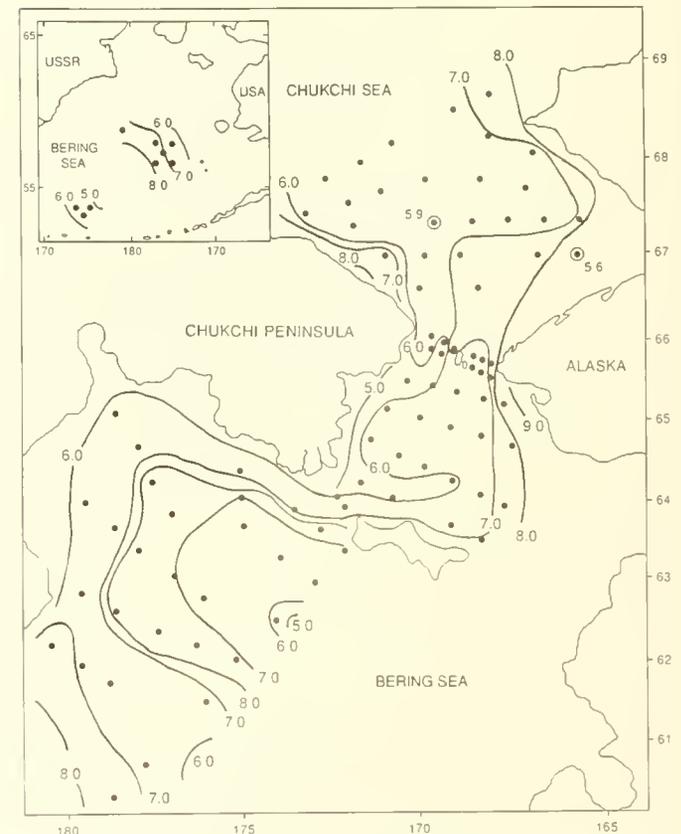


Fig. 10. Distribution of C/N ratios (wt./wt.) in surface sediments during August 1988.

international date line and the influence of refractory terrestrial material on this food source, coming into the marine systems from Alaskan rivers, is supported by previous work (Grebmeier *et al.*, 1988; Walsh *et al.*, 1989).

Natural Radioisotope (^{210}Pb) Content in Surface Sediments

A preliminary study of spatial ^{210}Pb -ex distribution in surface sediments at select stations in the Gulf of Anadyr, northern Bering Sea, and southern Chukchi Sea indicated a higher concentration of the particle-reactive radionuclide ^{210}Pb in the higher silt and clay content sediments of the Gulf of Anadyr and southern Chukchi Seas (Fig. 11). This limited data set had a high correlation between surface sediment TOC and ^{210}Pb content ($n=9$, $r^2=0.71$, $0.001 < p < 0.005$), indicating that regions of higher organic carbon content in the sediments were also regions of higher sedimentation and accumulation of organic matter from the overlying water column to the sediments. The highest ^{210}Pb -ex concentration in the Gulf of Anadyr occurred at the mouth of Kresta Bay, suggesting enhanced deposition of terrigenous and marine material at this site. In the Chukchi Sea, the highest ^{210}Pb -ex (3.8 dpm/g) occurred in the "hot spot" of high primary and benthic secondary productivity, and the lower total organic carbon in the sediments (1.3%) relative to surrounding stations may result from the high benthic consumption of organic matter at this site. The lowest ^{210}Pb -ex concentrations were measured in the sandy sediments of the northern Bering Sea (0.6–1.0 dpm/g), along with low

organic carbon content (0.3%). However, this area is a region of high water column chlorophyll and benthic biomass. Recent studies by Blackburn (1987) suggest that efficient grazing by the benthic amphipods, along with rapid mineralization of organic matter in the sediments, results in lower sediment organic carbon content in this region. The present study, in addition to earlier ^{210}Pb studies (Grebmeier, unpubl. data), supports a reduced sediment accumulation in this region, although carbon flux to the benthos is high (Grebmeier & McRoy, 1989; M. Fukuchi, personal communication).

An additional study was undertaken to determine the sedimentation rates based on vertical cores within each of the main study areas (Fig. 12). Preliminary data, based on natural log-normal distributions of ^{210}Pb -ex in sediment sections with depth down the sediment core in the Gulf of Anadyr and southern Chukchi Sea, indicate low but variable sediment accumulation rates. Sedimentation rates ranged from 0.01–0.03 mm/yr in the southern Chukchi Sea to 0.04 mm/yr in the Gulf of Anadyr. The difference between these two regions is evident in the highly variable ^{210}Pb -ex values in the top 0–10 cm in the southern Chukchi Sea stations (Stations 45, 55), due to the extremely high mixing of these sediments by the high benthic fauna populations (Fig. 7; Grebmeier, 1987; Grebmeier & McRoy, 1989). In comparison, the one station analyzed in the central Gulf of Anadyr (Station 22) occurred in a low benthic faunal abundance region in the central gulf (Fig. 7), such that the surface sediment was little mixed and the ^{210}Pb -ex profile was undisturbed. Further studies are needed on longer cores in both the Gulf of Anadyr and Chukchi Sea to evaluate organic carbon sedimentation and accumulation in the

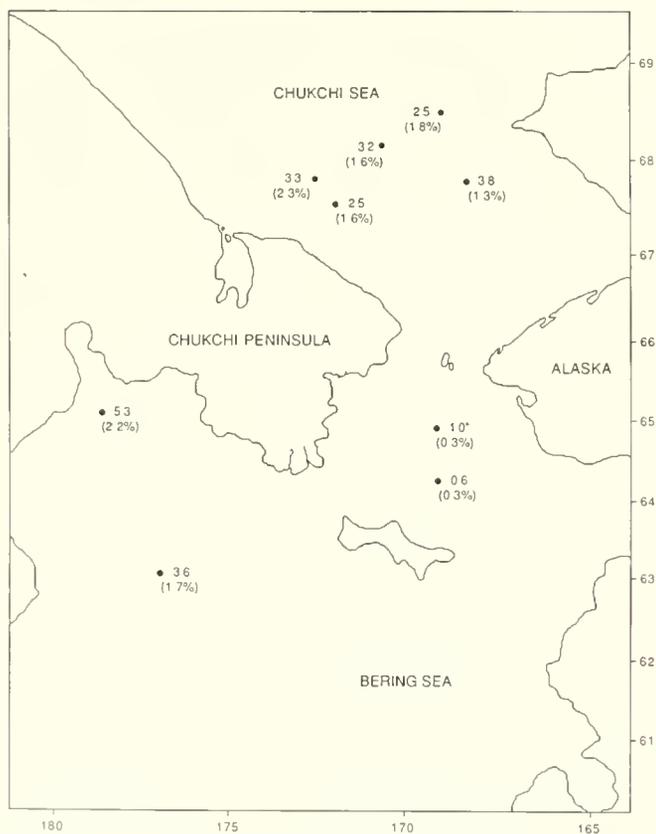


Fig. 11. Distribution of ^{210}Pb -ex (dpm/g) and total organic carbon (%) at select stations during August 1988.

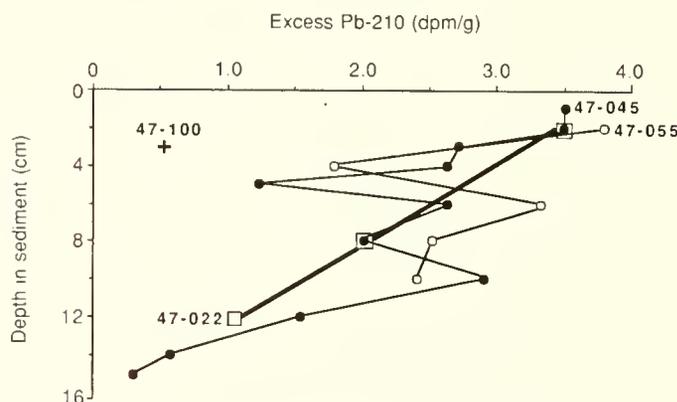


Fig. 12. Vertical profile of ^{210}Pb -ex (dpm/g) at select stations in the Gulf of Anadyr: Station 22 (AK47-022□); and southern Chukchi Sea: Station 45 (AK47-045 ●) and Station 55 (AK47-055 ○). An additional ^{210}Pb -ex concentration for a surface sample (0–3 cm) in the northern Bering Sea is presented for comparison: Station 100 (AK47-100 +).

sediments of these arctic regions. Previous data from the sandy sediments of the northern Bering Sea indicate little or no sediment accumulation in this region, with sedimentation rates a magnitude lower than values in the other two regions (Grebmeier, unpubl. data). These data support the conclusion presented earlier—that although organic matter is settling to the benthos in this region, highly efficient benthic faunal

consumption, sediment mineralization, and resuspension by benthic-feeding marine mammals inhibit fine sediment and organic carbon accumulation in this region.

In conclusion, the shallow continental shelf of the northern Bering and Chukchi Seas exhibits a direct coupling of water column primary production to secondary benthic production and carbon cycling. The deposition of a high quantity and quality of organic carbon to the western regions of this area supports extremely high populations of benthic fauna, which in turn provide a large food source for benthic-feeding marine mammals. Shallow marine shelves in polar regions are important sites for carbon cycling and are likely to be directly impacted by global climate changes.

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7.2 Characteristics of Benthic Biocenoses of the Chukchi and Bering Seas

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Introduction

Benthic fauna of the boreal and southern regions of arctic waters of the World Ocean are characterized by relatively high faunal diversity and biomass. Thus, the benthos plays a very important role in the energy balance of the marine ecosystem. At the same time most benthic organisms are quite sensitive to various environmental effects. In recent years the most prominent effect has been exerted by anthropogenic factors that have been increasing annually. In this respect, global ecological monitoring of the World Ocean is becoming more and more vital (Izrael & Tsyban, 1985).

The present article is a continuation of the work started in 1977 by the USSR Committee on Hydrometeorology and Environmental Control in the Bering Sea. In 1988, the group of scientists that studied problems of the benthos during the 47th cruise of the research vessel (R/V) *Akademik Korolev* put forward the following tasks: 1. definition of the structural characteristics of benthic communities in the regions covered by the expedition; 2. analysis of the quantitative distribution of benthic fauna; and 3. determination of annual variations in the structure of benthic ecosystems, if any, and reasons for these variations.

It should be noted that the regions studied were selected based on data available from previous investigations. First attempts to quantitatively study characteristics of the benthos in the northern part of the Bering and Chukchi Seas were made in 1933 during the cruise of the R/V *Krasnoarmeyets* (Deryugin & Ivanov, 1937; Makarov, 1937). Then, from 1950–52, more detailed studies of qualitative and quantitative characteristics

of the benthos of the northwestern part of the Bering Sea were carried out during the cruise of the R/V *Vityaz* (Vinogradova, 1954; Zenkevitch & Filatova, 1956; Belyaev, 1960; Filatova & Barsanova, 1964). Eastern and central parts of the Bering Sea were thoroughly studied during several cruises as part of Soviet expeditions in 1958–1960 (Neiman, 1963) and by American scientists in 1970–1974 (Alton, 1974; Stoker, 1981). In recent years investigations of the Bering and Chukchi Seas benthos were carried out by both Soviet (Sagaidachny & Chistikov, 1987) and American scientists (Grebmeier *et al.*, 1988, 1989; Grebmeier & McRoy, 1989).

On the basis of prior research and the present study, we investigated the annual variations of some benthic biocenoses and their quantitative characteristics in the Bering and Chukchi Seas.

Material and Methods

Samples of benthic fauna collected in 1988 during the 47th cruise of the R/V *Akademik Korolev* in the Bering and Chukchi Seas were used as materials for the present study. A total of 159 macrobenthic samples from 86 stations were collected during the cruise, including 48 samples collected with a trawl and 111 samples collected with a dredger. Of the dredger samples, 25 were tested for qualitative parameters, with the remainder analyzed for quantitative parameters. In addition, meiobenthic samples were obtained at 46 stations.

Samples were collected in three main regions: the Gulf of Anadyr and neighboring waters (14 trawl samples and 26 dredger samples); the northern Bering Sea from St. Lawrence

Island to Bering Strait (11 trawl samples and 35 dredger samples); and in the southwest Chukchi Sea (18 trawl samples and 43 dredger samples; Figs. 1,2). In addition, five trawl

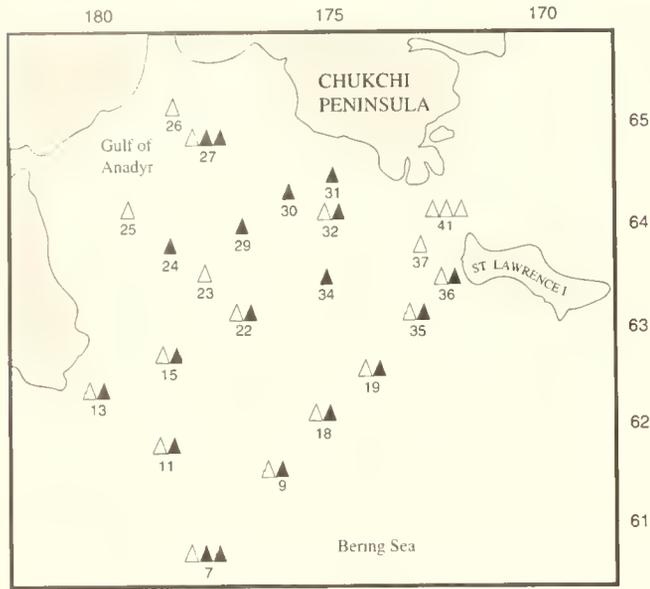


Fig. 1. Distribution of quantitative (▲) and qualitative (△) samples at stations in 1988 in the Gulf of Anadyr and neighboring waters in the Bering Sea.

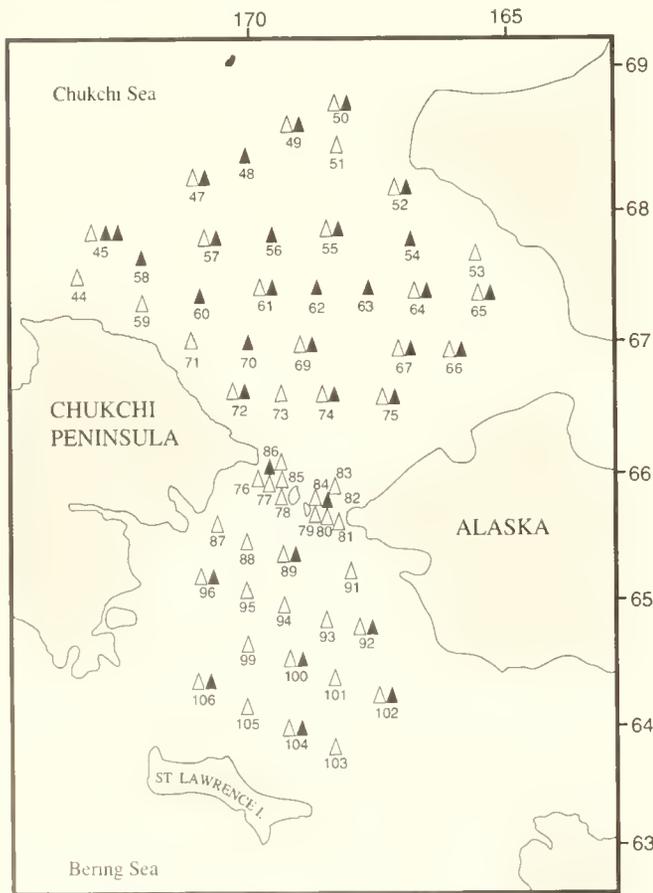


Fig. 2. Distribution of quantitative (▲) and qualitative (△) samples of benthos at stations in 1988 in the southeastern part of the Chukchi Sea and in the northern part of the Bering Sea.

samples and eight dredger samples were collected in sampling grids further south in the Bering Sea, designated as East and South Polygons. The East Polygon was in the central part of the Bering Sea covering both its continental shelf and slope, and the South Polygon was in the southern part of the Bering Sea, near the Aleutian Islands.

Samples were collected with the following equipment: Sigsby trawl (small size version: 0.9 m entrapment width, 0.5- mm mesh, 20-min trawl at 3 knots); dredger *Ocean* (entrapment area 0.25 m²), and van Veen bottom sampler (entrapment area 0.1 m²). Dredging and trawling were carried out from starboard using a winch on the bow of a ship. Trawling was carried out for 20-min time periods while the ship was adrift. Most of the dredged samples were collected with a van Veen sampler. Usually two dredger samples at one station were averaged and treated as one sample. Meiobenthos samples were taken from the dredger samples. Seabed fauna was washed off on a washer using a set of 10, 5, and 1 mm mesh sieves. After treatment, the extracted organisms were fixed in 4% formalin or 75% ethanol. The collected material was classified and treated in the ship lab. Preliminary identification of organisms was carried out to lowest taxon level possible. Final analysis of benthic material is still under way in the Institute of Zoology (USSR Academy of Sciences).

Results

The following section presents a brief review of the benthos of each of the investigated regions of the Bering and Chukchi Seas.

The Gulf of Anadyr and Neighboring Waters

The research work in the studied regions of the Gulf of Anadyr was carried out in the central part of the gulf and on the shelf at the gulf outlet. Due to the limited quantitative material obtained, only 5 biocenoses (Fig. 3) with 28 dominant benthic forms were determined (Table 1). Average biomass of benthos in the region equals 461 g m⁻². The most widespread benthic community is the biocenosis of ark shells *Macoma calcarea* that inhabit the entire central part of the Gulf of Anadyr at depths of 47–140 m. This biocenosis is subdominated by ark shells (*Leionucula inflata*, *Cyclicardia crebricostata*, and *Yoldia*), polychaetes (*Amphictene moorei*, *Nicomache humbricalis*, and *Nephtys ciliata*), ophiurids (*Ophiura sarsi*), and some other bottom organisms. Alongside *Macoma*, another widespread organism is *Leionucula*; at some peripheral stations its biomass is equal to that of the dominant biocenosis. At Stations 24, 29, 30, and others that are situated in the center of the biocenosis, *Macoma* dominates completely; its biomass equals 80–94% of the total biomass of all benthos. Maximum benthic biomass at these stations reaches over 1,000 g m⁻² (Fig. 4). Average biomass of the benthos in the *Macoma calcarea* biocenosis equals 616 g m⁻².

The biocenosis *Nuculana lamellosa radiata* occurs in the open sea, south from the *Macoma* biocenosis, at a depth of 63–88 m within the lowest temperature region in the study area.

TABLE 1

Dominant benthic forms of the Gulf of Anadyr (1), northern part of the Bering Sea (2) and southeastern part of the Chukchi Sea (3). Questionable determination indicated by (?).

Dominant forms	1	2	3	Dominant forms	1	2	3
Sponges				Mollusks			
<i>Halichondria panicea</i>	+	+	-	<i>Tridonta borealis</i>	-	-	+
Coelenterata				<i>Cyclocardia crebricostata</i>	+	+	+
<i>Haliactis arctica</i>	-	-	+	<i>Liocyma fluctuosa</i>	-	+	-
<i>Epiactis levisi</i>	-	-	+	<i>Macoma calcarea</i>	+	+	+
<i>Cersenia rubiformis</i>	-	+	-	<i>Leionucula inflata</i>	+	+	+
Polychaetes				<i>Nuculana lamellosa radiata</i>	+	-	+
<i>Ampharete acutifrons</i>	+	+	+	<i>Serripes groenlandicus</i>	-	+	+
<i>Lunbrineris</i> sp.	+	+	+	<i>Yoldia amygdalea</i>	+	+	+
<i>Nicomache lubricalis</i>	+	+	+	<i>Tachrhynchus erosus</i>	+	-	-
<i>Maldane sarsi</i>	+	+	+	Echinodermata			
<i>Nocamphitrite groenlandica</i>	-	-	+	<i>Ctenodiscus crispatus</i>	+	-	-
<i>Nephtys pente</i>	-	+	?	<i>Gorgonocephalus caryi</i>	-	+	+
<i>Nephtys caeca</i>	+	+	+	<i>Ophiura sarsi</i>	+	-	+
<i>Nephtys ciliata</i>	+	+	+	<i>Ophiura</i> sp.	+	+	-
<i>Cistenides granulata</i>	+	+	-	<i>Echinarachnius parma</i>	+	+	-
<i>Phyllodoce groenlandica</i>	+	-	+	<i>Strongylocentrotus pallidus</i>	+	+	+
<i>Amphictene moorei</i>	+	-	-	<i>Strongylocentrotus</i>			
<i>Scalibregma inflatum</i>	-	+	-	<i>droebachiensis</i>	-	+	-
<i>Sternaspis scutata</i>	-	-	+	<i>Myriotrochus rinkii</i>	-	-	-
Siphunculida				Holothuroidea	-	-	+
<i>Golfingia margaritacea</i>	+	+	+	Ascidia			
Echiurida				<i>Boltenia ovifera</i>	+	+	-
<i>Echiurus echiurus</i>	+	-	+	<i>Boltenia echinata</i>	-	-	+
Bryozon				<i>Peloniaia corrugata</i>	-	-	+
<i>Alcyonidium vermiculare</i>	-	+	-	<i>Synoicum solidum</i>	+	+	-
<i>Bryozoa</i> sp.	+	-	-	Total number of dominant forms			
Crustacea				for each region	28	28	29
<i>Balanus crenatus</i>	+	+	+				
<i>Ampelisca</i> sp.	+	+	+				

This is a pronounced biocenosis that was found at three stations (18, 19, and 22). *Nuculana* dominated the biocenosis, and its biomass constituted 80–90% of the total benthic biomass, which reached 2,811 g m⁻², average benthic biomass of the biocenosis of *Nuculana* equaled 1,413 g m⁻².

In the eastern part of the gulf, at a depth less than 50 m *Macoma* biocenosis is replaced by the biocenosis of sand dollars *Echinarachnius parma*. Station 25 was a boundary one where both dominant biocenoses are found.

In the southeast region of the study, at a depth of 97–140 m, there is a biocenosis that is characterized by domination of polychaetes *Nephtys ciliata* and *Nicomache lubricalis*, along with ophiurae. Average benthic biomass of this biocenosis is not large if compared to the previous one and equals only 78 g m⁻².

In the region between the continent and St. Lawrence Island, on mixed sediments of pebbles and rocks, there is a specific biocenosis dominated by sessile benthos (sponges *Halichondria panicea*, ceripedian *Balanus crenatus*, ascidiae *Ascidiae*, and sea hedgehogs *Strongylocentrotus pallidus*).

Northern Bering Sea

Due to the complexity of the hydrological regimes in the region north of St. Lawrence Island to Bering Strait, the biocenoses of the benthos are also very complicated. Three different water masses (waters of the Gulf of Anadyr, shelf waters of the Bering Sea, and Alaska Coastal waters) and enormous diversity of sediment grain size composition contribute to a mosaic structure of benthic faunal distribution. Small numbers of quantitative samples collected in this region

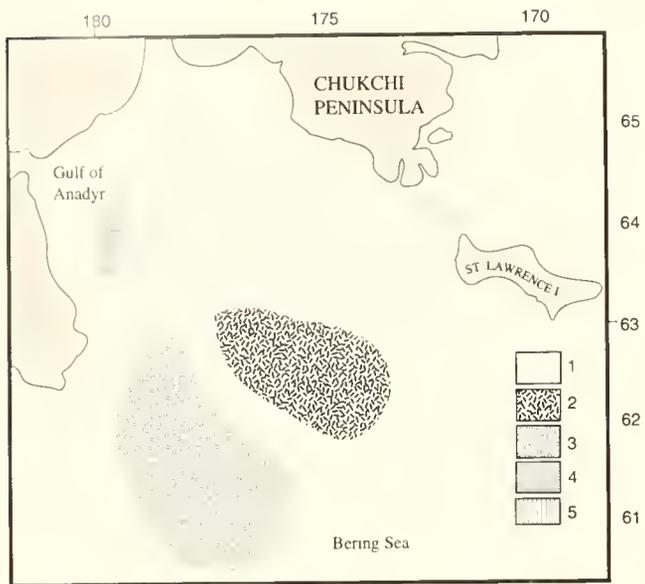


Fig. 3. Distribution of biocenoses in the Gulf of Anadyr and neighboring waters. 1-*Macoma calcarea*; 2-*Nuculana lamellosa radiata*; 3-*Polychaeta*; 4-*Echinaraclmius parma*; 5-*Halichondria panicea* + *Balanus crenatus* + *Strongylocentrotus pallidus*.

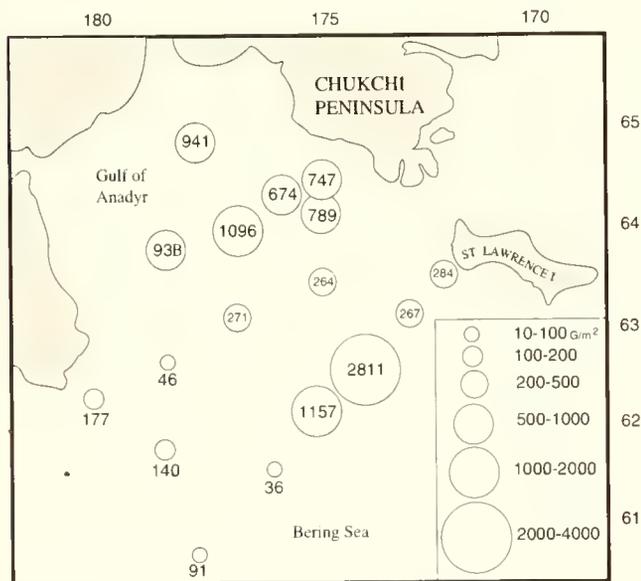


Fig. 4. Distribution of benthic biomass (g m^{-2}) at stations in the Gulf of Anadyr and neighboring waters.

only allow determination of three biocenoses (Fig. 5). The region is dominated by 28 forms of benthic organisms (Table 1). Similar to the Gulf of Anadyr, there is also *Macoma calcarea* biocenosis; it was found in two areas in both the north and south areas of this region. The region was subdominated, and sometimes even dominated alongside of *Macoma*, by other ark shells (*Yoldia amygdalae* and *Leionucula inflata*), polychaetes (*Nephtys caeca* and *Maldane sarsi*), amphipods, ceripediums (*Balanus crenatus*), and sponges. Maximum benthic biomass of this biocenosis (found at Station 89) is smaller than in the previous region and equals 649 g m^{-2} . North of St. Lawrence Island, in the eastern part at the banks of the Alaska coast and in the western area near the Soviet coast, we

can clearly identify a biocenosis of sand dollars (*Echinaraclmius parma*), with average biomass of $2,358 \text{ g m}^{-2}$ and an extremely high maximum biomass of $4,378 \text{ g m}^{-2}$ (Fig. 6).

The entire region of the Bering Strait proper, from the Chukchi Peninsula to Alaska, as well as a small area to the north of St. Lawrence Island, at a depth of 44–50 m, is characterized by pebble and gravel sediments with stones, sand, and shells. This area is inhabited by fauna that is typical for this part of the Pacific with solid and mixed sediments: sponges *Halichondria panicea*; alcionariae *Gersemia rubiformis*; hedgehogs *Strongylocentrotus pallidus*; ceripediums *Balanus crenatus*; and ascidiae *Didendum* sp. Benthic biomass in this biocenosis reaches 780 g m^{-2} .

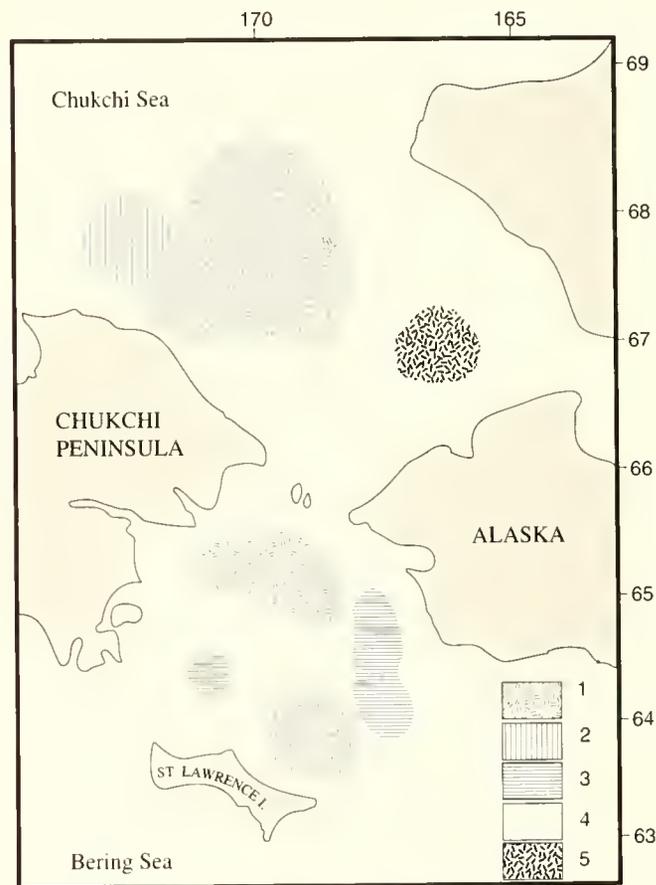


Fig. 5. Distribution of biocenoses in the southeastern part of the Chukchi Sea and northern part of the Bering Sea. 1-*Macoma calcarea*; 2-*Leionucula inflata*; 3-*Echinaraclmius parma*; 4-*Halichondria panicea* + *Balanus crenatus* + *Strongylocentrotus pallidus*; 5-*Serripes groenlandicus*.

Southeastern Chukchi Sea

Average benthic biomass of the region is 673 g m^{-2} . It is dominated by 29 various benthic faunal forms (Table 1). Differences in distribution of benthos in the eastern and western parts of the region had been distinguished earlier by Grebmeier *et al.* (1988) and were observed during the present expedition. These differences are determined by peculiar features of waters surrounding these regions. A more diverse western part of the region has a most productive biocenosis (*Macoma calcarea*) at a depth of 38–52 m on muddy and sandy sediments; average biomass of this biocenosis is rather high and equals 979 g m^{-2}

with maximal biomass equal to or greater than $2,000 \text{ g m}^{-2}$ (Stations 55, 69; Figs. 5, 6). At most of the stations (48, 55, 57, 60, and others), *Macoma* biomass by far exceeds that of other organisms of the biocenosis, equaling 60–70% of the total biomass. Alongside *Macoma*, this biocenosis is also dominated by ark shells (*Leionucula inflata* and *Yoldia amygdala*), polychaetes (*Nephtys caeca*, *Maldane sarsi*, *Nicomache lumbricalis*, and *Lumbrinaris* sp.), ophiurac (*Ophiura sarsi*), and amphipods (*Ampelisca* spp.).

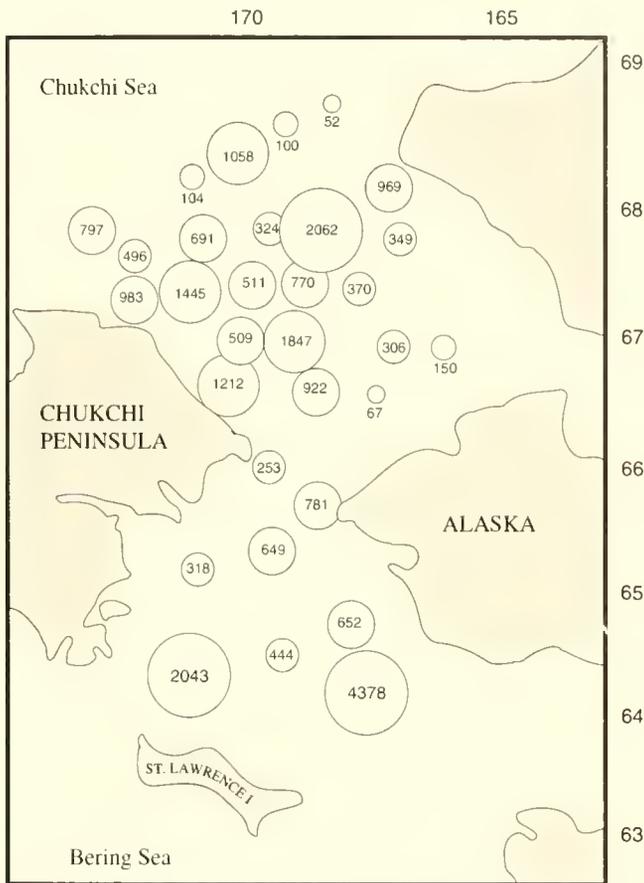


Fig. 6. Distribution of benthic biomass (g m^{-2}) at stations in the northeastern part of the Chukchi Sea and the northern part of the Bering Sea (symbols as in Fig. 4).

In the western part of the region, the *Macoma* biocenosis borders the *Leionucula inflata* biocenosis at a depth of 44–50 m. *Leionucula* is obviously dominant here, as its biomass is 60–80% of the total biomass of biocenosis organisms. Average benthic biomass in the *Leionucula* biocenosis is 647 g m^{-2} .

Closer to the Soviet coastline, there is a diverse biocenosis of ark shells (*Mya truncata*). The only bottom sample at Station 44 (entrainment area, 0.1 m^2) only penetrated to a shallow depth and cut off eight siphons of the large, deep-dwelling mollusks.

South from the *Macoma* biocenosis, closer to Bering Strait, there is a pronounced mosaic character of benthic organisms. Different bottom samples show domination by various groups, including ascidiae, polychaetes, ark shells, holothuria, and sipunculida.

In the eastern part of the region, near the Alaska coastline, at depths of 22–35 m, only an insufficient level of biocenosis of *Serripes groenlandicus* ark shells occurs, with an average biomass of 228 g m^{-2} . The degree of domination by this species is minimal in this biocenosis. Other stations were marked by domination of polychaetes (*Lumbrineris*, *Neoamphitrite*, *Maldane*, *Nephtys*, *Cistenides*, and *Niomache*), ark shells (*Leionucula*, *Nuculana*, and *Cyclocardia*), numerous small holothuriae (*Myriotrochus*), actiniae (*Haliactis* and *Epiactis*), and echiurids.

Sessile benthic fauna was collected at Station 52 in 50 m of water; the dominant species was *Balanus crenatus*, which had a very high biomass (about 970 g m^{-2} ; Fig. 6). In general, we should note a striking difference between abundance of benthos between the western and eastern parts of this region. In the west, there is an influence of the Gulf of Anadyr, Bering Sea Shelf waters, and waters of the Siberian shallows; in this region, average benthic biomass equals 673 g m^{-2} . In the east, there is an influence of depleted coastal waters of Alaska; average benthic biomass equals only 315 g m^{-2} (even with a relatively rich sample with *Balanus*), which is over two times less than in the western part.

Benthos at East and South Polygons

At East and South Polygons, 13 samples were taken at depths between 140 and 3,700 m; 8 of these samples were collected with a bottom sampler. Most of the samples are dominated by polychaetes (usually from the family Maldanidae); in abysses at 3,000 m, there is a domination by large monocelled organisms (Komokiacea). Biomass at all stations is not large and varies from 0.7 g m^{-2} (in abyss) to 14.4 g m^{-2} (in sublittoral regions); average biomass equals 7.5 g m^{-2} .

Discussion

Biogeographic Characteristics of Benthic Fauna of the Northern Bering and Chukchi Seas

In terms of biogeography, the investigated regions of the Gulf of Anadyr, northern Bering Sea, and southeastern Chukchi Sea have very few differences. There is an advantage for a few species to dominate the faunal distributions in the region; 14 of 45 species that are dominant within each of these three regions are common for all of the regions (Table 1). Twelve of the species can be found in two of the three regions. Only 19 species dominate in only one region. In all three regions, most of the area is occupied by *Macoma calcarea* biocenosis. The similarity of faunal characteristics between all three regions can be explained by the fact that they are all situated in the arctic area to the north of the Andriyashev Anadyr faunistic barrier (Andriyashev, 1939); this fact determines the similarity of most of the fauna. One can also note certain peculiarities within each of the regions. In this respect, the most demonstrative one is the southeastern area of the Chukchi Sea. The western part of this region is dominated by boreal–arctic species of the panarctic complex (*Macoma calcarea*, *Leionucula inflata*, *Yoldia amygdala*, *Haliactis arctica*, and *Epiactis levisi*); a narrower and relatively warmer eastern part is dominated by

warm water boreal–arctic species (*Serripes groenlandicus*, *Ampharete acutifrons*, and *Golfingiamargariacea*) with limited occurrence in the Arctic.

Preclassification of the collected benthic material indicates that some species that were found during the expedition had never been known to inhabit the Chukchi Sea before (e.g., coat-of-mail shells *Hanleyella asiatica*, some obelis shells, and some species of echinodermata).

Annual Variation in the Distribution of Benthic Organisms

Although the number of samples collected is not large, it allows us to compare the distribution of benthic organisms with that of previous expeditions (Deriugin & Ivanov, 1937; Makarov, 1937; Vinogradova, 1954; Neiman, 1963; Stoker, 1981; Grebmeier *et al.*, 1989). First of all, one can note that there is a coincidence in the location of principal biocenoses (i.e., *Macoma calcarea*, *Echinarachnius parma*, and sessile species biocenoses in the straits). According to data from the first quantitative benthos analyses in 1933, in the central part of the Gulf of Anadyr, there was a domination of *Macoma calcarea* (Makarov, 1937). Analysis of materials collected by the Institute of Oceanology, USSR Academy of Sciences, on the R/V *Vityaz* (1950–1952) provides a general confirmation for these data (Vinogradova, 1954; Filatova & Barsanova, 1964). We should also note that, in some works, an overemphasis was given to *Ophiura sarsi* (Vinogradova, 1954; Zenkevitch & Filatova, 1958), which entitled the biocenosis even though it has a much lower biomass than that of ark shells (Vinogradova, 1954). Obviously, it can be explained on the one hand by undue attention being paid to the number of individuals collected in a trawl (a Sigsby trawl usually collects echinodermata, including ephiuræ that inhabit the surface of the sediments), and on the other hand by density indices (Brotskaya & Zenkevitch, 1939) used for definition of communities and groups instead of the later accepted method of biocenosis definition based on biomass (Petersen, 1911, 1913; Vorobyov, 1949). A number of works based on the same material from the Gulf of Anadyr (Vinogradov, 1954; Zenkevitch & Filatova, 1958; Filatova & Barsanova, 1964) locate biocenosis and groups with domination of either *Ophiura sarsi* or *Macoma calcarea* in different regions. It is interesting to note that the biomass characteristic of *Ophiura sarsi* found in trawl catches in 1933 and 1950–52 in the central part of the Gulf of Anadyr was not confirmed by the material that we collected in 1988. *Ophiura sarsi* was traced only in 3 dredger samples out of 26; it constitutes from 2 to 10% of the total biomass of the sample. Only 3 out of 14 trawl samples collected in the Gulf of Anadyr at a mass scale contained *Ophiura sarsi*. One can assume that there was a decrease of habitation density of these ephiuræ during the recent 30–50 years, although to confirm this conclusion a more detailed investigation is required.

Alongside the above-mentioned biocenoses that had inhabited the same region for many decades, new biocenoses were found both in the regions that had never been investigated before in the Chukchi Sea (e.g., *Leionucula inflata* biocenosis) and in the well researched regions in the Gulf of Anadyr (e.g., *Nuculana lamellosa radiata* biocenosis). The latter example

requires a detailed study since it is of special importance for us as a vivid example of how one biocenosis is replaced by another.

According to some authors, 28–38 years ago other biocenoses were found on the site where today we find *Nuculana lamellosa radiata* (Figs. 7A,B,C). For example, according to the data collected by the R/V *Vityaz* in 1950–52 (Vinogradova, 1954; Filatova & Barsanova, 1958), *Ophiura sarsi* + *Macoma calcarea* biocenosis was found (Fig. 7A). According to a 1958–60 expedition, Neiman (1963) found there was a *Yoldia traciaeformis* biocenosis wedged in between *Ophiura sarsi* and *Macoma calcarea* biocenoses (Fig. 7B). In addition, Neiman (1963) found that the present site of the *Nuculana lamellosa radiata* biocenosis was partially inhabited by the three above-mentioned biocenoses in 1958–60, while according to the same data, biocenosis *N. lamellosa radiata* (probably defined as *N. pernula*) was located in the form of two small spots much farther to the south. The high degree of domination of *Nuculana* in our samples (80–90% of the total biomass) and high abundance values (up to 1,040–3,700 individuals m⁻²) and a low density of *Macoma* (up to 10 individuals m⁻²) leave no doubt that *N. lamellosa radiata* biocenosis was defined correctly. The earlier data mentioned above, as well as numerous old shells of *Macoma* in our samples, testify to the fact that earlier this region was inhabited by *Macoma calcarea* biocenosis.

It is interesting to note that according to Makarov (1937), in 1933, the region south of St. Lawrence Island was approximately the same region where, in 1958–1960, Neiman (1963) found *Nuculana* biocenosis with five stations dominated by small *Leda pernula* (*Nuculana lamellosa radiata*), while at the neighboring Station 6 (where there was a domination of *Macoma calcarea*), the benthic community was dominated by drilled shells of *Leda pernula*. One can assume that at least from the 1930's to the 1960's, *Nuculana* biocenosis remained in the same region and then started to expand, and by the late 1970's/early 1980's (i.e., during the last decade), it reached the region that we defined in 1988 where it replaced *Macoma calcarea* biocenosis. This conclusion is supported by our data where the age of *Nuculana lamellosa radiata* in our samples does not exceed 7–8 years. The fact that the replacement of *Macoma* by *Nuculana* occurred during the last decade is confirmed by an extremely small number of empty *Nuculana* shells that did not have enough time to pile up during the period equal to the average lifetime of these mollusks. Most likely, the northern boundary of *Nuculana* biocenosis that borders with the *Macoma* biocenosis was moving to the northwest; every year *Nuculana* biocenosis advanced into new areas, thus replacing *Macoma* biocenosis (Fig. 7D). Data from the 47th cruise of the R/V *Akademik Korolev* in 1984 indicated that the northern border of *Nuculana* biocenosis had moved northwards when compared to data collected in 1958–60 (Neiman, 1983; Fig. 7C).

In the Gulf of Anadyr, we observed the disappearance of *Cyclocardia crebricostata* as described earlier by Neiman (1963). At present, this earlier biocenosis has been replaced by biocenoses of Manocæ and polychaetes (Figs. 3,7).

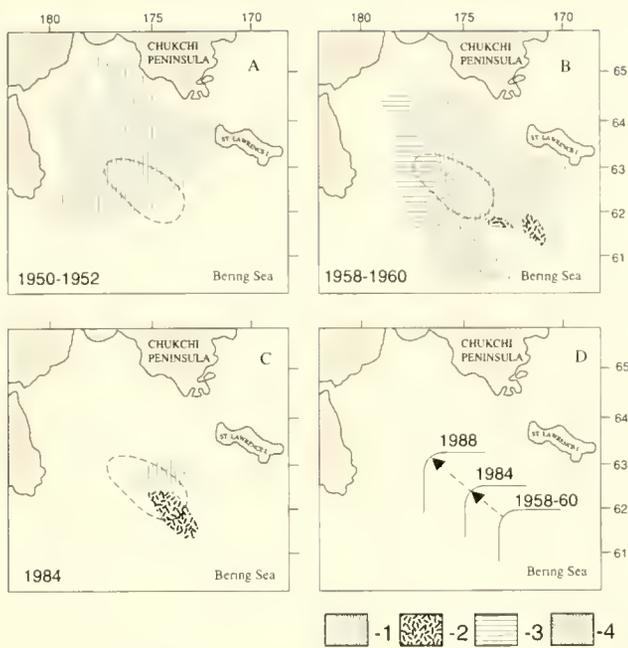


Fig. 7. Long-standing variations of distribution of *Nuculana lamellosa radiata*, *Macoma calcarea* et al., biocenoses in the Gulf of Anadyr and neighboring waters of the Bering Sea. Biocenoses distribution in various years: A-1950–1952 (Vinogradova, 1954); B-1958–1960 (Neiman, 1963); C-1984 (report on the 47th cruise of the R/V *Akademik Korolev*); dashed line—present habitation of *Nuculana lamellosa radiata* in 1988; D—gradual displacement of the northern boundary of *Nuculana lamellosa radiata* biocenosis for 30 years in the northwestern direction (indicated with arrow); 1-*Macoma calcarea*; 2-*Nuculana lamellosa radiata*; 3-*Ophiura sarsi*; 4-*Yoldia traciaeformis*.

In the eastern part of the Chukchi Sea (Stations 54, 63, and 64), which is presently dominated by various species of polychaetes, echiurids, and amphipoda, a great number of empty shells of *Macoma* were found, which testifies to a former biocenosis that might have been dominated by these mollusks.

There is also a tremendous increase in the average biomass of *Macoma* biocenosis in the Gulf of Anadyr that during the last 38 years has increased from 455 g m⁻² (Vinogradova, 1954) to 612 g m⁻² (our data). Our values of average biomass in the regions studied are 2–2.5 times higher than that recorded 50 years ago (Makarov, 1937).

It is hard to provide an unambiguous answer to the problem of variations within the same biocenosis and replacement of biocenoses. Most probably, there is a whole group of biotic and abiotic factors influencing changes in faunal populations and biomass. Let us consider the replacement of *Macoma* biocenosis with *Nuculana* biocenosis. It is quite obvious from the data presented by Makarov (1937) that most of the samples dominated by *Leda* (*Nuculana*) were collected in the coldest regions (below 0°C), both in the Chukchi and Bering Seas. At the same time, most often *Macoma* dominates in regions where bottom water temperature is above 0°C (though not in every case). Taking into account the direction of expansion of *Nuculana* biocenosis (which is a more coldwater species than *Macoma*), one could draw a conclusion that the cold spot expanded northward to the Gulf of Anadyr. In addition,

according to Deryugin and Ivanov (1937), the center of the cold Anadyr spot in 1933 was located in the region of the present location of the *Nuculana* biocenosis.

Another possibility for a change in faunal composition could be preference by the dominant fauna for certain sediment grain size or chemical composition. *Nuculana* prefers a muddier sediment regime than *Macoma* (Scarlatto, 1981); it was also noted that the sediment dominated by *Nuculana* smells of hydrogen sulphide (i.e., there is a shortage of oxygen for mollusks). *Nuculana*, which includes *Nuculana*, *Tellinacea*, and *Macoma*, incorporates species that are pocket detritus feeders. Still, if *Macoma* can use gills to change its feeding mode to sestonophagy, *Nuculana* are most likely to feed on particles of food from the seabed by collecting them using labial palpus. Their gills perform only the function of respiration (Kuznetsov, 1984). It is possible that monofunctionality of the gills of *Nuculana* under conditions of oxygen deficiency gives them an advantage over *Macoma*. It is also possible that *Nuculana*, like similar deepwater species, use the energy released from vital functions of sulfur bacteria; it may also give them the advantage over *Macoma* in case of inhabiting sludge contaminated with hydrogen sulphide.

Continuing our examination of biocenoses replacement, we would like to discuss the general mechanisms of biocenosis biomass variation both in the case when dominant species are preserved and in the case when they are replaced with other species. During the last 20 years, due to long-standing observations of benthic biocenoses in various water areas, we have accumulated a lot of facts testifying to time variation of benthic biomass (Antipova, 1973, 1975; Antipova et al., 1974; Rachor & Gerlach, 1975; Klimova, 1977; Golikov et al., 1986). Masse (1972) was the first person to distinguish three types of time variation of benthic organism's biomass. We will discuss the distribution of various types of dominant species' replacement in relatively stable (nonseasonal) biocenoses based on two types: reversible and irreversible.

Irreversible replacement occurs either in cases of developing siltation by sediments (e.g., in the Gulf of Possiet; Kobayakov, 1962; Golikov et al., 1986) or in cases of pollution (the Baltic Sea). Reversible types of replacement of dominant species with a long life cycle can occur with considerable variation of abiotic conditions in the environment (considerable change of temperature, salinity, etc.) that in most cases leads to a complete destruction of biocenosis. When normal environmental conditions are restored, the consequent succession in the long run will restore the previous biocenosis. Some of the shallow water biocenoses of the south Far East undergo similar changes; these biocenoses are characterized by a complete elimination of dominant species due to drastic desalination of water that occurs every 2–3 years.

Additionally, reversible types of change of the dominant species may occur due to the change of biotic conditions—for instance, due to an invasion of a large number of predators that almost completely devour the dominant species. One or several subdominant species that are not affected by predators then become dominant; after predators leave the region, the

succession leads to restoration of the number and role of the dominant species. This type of change is characteristic of *Ruditapes philippinarum* biocenosis in the Gulf of Possiet that is periodically subjected to an invasion of enormous numbers of the sea star *Asterias amurensis* that devour practically all adult individuals of those mollusks in the biocenosis.

Finally, the reversible type of replacement of dominant species with a long life cycle may occur due to shortage or a complete lack of a usual replenishment with young individuals of the population. In this case, non-occurrence of generations for several years may lead (at a natural limitation of older individuals) to a drastic decrease of biomass of the dominant species—in this case, former subdominant species with long life cycles become dominant. In addition, several species with short life cycles that manage to achieve a rapid and sufficient increase of their biomass due to absence of competition may also become dominant and increase their role in the biocenosis.

Later on, with aging of young individuals of the former dominant species of the biocenosis, it can regain its domination. In this case, its domination goes on until the new unfavorable period begins. This situation may be jeopardized if there is more than one dominant species.

Which of the various mentioned types of change in dominant species is characteristic of the Gulf of Anadyr is unknown. Only with continued studies of this biocenosis, on annual and interannual time scales, will we be able to determine the causes for the changes in benthic composition in this arctic system.

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Chapter 8:
BIOGEOCHEMICAL CYCLES

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Subchapter 8.1:

Fate of Chlorinated Hydrocarbons

8.1.1 Long-range Transport of Atmospheric Organochlorine Pollutants and Air-Sea Exchange of Hexachlorocyclohexane

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Introduction

Recent evidence implicates long-range atmospheric transport and deposition of organochlorine contaminants (OC) to Arctic ecosystems (Hargrave *et al.*, 1988; Pacyna & Oehme, 1988; Gregor & Gummer, 1989; Patton *et al.*, 1989). As a result, these contaminants have been found in arctic fish, marine mammals, birds, and plankton (Andersson *et al.*, 1988; Kawano *et al.*, 1988; Muir *et al.*, 1988, 1990a,b; Norstrom *et al.*, 1988). This raises concern because there are few species in the polar food chain, and arctic animals are able to bioconcentrate many of these hydrophobic pollutants due to their high lipid content. Muir *et al.* (1990a,b) found that atmospheric deposition of OC and subsequent bioconcentration may lead to high concentrations of pollutants in the diet of native Inuit.

The Third Joint US-USSR Bering & Chukchi Seas Expedition took place on the R/V *Akademik Korolev* (Cruise AK-47). The Soviet Union and United States share a border between territorial waters in this region and, as a result, most scientific studies have been on either the Soviet or American side. The ecology and air masses of the area, however, do not recognize this boundary and a comprehensive investigation is not possible under these constraints. Because this study was cosponsored by the US Department of the Interior and the USSR Academy of Sciences we were able to cross the dateline many times, providing the first complete survey of the area. This paper will address levels of organochlorine compounds found in the atmosphere, microlayer, and surface water during Cruise AK-47, and focus on the air-sea exchange of hexachlorocyclohexane (HCH) in the Bering and southern Chukchi Seas.

Hexachlorocyclohexane is an insecticide used throughout the world and is available in two formulations, technical-HCH and lindane. Technical-HCH is a mixture of five isomers in the following proportions (Metcalf, 1955): α , 55–80%; β , 5–14%; γ , 8–15%; δ , 2–16%; and ϵ , 3–5%. Although all isomers are toxic, only the gamma isomer is insecticidal, and it is produced in pure form as the insecticide lindane. The limited data available about the tonnages of HCH used in Northern Hemisphere countries are summarized in Table 1. Most listings are from the United Nations Food and Agricultural

Organization Production yearbooks (FAO, 1985, 1987). These should be considered lower limits of actual usage because many countries do not report such statistics to the FAO. Nevertheless, a usage pattern of technical-HCH in Asia and lindane in Europe can be seen. No use of technical-HCH in Europe during the 1980's is reported by the FAO. Technical-HCH has not been used in the United States since 1978, when manufacturers canceled their registrations or switched them to lindane, which is still registered for application (EPA, 1980a,b, 1985). The Soviet Union currently uses a fortified mixture of HCH that consists of 90% γ -HCH with the balance composed of the other isomers (IRPTC, 1983).

TABLE 1

Usage of HCH.
Metric Tons/y

Country	Year(s)	Technical		Reference
		HCH	Lindane	
India	1979–1981	21,390	283	FAO, 1985, 1987
India	1984–1986	24,412	-	FAO, 1985, 1987
Turkey	1979–1982	1,695	75	FAO, 1985, 1986
Mexico	1979–1985	220	31	FAO, 1985, 1987
Italy	1979–1985	-	1,556	FAO, 1985, 1987
Poland	1979–1985	-	138	FAO, 1985, 1987
Pakistan	1979–1982	138	-	FAO, 1985, 1987
Japan	1948–1970	18,180	-	Tanabe <i>et al.</i> , 1982
Peoples Republic of China	-	20,000	-	Tanabe <i>et al.</i> , 1982
Hungary	1979–1982	-	456	FAO, 1985, 1987
Scandinavian Countries	-	-	29	Pacyna & Oehme, 1988
USA	1972–1976	48	335	EPA, 1980

The deposition of organic compounds from the atmosphere is controlled by their physical properties. Vapor pressures and water solubilities of the HCH's are sufficiently high that they remain primarily as gases in the atmosphere or dissolved in the water column with relatively small fractions sorbed onto particles (0.5–2.5%) (Tanabe & Tatsukawa, 1983; Bidleman,

1988; Hargrave *et al.*, 1988). Taken together, the HCH isomers are the most abundant of the heavy organochlorines in northern troposphere and surface waters. As a result, low volumes of air (10–20 m³) are sufficient for the analysis of α -HCH, and α -HCH and γ -HCH can be determined in 2–4 l water. A knowledge of air and surface water HCH concentrations, along with the appropriate Henry's law constants and wind speed, allows the flux of HCH's across the air–sea interface to be calculated. For these reasons, the HCH's are appealing compounds for studying the air–sea exchange of a high molecular weight gas. Previous studies of air–sea exchange of halogenated organic gases have examined freons and low molecular weight chlorinated hydrocarbons such as CCl₄ and CHCl₃ (Hunter-Smith *et al.*, 1983; Khalil *et al.*, 1983; Singh *et al.*, 1983).

Experimental Methods

Cruise Track

Cruise AK-47 originated and terminated at the deep-water port of Dutch Harbor, Alaska, and lasted from 26 July–2 September 1988. Surface (2 m) water concentrations of α -HCH and γ -HCH determined at 19 stations of the AK-47 cruise, and air concentrations of α -HCH and hexachlorobenzene (HCB) were measured at 16 stations. Hexachlorocyclohexane and other OC concentrations in the microlayer (top 120 μ m) and surface water (2 m) were compared at one station. Four high volume air samples were taken for γ -HCH, heptachlor epoxide (HE), trans-chlordane (TC), cis-chlordane (CC), trans-nonachlor (TN), cis-nonachlor (CN), p,p'-DDT, o,p'-DDT, p,p'-DDD, p,p'-DDE, polychlorinated biphenyls (PCB), and polychlorinated camphenes (PCC).

Sample Collection

Surface water was collected using a sampler based on a design by Keizer *et al.* (1977). This was constructed using two empty 4-l glass bottles in protective plastic casings (Solvent bottle carriers, Nalgene Corp.) mounted on a wooden frame. Teflon elbows were cemented into the bottle caps, with a glass tube connecting the two bottles through the elbows. A messenger sent down the wire broke the glass tube, allowing water to fill the bottles within 5 min. Microlayer water samples were collected at one station from a small boat at least 1 km from the ship using a stainless steel screen (Garrett, 1965; Rice *et al.*, 1982). At each station the surface water temperature and salinity were noted from a conductivity/temperature/depth (CTD) probe, and wind speed was taken from the ship's meteorological station.

Low-volume air samples were taken using a pressure-vacuum pump (Millipore Corp.). Air was pumped through two or three polyurethane foam (PUF) plugs (4.8-cm diameter, 3.2-cm thickness) in a thick-walled glass tube (4.0-cm ID, 15-cm length) for 8–24 h at a flow rate of 20 l/min, yielding volumes of 9.2–28.3 m³. Flow rates were monitored using an in-line Top-Trak Model 820 mass flowmeter (Sierra Instruments). Because of the low air volumes only α -HCH and HCB were quantified with this system.

High volume air samples were taken using a Rotron DR-313 brushless pump. The air was pulled through a 20 \times 25-cm Gelman AE binderless glass-fiber filter (GFF) and two 7.8-cm diameter \times 7.5-cm thick PUF plugs at a flow rate of 0.4–0.5 m³/min for 3 days to yield 1,790–2,160 m³ air. Details of this system are provided by Billings and Bidleman (1980, 1983). In both high and low volume systems breakthrough of analytes from front to back PUF plugs was monitored by the separate analysis of each plug. Samples and field spikes were immediately analyzed on board ship or were stored in a freezer (-20°C).

Field high and low volume air sample spikes were prepared by pipetting 1.0 ml of a calibration standard containing 8–17 ng/ml organochlorine pesticides (OC) onto clean PUF plugs. Blank PUF's and GFF's were brought to the ship and returned with the samples. Water spikes were prepared by pipetting 1.0 ml of a calibration standard containing 10–17 ng/ml α -HCH and γ -HCH in acetone to 3.5 l water and extracting the spike using the method described below. Concurrent analysis of ambient water concentrations was done and the spike experiments were corrected for ambient HCH levels.

Preconcentration and Cleanup

Analytes from 3.5 l water were preconcentrated by two methods: liquid–liquid extraction into 300 ml dichloromethane (DCM) and adsorption onto C₈ bonded-phase cartridges (Hinckley & Bidleman, 1989). The C₈ bonded-phase cartridges were eluted with 3 ml 1:1 ethyl ether-hexane. Polyurethane foam plugs were extracted for 6–8 h in a Soxhlet apparatus with petroleum ether. Glass-fiber filters were cut into strips, placed in round-bottom flasks and refluxed in DCM for 8 h. All sample extracts were reduced and transferred to hexane or isooctane by rotary evaporation and nitrogen blowdown. High volume air samples were split into two fractions using a column of silicic acid and neutral alumina (Keller & Bidleman, 1984; Bidleman *et al.*, 1987). All extracts were treated with concentrated sulfuric acid for cleanup before gas chromatographic (GC) analysis.

Gas Chromatographic Analysis

Gas chromatographic analysis of air and water samples was done using a number of detection systems. Hexachlorocyclohexanes in water, HCH's and HCB in low volume air samples, and DDT and its breakdown products; and PCB in high volume air samples were determined by GC with electron capture detection (GC-ECD), carried out using a Hewlett Packard 5840, Varian 3700, or Carlo Erba 4160 chromatographs with ⁶³Ni ECD's. The instruments contained 25-m bonded-phase fused silica columns (polydi-methylsiloxane, 5% phenyl, 0.25 μ m film thickness, Hewlett Packard or SGE Corp.). Carrier gases were hydrogen or helium at 30–40 cm s⁻¹, the injector temperature was 240°C and the detector was 320°C. Samples were injected using a Grob technique (30 s split time). Chromatographic data were collected using the HP-5840 integrator, a HP-3390A, or Shimadzu Chromatopac CR3A integrator.

Two types of mass spectrometry were used for the analysis of high volume air samples. The HCH's, TC, CC, TN, HE, p,p'-DDE and p,p'-DDT were determined by gas chromatography-electron impact mass spectrometry (GC-EIMS) using a Hewlett Packard 5890 GC with a 5970 mass selective detector. The instrument contained a 30-m bonded-phase silica column (6% cyanopropylphenyl, 0.25 μ m film thickness, J & W Scientific). The carrier gas was helium at 30–40 cm s⁻¹; the injector and transfer line temperatures were 240°C and 250°C. A 3 m Grob time was used for these analyses. Multiple ion detection (MID) employing the following ions was used: HCH 217, 219; HE 353, 355; TC and CC 373, 375; TN 407, 409; p,p'-DDT 235, 237; and p,p'-DDE 246, 248, 316, 318.

TC, CC, TN, CN, and PCC's were determined by GC-negative ion mass spectrometry (GC-NIMS) with MID using a Finnigan 4521C fitted with the same type column as was used for GC-ECD. The carrier gas was helium and samples were injected splitless (3 m Grob time). The ion source was maintained at 80°C and methane at 0.18 torr was used. Ions monitored were: TC, CC, TN, and CN: 300, 302, 334, 408, 410, and 444; PCC's: 309, 311, 343, 345, 379, 381, 413, and 415 (Bidleman *et al.*, 1987).

Air–Sea Equilibration of HCH

When HCH is at equilibrium between the atmosphere and surface water:

$$C_A/C_W = H/RT = K_H \quad (1)$$

where C_A and C_W are the concentrations of HCH in air and water, respectively (mol m⁻³), R is the gas constant (8.2×10^{-5} atm m³ mol⁻¹ K⁻¹), T is the temperature in Kelvin, H is the Henry's law constant (atm m³ mol⁻¹), and K_H is the dimension exchange constant between the atmosphere and surface water. Equation 1 is an expression of Henry's law. H was determined in the laboratory for α -HCH and γ -HCH over the range of environmental temperatures in seawater using a gas stripping method (Mackay *et al.*, 1979) and a dynamic headspace method (Yin & Hassett, 1986). Details of these experiments are found in Hinckley (1989). The temperature dependence of H for α -HCH in seawater is

$$\log H \text{ (atm m}^3 \text{ mol}^{-1}\text{)} = (-3138 \pm 174)/T + (5.61 \pm 0.66) \quad (2)$$

and for γ -HCH the relation is:

$$\log H \text{ (atm m}^3 \text{ mol}^{-1}\text{)} = (-3183 \pm 99)/T + (5.29 \pm 0.34). \quad (3)$$

A two-layer model has been proposed for the study of gas exchange between air and sea (Liss & Slater, 1974). In this model an air film lies above and a water film below the interface. Transport of HCH through the interface occurs by molecular diffusion across the concentration gradients in both the air and water films. Usually resistance in one film dominates the exchange across the interface. Fick's first law applies to the flux of HCH across the air–water interface:

$$N = K_{OA}\Delta C \quad (4)$$

where N is the flux of HCH through the interface, ΔC the difference in HCH concentration between the air at the interface and the well mixed troposphere, and K_{OA} is the overall exchange constant that includes resistances in the air and water films. Since the ratio of resistances to gas exchange for HCH between the air and water phase, $R_{AW} > 100$ (Hinckley, 1989), K_{OA} is essentially the same as k_A (exchange constant for the air phase, m s⁻¹). Assuming that the concentration of HCH in interfacial air is in equilibrium with C_w , introduction of Equation 1 leads to

$$N = k_A (K_H C_W - C_A). \quad (5)$$

According to Equation 5, a negative flux is from air to sea and a positive flux is from sea to air.

Mackay and Yeun (1983) developed an equation relating k_A (m s⁻¹) in the environment to the wind speed (m s⁻¹) at 10 m (U_{10}) and the gas phase Schmidt number (Sc):

$$k_A \text{ (m s}^{-1}\text{)} = 46.2 \times 10^{-5} (6.1 + 0.63U_{10})^{0.5} U_{10} Sc^{-0.67}. \quad (6)$$

Using a procedure similar to that of Mackay and Yeun (1983), Sc was calculated for HCH, which was found to be independent of temperature, equal for both isomers of HCH, and equal to 2.9. Calculations for k_A were done by using Equation 6 for the locations listed in Table 5 and ranged from 1.2×10^{-3} m s⁻¹ at Station 110 (53°56'N, 175°58'E) to 1.0×10^{-2} m s⁻¹ at Station 100 (64°23'N, 169°09'W). Details of these calculations can be found in Hinckley (1989).

Results and Discussion

Quality Control

Spike recoveries of 10–17 ng HCH in water, 17 ng HCH from PUF (low volume air system), and 7–8 ng of chlordanes, and HCH and DDT's from PUF (high volume air system), shown in Tables 2a and 2b, ranged from 64 to 119%. Concentrations reported in this paper have been corrected for recovery. Breakthrough from front to back PUF (100 \times back PUF/front PUF) averaged 18% for γ -HCH and 12% for HCB in the low volume air collection. Breakthrough for α -HCH and γ -HCH ranged from 10–50% and 2–12% respectively in high volume air collection. Breakthrough of the chlordanes ranged from 1–5%, p,p'-DDT and p,p'-DDE 1–2%, o,p'-DDT 6%, and p,p'-DDD 13%. Concentrations reported are the sum of front and back PUF. Limits of detection (LOD) (Tables 2a,b), based on analysis of blank cartridges (Hinckley & Bidleman, 1989), analysis of liquid–liquid procedural and control blanks, and PUF plugs, were 0.10 ng/l for α -HCH and γ -HCH in water, 20 pg/m³ in air for α -HCH by ECD (low volume system), and 0.2–0.3 pg/m³ for chlordanes by MS and HCH's and DDT's by ECD in the high volume system. Since the levels of γ -HCH in air were only about three times the LOD with the low volume system, γ -HCH was only quantified in the high volume air samples.

TABLE 2a

Spike recoveries and limits of detection for water and low volume air samples.

Sample Type	ng Spiked	α -HCH		γ -HCH	
		% Recovery	LOD ^a	% Recovery	LOD ^a
Water ^b	10-17	119,95,81(98) ^c	0.10 ng/L	89,87,82(86) ^c	0.10 ng/L
Air	17	85.76 (80) ^c	20 pg/m ³	-	-

a. LOD by ECD.

b. Preconcentration by liquid-liquid and bonded-phase extraction.

c. Mean.

TABLE 2b

Spike recoveries and limits of detection for high volume air samples.

Pesticide	ng Spiked	% Recovery	LOD
α -HCH	7	64, 67 (66) ^a	0.2 pg/m ^{3b}
γ -HCH	7	67, 82 (74) ^a	0.2 pg/m ^{3b}
TC	8	80, 85 (82) ^a	0.3 pg/m ^{3c}
CC	8	75, 83 (79) ^a	0.2 pg/m ^{3c}
TN	8	77, 99 (88) ^a	0.2 pg/m ^{3c}
p,p'-DDE	8	99, 94 (97) ^a	0.2 pg/m ^{3b}
p,p'-DDD	8	79, 82 (81) ^a	0.2 pg/m ^{3b}
o,p'-DDT	8	94, 100 (97) ^a	0.3 pg/m ^{3b}
p,p'-DDT	8	91, 94 (93) ^a	0.3 pg/m ^{3b}

a. Mean.

b. LOD by ECD.

The HCH's mean concentrations in high volume air samples determined by ECD and EIMS and chlordanes determined by EIMS and NIMS are not significantly different (Table 3b) (t-test, $\alpha = 0.05$). Alpha-HCH was quantified using both the low and high volume air collections. Comparison of the average concentration of α -HCH by both methods reveals no significant differences (t-test, $\alpha = 0.05$) in mean concentrations, 266 pg/m³ by high volume and 251 pg/m³ by low volume.

Liquid-liquid extraction and C₈ cartridge methods of preconcentration were compared at four stations. Concentrations of α -HCH averaged 2.57 ± 0.16 ng l⁻¹ by extraction and 2.60 ± 0.12 ng l⁻¹ by bonded-phase cartridges, with no significant differences (T-test, $\alpha = 0.05$). Similarly, γ -HCH averaged 0.70 ± 0.09 ng l⁻¹ using extraction and 0.61 ± 0.07 ng l⁻¹ using bonded-phase cartridges, again revealing no significant differences. As comparable levels of HCH were found regardless of the preconcentration method, water at all remaining stations was analyzed using the liquid-liquid extraction method.

Atmospheric OC Concentrations

Airborne OC concentrations for the HCH's, chlordanes, and PCC found over the Bering and Chukchi Seas are listed in Table 3, DDT's and PCB in Table 4, both using the high volume system, and Table 5 shows concentrations of HCB and α -HCH for the low volume system. Concentrations of HCB and the

HCH's found over the Bering and Chukchi Seas are compared with literature values in Table 6. Concentrations of α -HCH were 200 pg m⁻³ lower in the Bering and Chukchi Seas than in the Beaufort Sea, and γ -HCH was 25 pg m⁻³ higher than levels found in the Beaufort Sea in 1986 and 1987 (Patton *et al.*, 1989). Tanabe and Tatsukawa (1980) determined atmospheric concentrations of HCH over the Bering Sea in July 1979. They reported the mean Σ HCH as 920 pg/m³ with a wide range of 460–1,700 pg/m³, higher than the mean Σ HCH found during this cruise of 323 pg/m³. The α -HCH/ γ -HCH atmospheric ratio has been suggested as a 'marker' for recent atmospheric transport of these pollutants (Pacyna & Oehme, 1988). During this expedition, the α -HCH/ γ -HCH ratio ranged from 2.0–3.7 and averaged 2.9. This is much lower than the value of 18 found in the Canadian Arctic in August 1986 (Patton *et al.*, 1989). Pacyna and Oehme (1988) referred to low α -HCH/ γ -HCH of 1–4 as a "European" source. Five-day back air trajectories for 6 of the days at sea (Fig. 1) show much of the sampled air to have been over the Soviet Union (trajectories D,E,F); however, no differences in α -HCH/ γ -HCH were observed for air masses from the North Pacific (trajectories B and C. $\alpha/\gamma=3.3$) compared to those passing over the Soviet Union (trajectories D,E,F, $\alpha/\gamma=3.1$). Pacyna and Oehme (1988) suggested that high α -HCH/ γ -HCH ratios (>100) found at Ny Alesund in the Norwegian Arctic may implicate a source from the Soviet Union, which is inconsistent with reported use of the 90% lindane formulation in the USSR (IRPTC, 1983).

TABLE 3a

High volume air collection data.

Collection Date	Sample	Start	Stop	m ³ Air
26–31 July	HAIR1	53°58'N, 166°30'W	58°31'N, 174°30'W	2,089
8–11 August	HAIR2	65°40'N, 165°60'W	67°44'N, 168°26'W	2,161
19–22 August	HAIR3	65°40'N, 168°30'W	64°23'N, 169°09'W	1,790
23–26 August	HAIR4	63°75'N, 170°00'W	54°25'N, 176°44'E	1,988

TABLE 3b

Airborne HCH's, chlordanes, and PCC measured over the Bering and Chukchi Seas in 1988^a (pg/m³).

Sample	α -HCH		γ -HCH		HE	TC		CC		TN		CN	PCC ^b
	ECD	EIMS	ECD	EIMS	EIMS	EIMS	NIMS	EIMS	NIMS	EIMS	NIMS	NIMS	NIMS
HAIR1	192	356	58	91	1.1	5.3	3.2	6.1	3.3	2.7	1.8	0.21	49
HAIR2	245	310	57	111	0.7	1.9	1.8	2.4	2.5	1.2	1.3	0.16	38
HAIR3	358	210	84	74	1.4	4.1	2.8	4.1	3.5	1.9	1.9	0.16	34
HAIR4	291	163	71	33	1.9	2.2	1.4	2.2	2.0	0.9	0.9	0.15	30
mean	272	261	68	77	1.3	3.4	2.3	4.2	2.8	1.7	1.5	0.17	38
sd	70	90	13	33	0.5	1.6	0.8	1.9	0.7	0.8	0.5	0.03	8

a. Based on GC-EIMS and/or GC-NIMS except α -HCH and γ -HCH which was GC-ECD and GC-EIMS.

b. PCC calculated as toxaphene.

TABLE 4a

Airborne DDT's over the Bering and Chukchi Seas in 1988.

Sample	pg/m ³				
	p,p'-DDT	o,p'-DDT	p,p'-DDD	p,p'-DDE	Σ -DDT
HAIR1	26	14	3.0	3.0	46
HAIR2	19	7.6	3.6	8.2	38
HAIR3	39	15	8.2	12	73
HAIR4	14	4.6	4.1	11	34
mean	25	10	4.7	8.6	48
sd	11	5	2.4	4.0	18

TABLE 4b

Airborne PCB over the Bering and Chukchi Seas in 1988.

Sample	pg/m ³			
	Light ^a	Heavy ^b	Total ^c	Total ^d
HAIR1	532	649	1,180	900
HAIR2	481	456	904	760
HAIR3	398	710	1,110	867
HAIR4	809	521	1,330	1,141
mean	555	584	1,130	917
sd	178	116	177	161

a. Calculated as Aroclor 1242.

b. Calculated as Aroclor 1254.

c. Sum calculated as Aroclors.

d. Sum calculated as individual congeners.

TABLE 5

Low volume air collection data and airborne α -HCH and HCB over the Bering and Chukchi Seas in 1988^a.

Collection Date	Sample	Start	Stop	m ³ Air	pg/m ³	
					α -HCH	HCB
29 July	LAIR1	57°30'N, 174°30'W	57°30'N, 174°30'W	13.9	264	216
29–30 July	LAIR2	57°56'N, 175°04'W	57°56'N, 175°04'W	27.5	252	228
1–2 August	LAIR3	60°30'N, 177°30'W	61°20'N, 176°10'W	15.9	156	144
2 August	LAIR4	61°20'N, 176°10'W	61°30'N, 178°40'W	14.1	276	228
2–3 August	LAIR5	62°50'N, 179°30'W	62°30'N, 174°00'W	27.4	216	228
6–7 August	LAIR6	64°00'N, 175°00'W	63°00'N, 173°00'W	27.3	276	180
9 August	LAIR7	67°00'N, 173°00'W	67°45'N, 171°00'W	13.6	192	324
10 August	LAIR8	68°25'N, 169°00'W	68°10'N, 168°29'W	13.7	252	264
11 August	LAIR9	67°40'N, 165°43'W	67°44'N, 168°26'W	12.8	168	192
12–13 August	LAIR10	67°42'N, 172°00'W	67°17'N, 166°43'W	27.2	228	216
15 August	LAIR11	66°33'N, 168°36'W	66°00'N, 169°00'W	13.5	144	144
17–18 August	LAIR12	64°29'N, 165°24'W	64°29'N, 165°24'W	28.3	360	192
20 August	LAIR14	65°14'N, 169°21'W	64°55'N, 168°00'W	11.5	228	156
22 August	LAIR15	64°23'N, 169°09'W	64°20'N, 167°25'W	12.4	288	192
23 August	LAIR16	63°51'N, 169°12'W	64°15'N, 170°50'W	12.5	240	180
26 August	LAIR17	54°25'N, 176°44'E	54°31'N, 175°28'E	9.2	312	204
27 August	LAIR18	53°55'N, 175°58'E	53°55'N, 175°58'E	9.5	408	276
a. Based on GC-ECD.				N	17	17
				range	144–408	144–324
				mean	251	210

Table 6

Comparison of HCH and HCB in Arctic Air.

Location	HCB	(pg m ⁻¹)		Σ HCH
		α -HCH	γ -HCH	
Bering Sea, 1988				
This Study				
range	144-324	144-408	57-84	201-492
mean	210	251	68	319
Bering Sea, 1979 ^a				
	-	-	-	540-1,700
Beaufort Sea, ^b				
1986–87	>119-233	283-731	24-53	324-767
Beaufort Sea, ^c				
May–June, 1986	73	425	70	495
Aug–Sept, 1986	63	253	17	270
Spitzbergen ^d				
Fall, 1982–83	75-227	407-1,416	0.1-6	-
*W/S, 1983–84	29-389	121-787	12-102	-
Summer, 1984	20-201	260-774	24-100	-
Bear Island ^d				
Fall, 1982–83	78-200	277-1,550	0.1-67	-
*W/S, 1983–84	87-201	110-469	23-80	-
Summer, 1984	42-149	38-305	5-41	-
Hope Island ^e				
1982–83	100-200	250-1,700	<5-75	-
Jan Mayen ^e				
1982–83	50-200	400-1,600	<5-50	-

a. Tanabe & Tatsukawa, 1980

b. Patton *et al.*, 1989c. Hargrave *et al.*, 1988, mean values

d. Pacyna & Oehme, 1988

e. Oehme & Ottar, 1984

* Winter/Spring

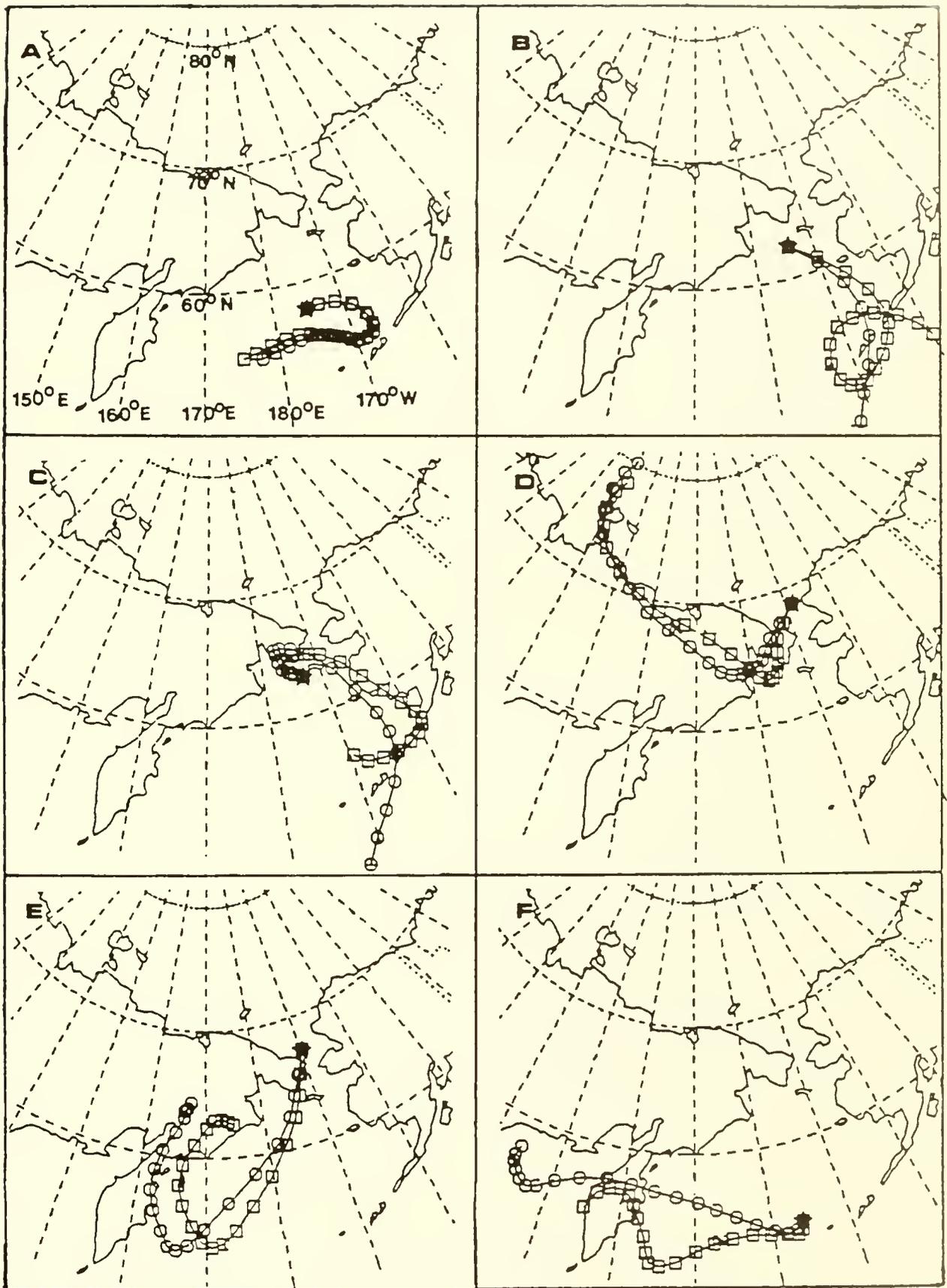


Fig. 1. Five day back air trajectories during Cruise AK-47. Location the samples were taken, and the termination of the air trajectory; \square 925 mb trajectory, \circ 850 mb trajectory. Each symbol denotes a six hour period. Following is the date of the sample and corresponding air: A, July 30, 1988-LAIR2, HAIR1; B, August 4, 1988-LAIR5; C, August 7, 1988-LAIR6; D, August 10, 1988-LAIR8, HAIR2; E, August 13, 1988-LAIR10; and F, August 28, 1988-LAIR18, HAIR4.

TABLE 7

Comparison of Chlordanes in Arctic Air.

Location	(pg m ⁻³)				ΣChlordanes
	TC	CC	TN	CN	
Bering Sea, 1988 This Study					
range	1.4-3.2	2.0-3.5	0.8-1.9	0.15-0.21	4.4-8.8
mean	2.3	2.8	1.5	0.17	6.8
Beaufort Sea, ^a 1986-87	0.6-3.4	1.9-5.1	0.8-5.1	0.15-0.8	3.6-13
Beaufort Sea, ^b May-June, 1986	-	-	-	-	3.6
Aug-Sept, 1986	-	-	-	-	1.9
Spitzbergen ^c					
Fall, 1982-83	0.6-6	-	-	-	-
*W/S, 1983-84	0.6-5.1	-	-	-	-
Summer, 1984	1.7-5.4	-	-	-	-
Bear Island ^c					
Fall, 1982-83	0.5-1.7	-	-	-	-
*W/S, 1983-84	1.2-1.3	-	-	-	-
Summer, 1984	0.6-2.1	-	-	-	-
Hope Island ^d 1982-83	1.0-2.0	-	-	-	-
Jan Mayen ^d 1982-83	0.5-2.0	-	-	-	-
Mould Bay ^c June, 1984	0.5-1.7	1.1-1.8	1.0-1.5	<0.2-0.4	2.1-3.7
a. Patton <i>et al.</i> , 1989		d. Oehme & Ottar, 1984			
b. Hargrave <i>et al.</i> , 1988		e. Hoff & Chan, 1986			
c. Pacyna & Oehme, 1988		* Winter/Spring			

Other OC's measured over the Bering and Chukchi Seas were HCB, TC, CC, TN, CN, and PCC (Tables 3b,5). Mean HCB levels were 210 pg m⁻³, close to the values found in the Canadian and Norwegian Arctic (Table 6). The average concentration of chlordane components (TC+CC+TN+CN) was 6.8 pg m⁻³, similar to levels found in the Canadian Arctic (Table 7). The average ratios of the chlordanes (R=CC:TN:TC) in the Bering and Chukchi were 1.0:0.46:0.81. Although the TC:CC ratio is less than unity, there appears to be more TC than TN, a reversal of the order found in northern Canada by Hoff and Chan (1986) (R=1.0:0.89:0.56) and Patton *et al.* (1989) (R=1.0:0.74:0.50).

Polychlorinated camphene concentrations of 38 pg m⁻³ were fourth highest of the atmospheric pesticides and were nearly the same as those observed in northern Canada (Table 8). Surveys of OC's in fish from the Canadian Northwest have found PCC's to be the most abundant pesticide residue (Muir *et al.*, 1988; 1990a; Norstrom *et al.*, 1988). Levels of PCC's in fish were sufficiently high that Muir *et al.* (1990a) noted that consumption of fish and fish livers by Inuit may lead

to an intake of PCC's that exceeds the US National Academy of Sciences' (1977) acceptable daily intake. Atmospheric transport has recently been suggested as the source of PCC's to the arctic ecosystem (Bidleman *et al.*, 1989).

High concentrations of the DDT's and PCB's were found over the Bering and Chukchi Seas (Table 4). These chemicals were entering the sampling system through the front end of the sampling apparatus (breakthrough of DDT's from front to back PUF was 1-13%) and no system contamination of either DDT or PCB was found in the blanks. The DDT's and PCB's were confirmed by GC-MS. As Table 8 shows, concentrations of DDT's and PCB's found during cruise AK-47 are significantly higher than have ever been reported in the arctic regions. Contamination of the ship with these chemicals is suggested by these comparisons. It was known that the ship had been fumigated for insects prior to the cruise and high DDT concentrations suggest that this insecticide is what was used. Hydraulic fluids, which were found all over the ship, are known to contain significant amounts of PCB's in the United States (Interdepartmental Task Force on PCB's, 1972). It is not

TABLE 8

Comparison of DDT's, PCB's, and PCC's in Arctic Air.

Location	Sum DDT	(pg m ⁻¹) PCB ^a	PCC
Bering Sea, 1988 This Study range	34-73	456-710	30-49
mean	48	584	38
Bering Sea, 1979 ^b	-	4.5-15	-
Beaufort Sea, ^c 1986-87	0.5-8.9	2.1-13	21-78
Beaufort Sea, ^d May-June, 1986	<1	<2	-
Aug-Sept, 1986	<1	<1	-
Spitzbergen ^e Fall, 1982-83	-	25-75	-
*W/S, 1983-84	-	25-150	-
Summer, 1984	-	-	-
Bear Island ^e Fall, 1982-83	-	10-40	-
*W/S, 1983-84	-	10-30	-
Summer, 1984	-	-	-
Hope Island ^f 1982-83	-	5.0-70	-
Jan Mayen ^f 1982-83	-	25-300	-

- a. Pentachlorobiphenyl or Aroclor 1254
b. Tanabe & Tatsukawa, 1980
c. Patton *et al.*, 1989
d. Hargrave *et al.*, 1988, mean values
e. Pacyna & Oehme, 1988
f. Oehme & Ottar, 1984
* Winter/Spring

known if PCB's are added to hydraulic fluids in the Soviet Union; however, it is a reasonable assumption that they are. Consequently, concentrations of DDT's and PCB's found during cruise AK-47 and reported in this paper probably represent contamination from the ship and are not an accurate atmospheric concentration for the Bering and Chukchi areas.

Water OC Concentrations

Levels of α -HCH and γ -HCH in surface water are given in Table 9 and are compared with literature values in Table 10. Kawano *et al.* (1988) measured HCH's in the Bering Sea in July 1981 and found concentrations of α -HCH very close to those found during Cruise AK-47, but our γ -HCH concentrations are about $\times 3$ higher than those found in 1981. Tanabe and Tatsukawa (1980) reported HCH in the Bering Sea in July 1979 about 1 ng/l less than was found during this cruise. Beaufort Sea locations further north appear to have higher α -HCH concentrations (Table 6), reflecting the Beaufort Sea's higher air concentrations (Hargrave *et al.*, 1988; Patton *et al.*, 1989) and enhanced air to sea exchange in the colder water (Beaufort Sea, -2°C ; Bering Sea, 5°C). No significant differences in surface water concentrations of either isomer of

HCH was found between the Chukchi Sea, Chirikov Basin, or Bering Sea (Tukey's test, $\alpha = 0.05$) during Cruise AK-47.

Concentrations of OC's in two microlayer and one 2-m water sample at Station 3 ($57^{\circ}56'\text{N}$, $175^{\circ}05'\text{W}$) are shown in Table 11. No enhancement of HCH's or HCB was found in the microlayer; however, TC, CC, and TN were enriched in two, and HE in one microlayer sample.

Flux of HCH Between the Atmosphere and Surface Water

The departure from equilibrium for α -HCH is shown in Figs. 2-4 for the Bering Sea, St. Lawrence Island to the Bering Strait, and the Chukchi Sea; similar results for γ -HCH are shown in Fig. 5. The disequilibrium is given as $C_w - C_w^0$, where C_w refers to the aqueous HCH concentrations found and C_w^0 denotes the aqueous HCH concentration in equilibrium with C_a (calculated from Equation 1). Average saturation indices ($SI = 100 * C_w / C_w^0$) in the Bering and Chukchi Seas were 86% for α -HCH and 26% for γ -HCH. The disequilibrium of HCH's was previously calculated for the Beaufort Sea (Patton *et al.*, 1989) using Henry's law constants for the HCH's, with their temperature dependence assumed similar to the PCB's (Burkhard *et al.*, 1985). Average SI in the Beaufort Sea were 93% and 24% for the α -HCH and γ -HCH. Recalculation of C_w^0

TABLE 9

Surface water (2m) collection data and α -HCH and γ -HCH in the Bering and Chukchi Seas in 1988^a.

Date	Station ^b	Location	Water Temp. (°C)	Salinity (ppt)	Wind Speed (m/s)	Corresponding Air	(ng/l)	
							α -HCH	γ -HCH
30 July	003	57°56'N, 175°04'W	8.8	32.6	5.5	LAIR2, HAIR1	2.56	0.72
1 August	007	60°29'N, 177°52'W	7.2	32.6	4.3	LAIR3, LAIR2	2.68	0.62
2 August	009	61°20'N, 176°06'W	6.8	31.7	4.1	LAIR3, LAIR2	2.55	0.74
4 August	019	62°25'N, 174°00'W	7.6	30.9	6.8	LAIR5	2.50	0.64
5 August	024	63°41'N, 178°28'W	5.6	32.0	2.1	none	1.95	0.50
7 August	035	63°00'N, 173°00'W	7.4	30.9	6.6	LAIR6	2.62	0.41
8 August	036	63°25'N, 172°10'W	7.3	31.6	6.7	LAIR6	2.10	0.79
9 August	045	67°44'N, 172°50'W	2.3	24.0	5.7	LAIR7, HAIR2	1.91	0.54
10 August	050	68°40'N, 168°29'W	6.1	31.7	5.1	LAIR8, HAIR2	2.33	0.6
12 August	055	67°44'N, 168°26'W	4.0	32.2	8.6	LAIR9, HAIR2	2.31	0.63
13 August	061	67°20'N, 169°45'W	5.1	30.3	4.9	LAIR10	2.75	0.64
15 August	074	66°33'N, 168°36'W	2.5	32.2	4.1	LAIR11	2.59	0.59
18 August	Nome	64°29'N, 165°24'W	18.0	25.0	4.0	LAIR12	2.83	0.49
19 August	83	65°40'N, 168°30'W	10.1	30.3	8.3	HAIR3	2.92	0.57
20 August	089	65°14'N, 169°21'W	6.1	31.7	8.8	LAIR14, HAIR3	2.19	0.62
21 August	096	65°05'N, 170°40'W	2.1	32.7	5.9	HAIR3	1.85	0.72
22 August	100	64°23'N, 169°09'W	6.3	31.8	12.0	LAIR15, HAIR3	1.91	0.51
23 August	104	63°51'N, 169°12'W	5.7	32.1	2.1	LAIR16	1.78	0.39
28 August	110	53°56'N, 175°58'E	9.7	32.9	1.9	LAIR18, HAIR4	2.25	0.49

a. Based on GC-ECD.

b. Figure 1.

N	19	19
range	1.78-2.92	0.39-0.74
mean	2.35	0.59
sd	0.36	0.11

TABLE 10

Comparison of α -HCH and γ -HCH concentrations in northern water from this study with reported values.

Location	Date	(ng/l)		Reference
		α -HCH	γ -HCH	
Bering and Chukchi Seas	August, 1988	2.35	0.59	This Work
N. Pacific and Bering Sea	July, 1981	2.75	0.17	Kawano <i>et al.</i> , 1988
Bering Sea	July, 1979		3.9 ^a	Tanabe & Tatsukawa, 1980
Beaufort Sea	June, 1986	4.40	0.57	Hargrave <i>et al.</i> , 1988
Beaufort Sea	August, 1986	4.53	0.65	Hargrave <i>et al.</i> , 1988
Beaufort Sea	June, 1987	7.1	0.81	Patton <i>et al.</i> , 1989
Hudson Bay Rivers	1980-81	6.42	0.86	McCrea & Fischer, 1988

a. Sum of α -HCH and γ -HCH.

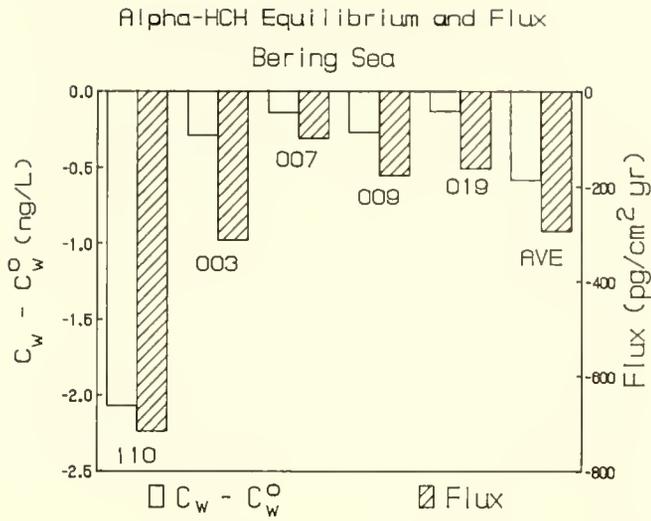


Fig. 2. α -HCH departure from equilibrium $C_w - C_w^0$, C_w = actual concentration, C_w^0 = water concentration at equilibrium with air, Eq. 1, (ng l^{-1}) and flux (Eq. 5, $\text{pg cm}^{-2} \text{ yr}^{-1}$) over the Bering Sea. Positive numbers indicate sea to air exchange and negative numbers air to sea exchange. Station numbers are provided below the bars.

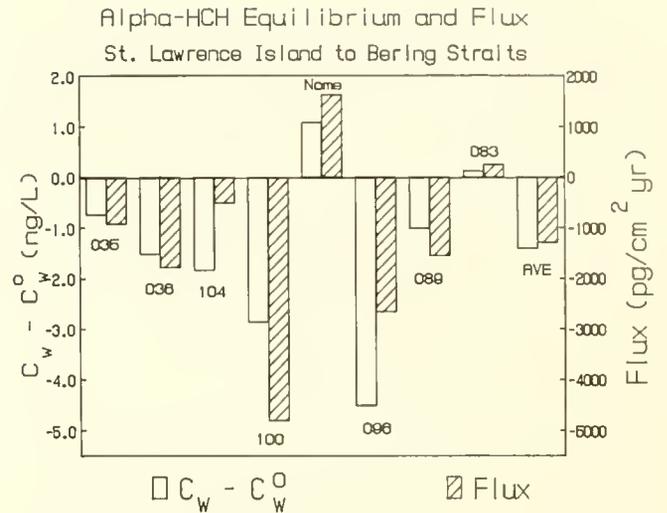


Fig. 3. α -HCH equilibrium ($C_w - C_w^0$, ng l^{-1}) and flux ($\text{pg cm}^{-2} \text{ yr}^{-1}$) from St. Lawrence Island to the Bering Strait. Positive numbers indicate sea to air exchange, negative numbers air to sea exchange. Note the increased flux relative to the Bering (Fig. 2) and Chukchi Seas (Fig. 4). Station numbers are provided below the bars.

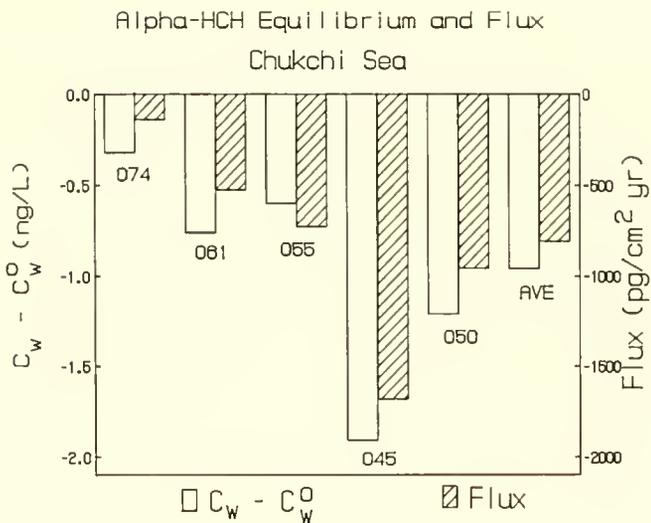


Fig. 4. α -HCH equilibrium ($C_w - C_w^0$, ng l^{-1}) and flux ($\text{pg cm}^{-2} \text{ yr}^{-1}$) over the Chukchi Sea. Positive numbers indicate sea to air exchange and negative numbers air to sea exchange. Station numbers are provided below the bars.

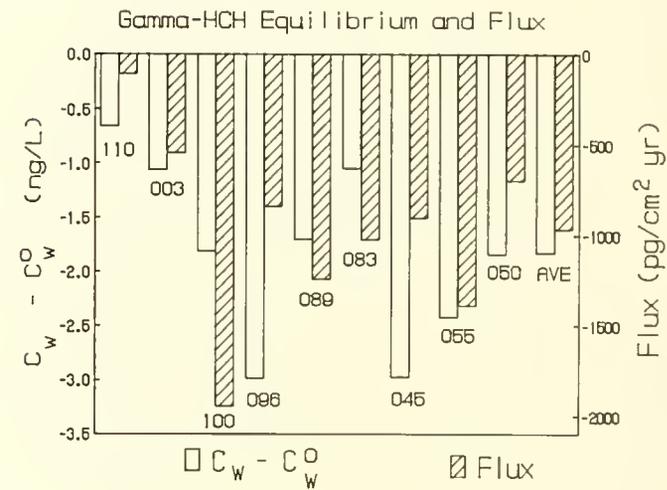


Fig. 5. γ -HCH equilibrium, ($C_w - C_w^0$, ng l^{-1}) and the flux of γ -HCH ($\text{pg cm}^{-2} \text{ yr}^{-1}$). Station numbers are below the appropriate bars. The flux of γ -HCH is from air to sea.

TABLE 11

Comparison of pesticides in microlayer and surface water,
Station 3: 57°56'N, 175°04'W.

Pesticide	ng/l	
	Microlayer ^a	Surface Water ^b
α-HCH	1.82, 2.31	2.56
γ-HCH	0.45, 0.59	0.63
HCB	<0.005	0.06
HE	0.05, 0.34	0.05
TC	0.30, 0.41	0.06
CC	0.25, 0.26	0.05
TN	0.13, 0.10	0.03

^a Sample volume 3.1-3.5 l layer thickness = 120 μm.

^b Sample volume 9.5 l, depth = 2 m.

in the Beaufort Sea using experimentally determined Henry's law constants (Equations 2,3) resulted in slight changes in the estimated SI to 71% and 28% for α-HCH and γ-HCH. Thus in the Bering, Chukchi, and Beaufort Seas the $SI(\alpha\text{-HCH}) > SI(\gamma\text{-HCH})$.

The SI's of α-HCH and γ-HCH at Nome Station (64°29'N, 165°24'W) were 155% and 68%. These SI's are greater than at other stations, and for α-HCH indicate a sea to air flux. This station was very shallow (15 m) and warm (18°C), and the salinity was low (25 parts-per-thousand) due to Yukon River input into Norton Sound. We could find no report of HCH's in the Yukon River, but average concentrations of α-HCH and γ-HCH in five rivers draining the Hudson Bay lowlands were 6.4 ng l⁻¹ and 0.9 ng l⁻¹ (McCrea & Fischer, 1986). These are above average HCH levels in the open Bering Sea. Influx of HCH's via cold Yukon River water and advection of cold Bering Sea water into Norton Sound followed by solar heating could lead to higher SI's, and in the case of α-HCH, to a reversal of the flux direction.

An explanation for the lower SI of γ-HCH at all stations is unknown, but our results suggest a more rapid disappearance of γ-HCH than α-HCH in the upper water column. The second-order base hydrolysis of lindane follows the equations (Ellington *et al.*, 1987):

$$dC/dt = -k_b[\text{OH}^-] \quad (7)$$

and

$$\ln k_b (\text{L mol}^{-1} \text{min}^{-1}) = -8895/T + 30.46 \quad (8)$$

A half-life of over 1,600 days was calculated for lindane at the average temperature found in the Bering Sea (5°C) and pH 8. The application of this freshwater rate constant to seawater is uncertain; however, hydrolysis alone probably cannot explain the deficiency of γ-HCH in surface water.

More rapid breakdown of the HCH's appears to occur by photolysis. Saleh *et al.* (1982) determined first-order photolysis rate constants for γ-HCH in purified water (Milli-Q) and three fresh waters in the pH range 7.3-9.2. Adjusted midwinter half-lives were given as 65 d in Milli-Q water and 14-150 d in the natural waters. Malyandi *et al.* (1982) reported a 48-d half-life for γ-HCH in distilled water with 5-25 mg/l added fulvic acids. Isomerization of a small percentage of γ-HCH to α-HCH occurred after 15-35 d irradiation. In distilled water alone, γ-HCH degraded slightly more rapidly than α-HCH. The relative photolytic stability of the two HCH isomers under arctic conditions is unknown.

Fluxes of HCH's were calculated by Equation 5 for all stations with concurrent air and surface water concentrations. It is important to note that these fluxes were estimated from k_a values calculated from wind speed (Equation 6) and were not directly measured. How closely these estimates represent the actual situation is unknown. Despite model predictions, Peng *et al.* (1979) found no correlation between the on-station wind speed and the flux of radon between the atmosphere and surface water in the open ocean.

Exchange rates in the Bering and Chukchi Seas ranged from -99 pg cm⁻² yr⁻¹ (air to sea) at Station 7 (60°28'N, 177°50'W) to -1681 pg cm⁻² yr⁻¹ at Station 45 (67°44'N, 172°50'W) (Figs. 2-5). Station 45 was different from others in this region in having sea ice and a low salinity of 24 parts-per-thousand from melting ice. Average fluxes were -290 pg cm⁻² yr⁻¹ in the Bering Sea and -810 pg cm⁻² yr⁻¹ in the Chukchi Sea. More dynamic fluxes were estimated from St. Lawrence Island to the Bering Strait, ranging from 1.620 pg cm⁻² yr⁻¹ sea to air flux at Nome (64°29'N, 165°24'W) to -4,800 pg cm⁻² yr⁻¹ air to sea flux at Station 100 (64°23'N, 169°09'W) (average = -1,290 pg cm⁻² yr⁻¹). This is a shallow area (40-50 m) with a complicated geometry and a relatively high flow of 1.2 Sv (Coachman & Aagaard, 1988) producing a high degree of vertical mixing that may explain the variability of flux.

Average fluxes over the entire cruise were -880 pg cm⁻² yr⁻¹ for α-HCH and -965 pg cm⁻² yr⁻¹ for γ-HCH. Atlas's (1988) "best" estimate of HCH fluxes for the North Atlantic and North Pacific Oceans were -466 to -715 pg cm⁻² yr⁻¹ for α-HCH and -100 to -240 pg cm⁻² yr⁻¹ for γ-HCH. Atlas arrived at these fluxes using literature values of air and surface water HCH concentrations, Henry's law constants estimated as functions of temperature, and $k_a = 7.5 \times 10^{-3} \text{ m s}^{-1}$. Atlas assumed an SI of 90% for both HCH isomers. Our higher estimate of the γ-HCH flux results from the considerably greater undersaturation of this isomer.

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8.1.2 Migratory and Bioaccumulative Peculiarities in the Biogeochemical Cycling of Chlorinated Hydrocarbons

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Introduction

Among the multiple organic compounds polluting the environment, chlorinated hydrocarbons are of great importance, especially pesticide preparations (OC's and PCB's). These compounds, owing to their exclusive properties, were widely used in the past and they are still being heavily used in certain countries, in spite of the fact that since 1971–1972 many developed countries have imposed restrictions or even a full ban on the use of certain pesticides (for example, DDT). In fact, the world production of these preparations has hardly reduced in the recent decade, becoming stable at approximately 1.2 million tons of PCB's (Bletchly, 1984), 3 million tons of DDT (Goldberg, 1975; Tanabe, 1982), and about 1 million tons of lindane (Tanabe, 1985). Their use over many years has resulted in the widespread distribution of these raw compounds that now have become a constituent part of practically all environmental compartments including marine ecosystems (Izrael & Tsyban, 1985a), and owing to the processes of atmospheric transfer, these contaminants have now gotten into quite remote regions rather quickly (Izrael & Tsyban, 1985b). Thus, for example, residues of PCB have been found in fish and mollusks of the Antarctic (Subramian *et al.*, 1987) and in penguins (Subramian *et al.*, 1985). Note that the ocean, if one may put it that way, has a role of an accumulator of chlorinated hydrocarbons since, according to Tanabe (1985), up to 70% of all chloroorganic compounds discharging into the environment are concentrated in marine ecosystems. Having significant molecular resistance and a high degree of affinity with lipids and suspended agents, chlorinated hydrocarbons can be accumulated in hydrobionts and transmitted along the food chain. It is determined that the process of concentration in living beings depends both on physical and chemical properties of contaminants and on peculiarities of organism and environmental conditions (Tanabe, 1985). Sea organisms not only accumulate and transform contaminants but they also transfer them into different compartments, which leads to their wide distribution in marine ecosystems.

In this connection, the study of the processes of chlorinated hydrocarbon accumulation and distribution in different components of marine ecosystems and the study of their interaction with the environment assume ever greater

importance. Note that investigations of the mentioned processes in background regions of the ocean that do not experience the permanent anthropogenic influence, including ecosystems of the Bering and the Chukchi Seas, are of a special significance.

Materials and Methods

Seawater samples, 100 l each, were passed through resin (XAD-2) at the rate of 20 l per hour. The adsorbed chlorinated hydrocarbons were eluted using 80 ml of ethanol to which an equal volume of the 2% sodium sulfate solution was added. The water–alcohol solution was extracted twice with *n*-hexane (25 ml). The extract was concentrated with the rotary evaporator to 4–5 ml volumes; it was then purified by mixing it with concentrated sulfuric acid, neutralized with a 5% NaHCO_3 solution, washed with the water, dried over sodium sulfate, and concentrated by evaporation with pure nitrogen gas to a volume of 1 ml. The concentrate was then injected into a Hewlett-Packard 5840A gas chromatograph with an autosampler. The chromatography was performed under the following conditions: a capillary 30 m fused quartz column with the 0.32 internal diameter; a DB-1 chromatography phase (0.25 μm). The analyses were carried out under the conditions of column thermostat temperature programming: the starting temperature was 120°C for 1 min, the programming rate was 5°C/min up to 250°C. The chromatography time was 40 min. The injector temperature was 225°C; the electron capture detector temperature was 300°C. Based on tests of this method, it was found that the overall approach produced results that were within 15–20% of the expected values for the concentrations of chlorinated hydrocarbons in seawater.

The bottom sediments were centrifuged for 20 min at a speed of 2,000 rpm to completely separate the silt from the water, then they were extracted with acetone, followed by a shaking with a hexane–acetone mixture (3:1). The combined extract was mixed with an equal volume of the 2% sodium sulfate solution. The hexane layer was separated and the water–acetone layer was subjected to reextraction. The combined hexane extract was concentrated and then purified by mixing it with sulfuric acid to remove organic substances and with tetrabutylammonium sulfate to remove sulphur and sulfur–organic compounds. The purified solution was

concentrated in the flow of high-purity nitrogen gas to 1 ml and subjected to the chromatography analysis. The accuracy of this method was about 50%; therefore, the observed results should be interpreted only qualitatively.

The samples of the marine biota were first separated from their shells (crabs, bivalves, urchins, etc.) and the soft tissues ground into a homogeneous mass, defatted with acetone, and subjected to preliminary processing similar to the analysis of bottom sediments. Simultaneously, separate subsamples were weighed for the determination of dry weight and fat content. Recoveries in these experiments were in the 93-97% range.

The suspended materials were secured by filtering large water volumes (up to 300 l) through 0.45 μ m pore diameter membrane filters, which were previously cleaned with organic solvents. The chlorinated compounds were extracted from the suspended materials on these filters by extracting them with

n-hexane in Soxhlet concentrators over 4-h periods (10 cycles per hour); thereafter, they were analyzed similarly to the seawater samples.

Results and Discussions

Table 1 presents the data on the concentration of chlorinated hydrocarbons in water of the Bering and Chukchi Seas. The comparative analysis of these findings shows the peculiar distribution of each of the studied xenobiotics. The most interesting results are for the hexachlorocyclohexanes. Thus, it is found that their concentration in water samples exceeds by approximately 10 times the concentration of other identified chloroorganic hydrocarbons such as PCB's and DDT's. These rather high concentrations of HCH isomers (up to 5 ng/l) with their low concentration in the atmospheric air samples

TABLE 1
The concentration of chlorinated hydrocarbons in the seawater.

Chlorinated hydrocarbon concentration (ng/l)

Stat.	α -HCH	β -HCH	γ -HCH	pp'-DDE	pp'-DDD	pp'-DDT	PCB	cis-clrdn	tr-clrdn	tr-nchl
3	2.33	0.44	0.99	0.008	0.001	0.003	0.2	0.005	0.004	0.002
7	2.45	0.52	1.32	0.005	0.002	0.002	0.3	0.004	0.003	0.001
9	2.15	0.12	1.48	0.002	0.002	0.003	0.2	0.004	0.004	0.001
13	1.64	0.35	0.75	0.007	0.001	0.002	0.4	0.008	0.006	0.002
15	1.20	0.62	0.62	0.006	0.001	0.002	0.2	0.004	0.003	0.001
18	1.40	0.09	0.44	0.005	0.001	0.001	0.3	0.005	0.003	0.001
22	1.40	0.19	0.59	0.003	0.002	0.003	0.2	0.008	0.005	0.003
24	1.76	0.23	0.36	0.007	0.002	0.006	0.8	0.007	0.007	0.002
26	1.58	0.32	1.25	0.009	0.002	0.007	0.4	0.008	0.006	0.002
27	1.67	0.54	0.99	0.002	0.001	0.002	0.2	0.009	0.007	0.002
32	1.80	0.42	1.12	0.004	0.002	0.003	0.3	0.004	0.003	0.001
36	1.91	0.82	1.25	0.005	0.001	0.002	0.4	0.003	0.002	0.001
41	1.64	0.44	1.02	0.009	0.002	0.007	0.8	0.007	0.006	0.003
45	1.40	0.04	1.12	0.005	0.001	0.003	0.2	0.007	0.007	0.003
47	1.26	0.88	0.75	0.002	0.001	0.002	0.6	0.008	0.009	0.002
49	2.02	1.09	1.02	0.005	0.001	0.002	0.7	0.007	0.008	0.002
50	2.38	0.73	1.30	0.004	0.001	0.004	0.8	0.004	0.003	0.001
53	2.50	0.64	1.12	0.012	0.002	0.006	0.7	0.004	0.002	0.001
55	2.78	0.92	1.17	0.005	0.001	0.003	0.2	0.005	0.009	0.001
57	2.54	1.13	1.12	0.002	0.001	0.002	0.4	0.007	0.005	0.004
59	2.50	1.21	1.59	0.003	0.002	0.003	0.2	0.004	0.003	0.001
61	3.02	0.95	1.87	0.011	0.002	0.007	0.6	0.008	0.006	0.002
64	2.18	0.71	0.59	0.006	0.001	0.005	0.8	0.008	0.005	0.004
67	1.80	0.55	0.31	0.004	0.002	0.004	0.6	0.009	0.005	0.009
69	1.40	0.38	0.28	0.001	0.001	0.003	0.5	0.004	0.003	0.001
72	1.01	0.68	0.13	0.002	0.002	0.007	0.2	0.004	0.003	0.001
74	3.34	0.44	0.67	0.002	0.002	0.004	0.2	0.009	0.006	0.002
82	2.65	0.52	1.17	0.002	0.003	0.005	0.2	0.008	0.007	0.002
86	2.12	0.23	0.95	0.011	0.002	0.007	0.4	0.008	0.006	0.002
89	2.12	0.64	1.02	0.011	0.003	0.004	0.6	0.007	0.004	0.004
96	1.98	0.38	0.86	0.012	0.004	0.004	0.5	0.008	0.005	0.004
100	1.89	0.52	0.71	0.006	0.001	0.003	0.8	0.009	0.006	0.003
104	1.64	0.68	0.25	0.006	0.001	0.005	0.5	0.008	0.005	0.002
106	1.58	0.88	0.48	0.006	0.009	0.008	0.7	0.007	0.003	0.005

(according to the American specialists) were revealed for the first time in these arctic regions remote from human activities.

Also, it was found that the concentration of HCH isomers in the Chukchi Sea water was 20 to 25% higher compared with the Bering Sea water (Table 1). These data can be explained with the Henry's law for volatile compounds. Such compounds as HCH isomers with relatively high volatility at low temperatures are usually dissolved in the water, and when temperatures rise they change into the gas phase. Since the Bering Sea water is generally warmer than the Chukchi Sea water, the Bering Sea water should retain less of these compounds (assuming they both have the same levels overlying them in the air).

The data on the study of the HCH isomeric composition confirms (3 to 4 times excess of the alpha-isomer concentration over the gamma-isomer concentration) that the main source of the HCH discharge into these regions is atmospheric from Southeast Asia where the hexachloran preparation with the 35% alpha-isomer concentration is mainly used. In the USSR and the USA, whose shores are washed by the Bering and the Chukchi Seas, only the lindane preparation with 98% of gamma-isomer is used.

A number of interesting conformities to natural laws can be derived from a study of the distribution of the DDT group compounds in this investigated-region water (Table 1). First of all, DDT and its metabolites, DDD and DDE, are the only group of chlorinated hydrocarbons whose concentration in the Bering Sea has declined considerably since 1984 (from 0.8 ng/l down to 0.01 ng/l on average). In fact, the concentration of the DDT group compounds in a number of samples was at the level of minimum detection limit of the method which was, respectively for each analyte reported in Tables 1-4, the lowest value which could be reported for the number of significant digits reported (e.g., if the results were presented as 2.1 ng/g, then the detection limit for this column of data was 0.1 ng/g).

The contamination of marine ecosystems with polychlorobiphenyls excites serious apprehension. These contaminants are a mixture of 209 different components having multiple

physical and chemical properties. Every congener undergoes transformation processes at different rates and in different directions depending on the environmental conditions.

As our investigation showed, the general PCB concentration did not change significantly over the last 5 years (1984-1988) remaining at the 0.7 to 0.8 ng/l levels (Tables 1,2). Furthermore, in addition to looking at total PCB's, individual PCB congeners were also identified in all of the samples. Measuring the individual congeners provides additional information about the chemical and physical processes that interact to distribute the separate components of the PCB mixtures within each of the environmental compartments that were investigated. The comments that follow are some of the preliminary conclusions that resulted from these data. Of the total mix of possible hexa-through monochlorobiphenyls, di- and trichlorobiphenyls were the most abundant in the water samples. These data demonstrate, firstly, the primary accumulation of the more soluble components of the PCB's were appearing in the water and, secondly, the intensity of photochemical process in this geographic region appeared to be causing the formation of many low-chlorinated components.

The results of the study relating to the general mix of CHC's identified, also allowed identification of new compounds that were not found earlier in these regions—viz., cis-chlordane, trans-chlordane, cis-nonachlor, trans-nonachlor, and oxychlordane. These compounds are mainly used in temperate latitudes of the globe for control of termites and other insects. Their appearance in this arctic region, therefore, appears to occur as a result of long-distance atmospheric transfer processes. Their concentration in the water reaches the 0.02 ng/l level (Table 1), with cis-chlordane and trans-chlordane usually making up most of the total; in many samples it exceeded the concentration of even the widely-used pesticide DDT, and in a number of cases it equaled the PCB concentrations.

In the study of vertical distribution of chlorinated hydrocarbons, it was found they all reached depths of a few thousand meters (Table 2). The distribution of PCB's and DDT's was uniform while the HCH isomer concentrations

TABLE 2

The vertical distribution of chlorinated hydrocarbons in the Southern Bering Sea (South Polygon).

Depth (m)	Chlorinated Hydrocarbon Concentration (ng/l)						
	α -HCH	β -HCH	γ -HCH	p,p'-DDE	p,p'-DDD	p,p'-DDT	PCB
0	2.29	0.38	1.11	0.003	0.002	0.002	0.3
10	2.25	0.4	1.05	0.003	0.002	0.003	0.4
100	1.15	0.28	0.55	0.005	0.003	0.003	0.5
200	1.21	0.31	0.48	0.005	0.006	0.005	0.5
1000	0.95	0.12	0.40	0.006	0.005	0.005	0.4
3850	0.40	0.05	0.27	0.004	0.003	0.003	0.2

decreased sharply depending on the depth. It is considered (Tanabe, 1985) that the circulation of water masses and biogenous sedimentation (one of the most important processes for contaminant removal from the ocean surface layers) contribute to the passing of chlorinated hydrocarbons through the deep-water layers of the aquatic system.

Investigation of the ice sample in the Chukchi Sea show that the concentration of HCH isomers reaches 3.4 ng/l, the DDT amount reaches 0.016 ng/l and the PCB amount reaches the 0.9 ng/l level.

The availability of chlorinated hydrocarbons was identified in practically all samples of suspended matter (Table 3). Thus, using these data, it was found that the DDT accumulation coefficients (DDT concentration in the suspended matter/DDT concentration in the water) for the suspensions were greater than 100 and even reached as high as 1,000 in some of the surface collections.

The analyses of the suspended matter also showed that the HCH isomers are mainly in a dissolved state while the PCB concentration is evenly dispersed between two phases. It was also noted that the dissolved PCB forms usually included components with a low number of chlorine substituents, and the adsorbed forms mainly consisted of components with a larger number of chlorine substitutions. When studying the deepwater samples, however, and the relationship between the concentration of the adsorbed forms, the reverse correlation was found out—that is, the lower the level of chlorinated hydrocarbons dissolved in the water, the more was their affinity with the suspended phase. Therefore, the agents with low water solubility—for example, DDT's and highly chlorinated PCB's are sorbed by the suspended matter and easily transferred from the surface layers to the deep ones. At the same time, this process for low-chlorinated PCB's (the more soluble forms) and lindane is less active.

Based on the suspended sediment data it was also found that the fraction of sorbed chloroorganic compounds increases with the transition to the higher latitudes where the volume of the suspended agents was higher.

Chlorinated hydrocarbons were also identified in all samples of plankton and neuston (Tables 4,5). Note that the accumulation coefficients in zooplankton were 10,000 to 100,000, and the absolute concentration was 45 to 90 ng/g of fat. The PCB accumulation coefficients in samples of plankton and neuston also ranged from 1,000 to 100,000. In contrast with the suspended solids, there was a more even concentration of all polychlorobiphenyl components in samples of plankton and neuston, which can evidently be explained by their overriding uniform lipophilic properties. Some residue data for chlordanes was also collected for the plankton; however, because of some methods problems, we can only qualitatively state that cis-chlordane, trans-chlordane, and trans-nonachlor appear to contribute a great amount to the total of CHC's measured in the plankton.

The bioaccumulation of chlorinated hydrocarbons is even more obvious in benthic organisms (Table 6). The concentration of the DDT group in samples of benthic organisms varies from 3 to 49 ng/g of dry weight; the concentration of polychlorobiphenyls ranges from 2 to 102 ng/g of dry weight, with the PCB fractions having a balanced concentration both of low- and high-chlorinated biphenyls, and the DDT fraction had an increased concentration of 2,4'- (not reported in the tables, but indeed observed) and 4,4'-DDE components, which is evidently connected with the consumption of the partially dehydrochlorinated DDT mixture by benthic organisms.

This investigation did not permit a determination of the dependence of the chlorinated hydrocarbon concentration in benthic organisms on the concentration of this material in the respective bottom sediments since contamination of the upper

TABLE 3

The concentration of chlorinated hydrocarbons in suspended matter.

Station	Chlorinated Hydrocarbon Concentration (ng/g dry wt)					
	α -HCH	β -HCH	p,p'-DDE	p,p'-DDD	p,p'-DDT	PCB
7	54	66	92	58	162	229
13	44	51	80	25	104	185
69	95	104	155	67	380	425
74	84	98	161	80	350	603
82	101	125	208	95	409	685
84	87	95	161	74	340	523
86	88	93	146	58	302	399
89	177	188	182	84	388	411
100	173	188	219	112	502	942
110	145	155	260	124	525	712
113	90	101	166	74	340	504

layer of bottom sediments was found to be rather uniform in these seas, viz., 0.3 to 3.4 ng/g of dry mass of DDT, 0.5 to 9.2 ng/g of dry mass of PCB.

In conclusion, it should be noted that these experiments allow us to make a quantitative assessment of the influence of chlorinated hydrocarbons on different elements of the Bering Sea ecosystems. Therefore, on the basis of the data it was calculated that the seawater in these regions contain, at present, 1.6 t of PCB's, 32.5 t of hexachlorocyclohexanes, 42 kg of DDT's, and 82 kg of chlordanes. Based on the preliminary estimated data, bottom sediments have accumulated 1.8 t of

DDT's and 6 kg of HCH's. Thus, the following conclusion can be drawn. The PCB mass discharged into the ecosystem of the Bering Sea is distributed in equal portions between the waters and the upper layer (0–5 cm) of the bottom sediments. Dichlorodiphenyltrichloroethanes and their metabolites are mainly sorbed by the suspended solids and sedimented into bottom sediments. As regards HCH isomers, their behavior is conditioned by high volatility and dissolubility that results in the accumulation of the main mass of the agent that is discharged into an ecosystem from the waters of warmer climates.

TABLE 4

The concentration of chlorinated hydrocarbons in neuston.

Station	Chlorinated Hydrocarbon Concentration (ng/g dry weight)			
	pp'-DDE	pp'-DDD	pp'-DDT	PCB
2	1.0	0.5	1.1	3.5
3	1.0	0.4	1.1	3.7
5	0.9	0.2	1.0	2.5
4	0.8	0.2	0.8	2.3
5	0.9	0.2	1.0	2.5
6	0.9	0.6	1.0	2.6
7	1.0	0.6	0.9	2.8
9	0.9	0.3	1.0	2.3
11	1.0	0.5	1.0	3.1
13	0.9	0.3	1.0	4.1
15	1.3	0.7	1.5	3.7
18	1.3	0.7	1.3	3.5
19	1.2	0.6	1.2	3.8
22	1.3	0.6	1.4	3.5
24	0.6	0.2	0.7	1.9
32	1.0	0.4	1.3	3.5
35	0.9	0.7	0.4	6.5
36	1.8	0.9	4.5	7.1
41	2.0	1.5	2.6	5.1
45	2.1	1.0	2.7	7.1
47	1.6	1.2	1.9	3.3
49	1.8	1.0	2.1	3.5
50	1.0	0.4	1.5	2.8
52	1.8	1.2	1.7	3.6
53	1.9	1.2	1.8	5.5
55	1.5	1.0	1.3	4.3
59	2.4	1.1	2.4	6.0
61	1.5	1.0	1.3	3.3
64	1.4	0.9	1.2	3.4
74	1.2	1.0	1.1	3.9
82	0.9	1.0	1.0	3.5
86	0.5	0.5	0.7	3.3
89	1.5	1.0	1.9	4.3
96	1.5	0.8	1.9	4.6
104	2.2	1.0	2.5	5.9
106	1.9	0.6	2.2	4.8
109	1.4	0.9	1.8	4.9
111	1.4	1.0	1.8	4.8

TABLE 5

The concentration of chlorinated hydrocarbons in plankton.

Station	Chlorinated Hydrocarbon Concentration (ng/g of dry weight)			
	p,p'-DDE	p,p'-DDD	p,p'-DDT	PCB
1	1.2	1.2	1.3	3.4
2	1.1	1.1	1.1	2.9
3	0.5	0.2	0.8	1.9
4	1.1	0.4	0.9	3.7
5	0.9	0.3	1.0	1.8
6	0.9	0.2	0.9	1.8
7	0.6	0.2	0.8	1.5
9	0.6	0.2	0.7	1.7
11	0.8	0.2	0.7	3.2
13	1.2	0.4	0.9	2.9
15	1.2	0.6	1.1	2.5
18	1.3	0.6	1.2	3.9
24	1.4	1.4	1.5	5.7
27	1.8	1.6	1.7	5.5
32	0.8	0.2	0.8	2.3
35	1.9	1.6	1.9	6.1
36	1.5	1.5	2.0	6.6
41	1.2	1.2	1.4	6.2
45	1.5	1.0	3.1	6.2
47	0.8	0.2	0.8	6.3
49	1.0	0.4	0.8	2.7
50	1.0	0.8	1.0	3.0
52	2.0	0.8	0.8	4.4
53	1.3	0.6	1.2	3.3
55	1.1	1.2	1.2	4.2
57	1.1	1.0	1.2	3.7
59	2.2	1.0	1.5	5.5
61	0.5	0.6	0.6	2.8
64	0.5	0.4	0.6	3.0
67	1.0	0.6	0.6	2.9
69	0.4	0.2	0.9	1.5
72	1.3	1.2	1.2	4.8
74	1.2	1.2	1.2	4.0
82	1.3	0.8	1.2	3.2
86	0.7	0.5	0.9	2.8
92	0.9	0.2	2.0	3.4
111	1.5	0.8	1.2	3.9

TABLE 6

The concentration of chlorinated hydrocarbons in benthic organisms (soft tissues).

Station	Objects	Concentration (ng/g of dry weight)			
		DDE	DDD	DDT	PCB
3	Phaeophyta				
	<i>Laminaria</i> (seaweed)	3	3	2	15
	<i>Anthozoa, Nephydæ</i>				
12	<i>Eunephtya tubiformis</i> (corals)	10	8	8	68
	Actinoidea				
69	<i>Actinia</i> sp.	2	5	5	67
	Bivalvia				
13	<i>Nuculana</i> sp.	18	11	26	114
19	"	1	1	1	95
27	"	15	10	11	83
35	"	16	11	10	98
45	"	6	7	4	43
50	"	11	12	14	58
65	"	20	10	11	93
47	<i>Goldia hyperborea</i>	8	4	4	85
55	"	6	5	9	85
52	<i>Elliptica elliptica</i>	7	8	4	23
53	"	13	5	10	82
	Gastropoda				
52	<i>Margarites</i> sp.	9	10	6	33
53	"	2	2	1	29
50	Gastropoda	3	3	2	29
72	"	12	9	44	57
102	Nudibranchia	11	15	14	87
	Crustacea				
	Amphipoda				
47	<i>Stegocephalus</i> sp.	5	3	3	99
55	<i>Ampilisca</i> sp.	8	3	6	73
59	"	7	7	5	71
61	"	12	8	5	54
	Decapoda				
13	<i>Chinocetis opilio</i> (crab)	17	21	7	73
36	"	12	7	8	40
45	"	4	4	3	29
64	"	10	10	4	66
67	"	7	7	5	43
72	"	12	8	16	59
	<i>Pagurus</i> sp. (hermit crab)				
13	"	12	9	6	82
24	"	20	12	17	55
52	"	15	9	12	51

TABLE 6 - continued

Concentration
(ng/g of dry weight)

Station	Objects	Concentration (ng/g of dry weight)			
		DDE	DDD	DDT	PCB
	<i>Pagurus</i> sp. (hermit crab)				
53	"	21	13	14	92
55	"	11	9	9	74
65	"	12	10	11	93
72	male "	20	10	11	94
72	female "	2	2	1	75
96	"	9	5	3	53
102	"	12	9	17	68
89	crab "	20	12	10	82
92	crab "	20	15	10	91
	Crustacea				
	Pandalidae				
92	"	14	12	11	76
96	"	8	8	3	63
	Crangonidae				
66	"	12	10	14	67
	<i>Sclerocrangon</i> sp.				
36	"	22	12	11	103
41	"	2	3	5	39
	Shrimps				
7	"	10	6	13	46
45	"	15	17	13	74
72	"	7	2	1	21
	Echinodermata				
	Asteroidea				
2	<i>Ctenodiscus cristatus</i> (star)	3	3	2	15
7	"	23	18	17	71
	Ophiuroidea				
7	<i>Ophiura sarsi</i>	28	23	14	54
19	"	12	10	13	73
35	"	21	12	15	62
64	"	5	6	5	25
69	"	5	3	3	21
18	<i>Ophiura</i> sp.	4	3	4	53
45	"	5	6	3	42
34	<i>Gorgonocephalus</i> sp.	10	7	10	44
	Echinoidea				
86	Sea Hedgehog	8	10	13	67
	Holothuroidea				
45	<i>Myriotrochus rinkii</i>	24	10	7	74
47	"	2	2	1	12
55	"	24	10	7	74
52	<i>Holothuria</i>	10	8	19	64
	Bryozoa				
21	Sea-mosses	19	21	12	45
102	"	2	3	8	99
105	"	2	2	7	29
	Tunicata				
41	"	8	12	15	73
96	<i>Boltenia ovifera</i>	4	5	3	27

8.1.3 Organochlorine Contamination of Sediments, Fish, and Invertebrates

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Introduction

Organochlorine (OC) contamination in the Bering Sea and Chukchi Sea ecosystems is relatively unstudied. Some data are available on walrus (*Odobenus rosmarus divergens*) from Little Diomed (Taylor *et al.*, 1989), and some fish, seals (*Leptonychotes weddelli*), and lower food chain organisms from the southern Bering Sea Tanabe & Tasukawa, 1980; Kawano *et al.*, 1986; Kawano *et al.*, 1988), but no comprehensive study of OC's in the northern Bering Sea and Chukchi Sea ecosystems has been attempted. The present account fills this data gap and was made possible through the Third Joint US-USSR Bering & Chukchi Seas Expedition aboard the research vessel (R/V) *Akademik Korolev*.

Atmospheric sampling in other regions of the Arctic suggested that hexachlorocyclohexanes (HCH's), polychlorinated biphenyls (PCB's), hexachlorobenzenes (HCB's), and toxaphene might be found in the food webs of the Bering and Chukchi Seas (Bidleman *et al.*, 1989; Patton *et al.*, 1989). Toxaphene was of special interest as few reports exist for this purported global contaminant despite evidence since 1978 that it occurs in biota in remote pristine environments (Zell & Ballschmitter, 1980).

Materials and Methods

Samples

All samples were collected from the R/V *Akademik Korolev* while participating on a joint US-USSR expedition to the Bering and Chukchi Seas from 26 July to 2 September 1988. The stations that were occupied are shown on the frontispiece to this volume and the numbering here corresponds to numbering shown in that figure. Zooplankton and phytoplankton were collected by net tows. Surface film organisms—neuston—were collected using a special surface trawl described by Zaitsev (Subchapter 5.2.5, this volume). All samples were stored in precleaned I-Chem jars (I-Chem Research Inc., New Castle, Delaware) after excess water was decanted. Samples were stored frozen (-10°C).

A bottom trawl was used to obtain benthic organisms, including shrimp, family Pandalidae; crabs, family Paguridae; molluscs, family Nuculidae; and urchins, family Strongylocentrotidae. Large samples were placed in plastic Whirl-pak bags and frozen for storage. Fish (pollack, *Theragra*

chalcogramma; and a sculpin, *Cottus* sp.) were obtained by hook and line, wrapped in aluminum foil, and kept frozen until analysis.

Sediments were obtained using a box corer provided by Texas A&M University. To secure the core samples from this collector, 10-cm core tubes were pushed into the box cored samples so that vertical profiles of the bottom samples could be obtained for later sectioning. Cores containing the sediment samples were capped and frozen in an upright position and were kept frozen until they were sectioned. Additional bulk samples were also taken from the box core collections. Nearsurface, 0–2-cm layers were scraped off and placed directly in I-Chem jars. Deeper cuts, 0–10-cm layers were collected using a stainless steel spoon. These samples (4–8 kg) were placed in 1-gal polyethylene jars, thoroughly mixed and subsampled in 100–200 g portions for OC and metals analyses. All collected sediment samples were kept frozen until preparation for gas chromatography (GC) analysis.

Analysis

All samples were analyzed for organochlorines by electron capture gas chromatography; selected samples were analyzed for toxaphene using negative chemical ion GC mass spectrometry (GC/MS).

Biota samples were homogenized whole without any separation of soft tissues from shells and exoskeletons, mixed with ignited Na₂SO₄ (150 g to 10 g wet biota sample), dried overnight in a desiccator, then Soxhlet-extracted for 7 h using pesticide grade hexane. Biota extracts were split into two equal portions; one was dried and weighed for lipid determinations, the other was processed further prior to GC analysis. The sediment samples (20 g of slightly moist material) were extracted by Soxhlet using a 50:50 mixture of pesticide grade acetone and hexane. To remove the water and acetone from the extracts, they were alternately washed with water and then hexane. The final hexane extract was dried by passing it through a column of ignited Na₂SO₄. The entire soil extract was processed for GC analysis.

For initial removal of fats and other interfering materials from the extracts, we used the florisil column cleanup method of Cromartie and associates (Cromartie *et al.*, 1975). Silica gel column chromatography was used to separate PCB's in the extracts from the majority of OC pesticides (Cromartie *et al.*, 1975; Kaiser *et al.*, 1980). For removal of phthalates and traces

of fats, sulfuric acid was used as the final step of cleanup just prior to injection of the samples into the GC (Patton *et al.*, 1989). The florisol and silica gel absorbent materials had to be extensively cleaned prior to use in order to reduce their blank contributions to acceptable levels. These cleanup steps involved ignition of the florisol overnight in a muffle furnace at 600°C and batch extraction by Soxhlet of the silica gel with pesticide grade petroleum ether.

Extracts were analyzed by electron capture detection using a Hewlett-Packard model 5890 GC equipped with an autosampler. All data were processed using Nelson chromatography software. The GC separation was completed on a J&W DB-1701 (J&W Scientific, Folsom, California) megabore fused silica capillary column, 30 m × 0.53 mm ID. The carrier gas was H₂ at a flow rate of 20 ml/min. The heated zones were 250°C for the injector and 325°C for the detector. The GC program was as follows: 120°C hold for 1 min; increase to 160°C at 20°C/min; then programmed at 2°C/min up to 225°C; and finally held for 5 min. Quantitation was performed using the external standard method. Standard peak area integration was used for all single component pesticides; however, peak heights were used for PCB quantitation. The heights were summed for all peaks that matched the retention times of Aroclor 1242, Aroclor 1254, or Aroclor 1260.

Each extract collected from a silica gel fraction was prepared for injection into the GC by volume reduction to about 1 ml via a Kuderna Danish concentrator assembly, shaking with 1 ml of concentrated sulfuric acid for 30 s, and reduction of the acid-treated extract to 0.5 ml by blowdown with N₂ gas. With the sediment extracts, it was necessary to add 2–3 drops of elemental mercury to each 0.5 ml of final extract, and mix it until all elemental sulfur was removed.

Samples selected for toxaphene analysis were not treated with sulfuric acid in order to preserve structural integrity of the toxaphene components. Also, the fractionated silica gel extracts were recombined to allow for maximum recovery of any toxaphene that might have partially split into separate fractions. In preparation for injection these extracts were reduced by N₂ blowdown to 0.2 ml and injected into the Varian GC attached to a Finnigan TSQ-70 mass spectrometer operated in the negative chemical ionization mode. The mass spectrometer was set up according to the procedures of Swackhammer and associates (Swackhammer *et al.*, 1987) except for modifications to the choice of the GC column (DB-1, 30 × 0.32 mm ID—1 μ film thickness), minor changes to the GC operating conditions, and use of the external standard method for quantitation. For qualitative verification of toxaphene in the samples, the retention times of the peaks of each of the characteristic mass chromatograms were compared to similar chromatograms of the standards. The capillary column was able to resolve 68 peaks in the standard. The quantitation routine in this method allows for both retention-time-matched and nonretention-time-matched peaks to be included if they are present in the appropriate mass ranges; therefore, there was always plenty of integrated area above the blank levels to be used in the quantitations. Because of the selectivity of this program for identifying only toxaphene peaks, the toxaphene results should be considered very reliable.

Procedural blanks were carried through each analytical step to correct for background interferences from reagent contamination and handling. Samples were processed in batches of 10 to 20, with at least one matrix spike, duplicate, and blank to monitor the accuracy and precision of the analysis for each batch. To report a residue as detectable, the raw number had to be at least twice the blank.

Recoveries were monitored by carrying out matrix spikes with mixtures of the expected pesticides and Aroclor mixtures. The levels for spiking ranged from 2.5 to 12.5 ng/g for the organochlorine pesticides and 12.5 to 125 ng/g for the PCB's. For the biota the average recoveries were as follows: Total PCB—49%; p,p'-DDE [2,2-Bis(p-chlorophenyl)-1,1-dichloroethylene]—86%; HCB—73%; alpha-HCH—95%; gamma-HCH—81%; oxychlordane—77%; trans-chlordane—88%; cis-chlordane—88.6%; trans-nonachlor—78%; p,p'-DDD [2,2-Bis(p-chlorophenyl)-1,1-dichloroethane]—88.4%; cis-nonachlor—76%; and p,p'-DDT [2,2-Bis(p-chlorophenyl)-1,1,1-trichloroethane]—65%. For the sediment, the recoveries were all low but consistent as follows: Total PCB—39%; p,p'-DDE—57%; HCB—46%; alpha-HCH—45%; gamma-HCH—44%; oxychlordane—44%; trans-chlordane—40%; cis-chlordane—42%; trans-nonachlor—41%; p,p'-DDD—55%; cis-nonachlor—42%; and p,p'-DDT—36%.

Duplicate results were collected for each batch of 20 or less samples. Generally there was good agreement between the two values, with the relative percent differences averaging less than 25%.

Both electron impact and negative chemical ionization mass spectrometry were employed to confirm the residues identified by electron capture GC. In some cases, residues were identified even though they were below the detection limits of the electron capture methods.

Results and Discussion

Organochlorine residues were present in all of the samples analyzed (Tables 1,2,3). The highest single component OC measured was the HCH class of compounds, especially alpha-HCH at 8.12 ng/g in one of the bivalve samples. In the mixed OC component classes of compounds, PCB's and toxaphene comprised the highest residues. For example, in neuston there was 67.9 ng/g total PCB's (Station 22); in zooplankton 23.9 ng/g total PCB's (Station 113, Table 1); and in pollack 10.8 ng/g toxaphene (Station 4, Table 3). Of the single-component organochlorine pesticides other than HCH's, HCB was relatively high in some of the crabs and bivalves, and trans-nonachlor and p,p'-DDD were generally high in fish, zooplankton, and phytoplankton. The sediment was notably devoid of most of the OC's found in biota (Table 2). Alpha-HCH was found in a few sediment samples, detectable levels of DDT and PCB's were measured in sediment surface layer (Station 45), and some chlordane peaks were evident in the deeper homogenized sample (Station 13). Our data suggests that sediments are not reservoirs supplying organochlorines to the biota but rather acting as sinks. Further, it appears that the atmosphere is the major loading factor in this system.

TABLE 1

Organochlorine concentrations (ng/g fresh wt.) in biota from the Bering and Chukchi Seas.

Sample Type	Sta. No.	% lipid	PCB-1242	PCB-1254	PCB-1260	Total PCB	HCB	α -HCH	γ -HCH	β -HCH	OXY	trans-CHL	cis-CHL	trans-NON	cis-NON	DDE	DDD	DDT
Hermit Crab	5	2.68	10.99	<3.07	<2.37	13.71	0.93	1.54	0.34	0.63	<0.19	<0.20	0.31	0.45	<0.19	0.43	<0.18	3.48
Hermit Crab	13	1.89	<5.56	<3.03	<2.33	<10.92	2.90	1.84	0.32	0.93	<0.19	<0.20	0.24	0.49	<0.19	0.44	<0.18	<0.19
Hermit Crab	53	1.74	<6.62	<3.06	<2.36	<11.04	<0.45	1.80	0.33	1.57	0.21	<0.20	<0.17	0.20	<0.19	<0.38	<0.18	0.27
Hermit Crab	100	1.48	<5.84	<3.18	<2.45	<11.47	<0.47	1.53	0.32	0.91	<0.20	<0.21	0.18	0.29	<0.20	<0.40	<0.19	<0.20
Hya (Crab)	100	0.81	<5.84	<3.18	<2.45	<11.47	<0.47	2.33	<0.21	0.54	<0.20	<0.21	<0.18	0.13	<0.20	0.71	<0.19	<0.20
Hermit Crab	105	NA	<7.8	3.22	2.49	9.61	0.32	0.59	0.27	0.51	0.05	<0.3	<0.2	0.20	0.07	1.10	0.43	0.48
Urchins	41	0.67	<5.84	<3.18	<2.45	<11.47	<0.47	<0.32	<0.21	<0.49	<0.20	<0.21	<0.18	<0.03	<0.20	<0.40	<0.19	<0.20
Bivalve	35	2.10	<4.46	<2.43	<1.87	<8.76	0.95	2.00	19.50	<0.37	<0.15	<0.16	<0.14	0.07	<0.15	<0.31	<0.15	<0.15
Bivalve	45	0.99	<5.84	<3.18	<2.45	<11.47	4.98	8.12	0.31	2.12	<0.20	<0.21	<0.18	<0.03	<0.20	<0.40	<0.19	<0.20
Bivalve	59	0.50	<5.81	<3.16	<2.44	<11.41	3.61	0.35	<0.21	<0.49	<0.20	<0.21	1.10	<0.03	<0.20	<0.40	<0.19	<0.20
Bivalve	59	0.44	<5.84	<3.18	<2.45	<11.47	<0.47	0.60	<0.21	<0.49	<0.20	<0.21	<0.18	<0.03	<0.20	<0.40	<0.19	<0.20
Bivalve	22	2.34	3.69	2.79	1.40	7.88	0.27	1.22	0.25	<0.12	<0.01	0.13	0.24	0.91	<0.01	0.64	0.67	<0.01
Sculpin	41	5.37	<5.84	<3.18	<2.45	<11.47	<0.47	0.74	<0.21	<0.49	0.40	<0.21	0.22	0.27	<0.20	5.04	0.82	0.37
Pollack	4	2.71	<5.84	8.03	3.70	14.65	0.63	1.45	0.31	<0.49	0.30	0.53	1.42	1.45	0.26	4.05	3.46	1.65
Pollack	4	NA	<3.9	3.08	1.45	6.47	0.63	1.44	0.25	0.19	0.10	0.32	0.99	1.54	0.28	3.36	1.53	0.58
Shrimp	13	1.44	<5.84	<3.18	<2.45	<11.47	<0.47	0.84	0.34	<0.49	<0.20	<0.21	<0.18	0.07	<0.20	<0.40	<0.19	0.24
Shrimp	41	NA	<7.8	<2.4	<1.5	<11.7	0.65	1.28	0.21	<0.3	0.11	<0.3	<0.2	0.14	0.03	1.10	<0.2	0.00
Zooplankton	113	NA	<12.3	6.98	10.78	23.90	1.06	1.08	0.30	1.88	0.16	<0.5	<0.4	0.21	0.00	1.34	1.14	1.65
Zooplankton	57	0.05	1.95	1.99	<1.63	4.76	<0.31	0.19	<0.14	<0.24	0.02	<0.14	0.08	0.10	<0.02	0.37	0.30	0.38
Zooplankton	32	2.27	5.10	3.63	2.13	10.86	0.31	1.91	0.41	0.69	<0.01	0.46	0.44	0.35	2.53	0.91	10.37	6.82
Zooplankton	11	1.63	2.42	7.21	8.54	18.16	0.45	0.95	0.32	0.40	NA	NA	NA	0.02	NA	1.14	NA	NA
Neuston	22	0.91	28.31	26.32	13.23	67.86	0.92	2.78	0.84	0.91	<0.04	0.91	1.12	1.30	0.57	5.65	4.58	4.01
Phytoplankton	108	0.76	3.18	3.00	1.97	8.14	<0.19	0.62	0.16	<0.14	<0.01	0.09	0.18	0.29	<0.01	0.57	0.39	0.56
Phytoplankton	86	0.06	3.49	3.23	<1.63	7.54	<0.31	<0.21	<0.14	<0.24	0.02	0.06	0.09	0.63	<0.01	0.23	<0.15	0.11
Phytoplankton	69	0.05	2.52	2.09	1.31	5.91	<0.16	<0.11	<0.07	<0.12	<0.01	0.12	0.17	0.50	<0.01	0.51	1.01	1.31

HCB = hexachlorobenzene; α -HCH, γ -HCH & β -HCH = alpha, gamma & beta hexachlorocyclohexane; DDE, DDD & DDT = p,p'-DDE,DDD & DDT; OXY = oxychlorodane; cis-CHL = cis-chlordane; trans-CHL = trans-chlordane; trans-NON = trans-nonachlor; cis-NON = cis-nonachlor.

TABLE 2

Organochlorine concentration (ng/g dry wt.) in sediment from the Bering Sea and Chukchi Seas.

Sediment Layer Sampled	Sta. No.	PCB-1242	PCB-1254	PCB-1260	Total PCB	HCB	α -HCH	γ -HCH	β -HCH	OXY	trans-CHL	cis-CHL	trans-NON	cis-NON	DDE	DDD	DDT
UPPER 0-1 CM	45	<6.7	4.27	5.37	12.98	0.45	0.92	0.21	<0.2	<0.01	<0.3	<0.2	<0.1	<0.02	0.95	0.66	3.49
UPPER 0-2 CM	13	<6.60	<5.93	<6.62	<19.2	<0.20	<0.09	<0.09	0.22	<0.01	<0.19	<0.18	<0.08	<0.04	<0.76	<0.56	0.64
HOMOG. 0-10 CM	13	<3.30	<2.97	<3.32	<9.59	<0.10	0.24	<0.05	0.12	<0.01	<0.10	0.17	0.18	<0.02	<0.38	<0.28	<0.16
UPPER 0-2 CM	75	<7.70	<6.91	<7.72	<22.3	<0.23	0.27	<0.11	<0.04	0.05	<0.23	<0.21	<0.10	<0.04	<0.88	<0.65	<0.37
HOMOG. 0-10 CM	75	<2.99	<2.68	<3.00	<8.67	<0.09	0.12	<0.04	0.04	<0.01	<0.09	<0.08	0.13	<0.02	<0.34	<0.25	<0.14
UPPER 0-2 CM	96	<6.61	<5.94	<6.63	<19.1	<0.20	<0.09	<0.09	<0.03	<0.01	<0.19	<0.18	<0.08	<0.04	<0.76	<0.56	<0.32
HOMOG. 0-10 CM	96	<2.96	<2.66	<2.97	<8.59	<0.09	<0.04	<0.04	0.04	<0.01	<0.09	<0.08	<0.04	0.02	<0.34	<0.25	<0.14
UPPER 0-2 CM	109	<7.30	<6.56	<7.32	<21.2	<0.22	<0.10	0.15	<0.03	<0.01	<0.21	<0.20	<0.09	<0.04	<0.84	<0.62	<0.35
HOMOG. 0-10 CM	109	<3.80	<3.41	<3.81	<11.0	<0.11	<0.05	<0.05	<0.02	<0.01	<0.11	<0.10	<0.05	<0.02	<0.44	<0.32	<0.18
HOMOG. 0-10 CM	110	<5.20	<4.67	<5.22	<15.1	<0.16	<0.07	<0.07	0.04	<0.01	<0.15	<0.14	<0.06	<0.03	<0.60	<0.44	<0.25

HCB = hexachlorobenzene; α -HCH, γ -HCH, β -HCH = alpha, gamma & beta hexachlorocyclohexane; DDE, DDD, & DDT = p,p'-DDE,DDD & DDT; OXY = oxychlorodane; cis-CHL = cis-chlordane; trans-CHL = trans-chlordane; trans-NON = trans-nonachlor; cis-NON = cis-nonachlor.

TABLE 3

Concentration of toxaphene in selected samples.

Sample	Station	Concentration (ng/g wet wt.)	Number of Retention-Time- Matched Peaks**
Pollack	4	10.8	29
Pollack	4	(10)*	20
Neuston	22	(4)	15
Hermit Crab	53	(2)	7
Zooplankton	57	(2)	15
Phytoplankton	86	(1)	6
Shrimp	41	(1)	6
Sediment	13	(0.3)	4

* The parentheses indicate that these are estimated concentrations.

** There were a possible 68 peaks from the standard to be matched.

For example, neuston, which were collected at the sea surface, had some of the highest residues found in our collections. Hinckley and associates (Subchapter 8.1.1, this volume) make a strong case for atmospheric loading of the HCH class of insecticides that were found in this study. Other researchers also stress the atmosphere as the major loading mechanism for contaminants into remote areas of the Arctic (Norstrom *et al.*, 1988; Bidleman *et al.*, 1989; Patton *et al.*, 1989).

There were traces of toxaphene evident in each of the eight samples that were selected for GC/MS analysis for toxaphene (Table 3). The highest levels were found in two pollack samples, 10.8 ng/g and an estimated 10 ng/g. These two samples also produced the best retention time matches to the toxaphene standard (e.g., matched percentages of 43% [29/68] and 29% [20/68], respectively). The neuston and zooplankton samples had lower but identifiable toxaphene residues. The remaining samples (shrimp, crab, phytoplankton, and sediment) had only traces of toxaphene; the sediment contained the lowest level (estimated concentration of 0.25 ng/g and a match percentage of 6%).

For the PCB's, detection limits ranged from a high of 7.8 ng/g for Aroclor 1242 to a low of 0.8 ng/g for Aroclor 1260. For the individual OC's, the range was 0.5 ng/g for beta-HCH to 0.01 ng/g for oxychlordanes. The last group of biota samples analyzed had detection limits as shown in Table 4. The blanks for the sediment often were higher than those for the biota, which therefore caused the detection limits for the sediment to be higher than the biota. The detection limits for sediment, in ng/g, are shown in Table 4.

Organochlorines in northern latitude regions, especially Canada, have been investigated. Muir and associates (Muir *et al.*, 1988) sampled arctic cod (*Boreogadus saida*), seals (*Phoca hispida*), and polar bears (*Urus maritimus*) from the Canadian Arctic and found a number of OC's in these organisms at low to moderate levels. In cod, toxaphenes were the single highest compound class at 14 to 23 ng/g. Next highest were the HCH class of compounds at 2 to 18 ng/g, followed by PCB's, chlordanes, and DDT's. Muir and associates' (Muir *et al.*, 1988) results for fish from this area are comparable with ours.

TABLE 4

Method detection limits for the organochlorines by electron capture gas chromatography.

	BIOTA* (ng/g wet wt.)	SEDIMENT** (ng/g dry wt.)
Total PCB	3.8	10.50
Hexachlorobenzene	0.2	0.11
α -Hexachlorocyclohexane	0.1	0.05
β -Hexachlorocyclohexane	0.1	0.05
γ -Hexachlorocyclohexane	0.1	0.02
p,p'-DDE	0.1	0.41
p,p'-DDD	0.2	0.31
p,p'-DDT	0.01	0.17
oxychlordanes	0.01	0.01
cis-nonachlor	0.01	0.02
trans-nonachlor	0.01	0.04
cis-chlordane	0.1	0.1
trans-chlordane	0.1	0.11

* The biota detection limits are based on extraction of 10 g of sample and concentration of the extract down to 0.5 ml for injection.

** The sediment detection limits are based on extraction of 20 g of sample and concentration of the extract down to 0.5 ml for injection.

Their results for arctic cod muscle versus ours for whole pollack in ppb, were, toxaphene, 14 to 23 versus 10.8; cis-chlordane, 2 to 3 versus 3.5; total HCH, 2 to 28 versus 2.0; total DDT, 2 to 3 versus 6.5; total PCB's, 3 to 5 versus 6 to 15; and HCB, 1.9 versus 0.63.

Kawano and associates (Kawano *et al.*, 1988) sampled water, zooplankton, pollack, salmon, porpoises (*Phocoenoides dalli*), and thick billed murres (*Uria lomvia*) from the central area of the Bering Sea (near our Station 4) in 1982. Their data were presented in terms of ng/g lipid. By reporting our data on a lipid basis (Table 5), a comparison was possible. For zooplankton, there was remarkably good agreement between our two data sets. For example, the agreement was good for the chlordanes except that we found higher levels of cis-nonachlor. These data were also comparable for the HCH. We found relatively higher levels of DDT's than did Kawano and coworkers (Kawano *et al.*, 1988). The two data sets for pollack were also generally comparable. In view of the few data points, however, it would be difficult to establish any significance in the way of trends to these comparisons. The most we can say at this point is that our data give further evidence that low-level OC residues appear to be widely spread throughout the Bering and Chukchi Seas. Kawano and associates (Kawano *et al.*, 1986) reported PCB results for samples from the central Bering Sea in zooplankton and pollack that are in agreement with ours.

We acknowledge the able assistance of Julie Himelrick Anderson and Valerie McPhatter in preparing these samples for analyses. The patience and expert assistance of the crew of the R/V *Akademik Korolev* are deeply appreciated, especially in helping us with our numerous special needs. We also thank Texas A&M University for the use of their box corer and other coring equipment.

TABLE 5

Lipid adjusted organochlorine concentrations (ng/g lipid wt.) in biota from the Bering and Chukchi Seas.

Sample Type	Sta No.	% lipid	PCB-1242	PCB-1254	PCB-1260	Total PCB	HCB	α -HCH	γ -HCH	β -HCH	OXY	trans-CHL	cis-CHL	trans-NON	cis-NON	DDE	DDD	DDT
Hermit Crab	5	2.68	409.3	<114.4	<88.3	510.79	34.7	57.2	12.8	23.6	<7.1	<7.5	11.5	16.9	<7.1	16.2	<6.78	129.6
Hermit Crab	13	1.89	<293.5	<160.0	<123.0	<575.41	153.1	97.0	16.8	49.2	<10.0	<01.6	12.6	25.9	<10.0	23.1	<9.5	<10.0
Hermit Crab	53	1.74	<323.8	<176.3	<136.0	<633.80	<25.9	103.6	19.1	90.7	12.2	<11.5	<9.87	11.4	<10.9	<21.9	<10.4	15.5
Hermit Crab	100	1.48	<395.80	<215.52	<166.05	<722.62	<31.85	103.69	21.35	61.94	<13.55	<14.23	12.20	19.32	<13.55	<27.11	<12.88	<13.55
Hya (Crab)	105	0.81	<718.3	<391.1	<301.4	<744.61	<57.8	286.6	<25.8	66.5	<24.6	<25.8	<22.1	15.4	<24.6	87.3	<23.4	<24.60
Bivalve	35	2.10	<212.76	<115.92	<89.21	<417.88	45.08	95.25	930.22	<17.65	<7.16	<7.63	<6.68	3.22	<7.169	<14.79	<7.16	<7.16
Bivalve	45	0.99	<589.0	<320.7	<247.1	<1,149.77	411.0	819.0	30.8	213.7	<20.2	<21.2	<18.2	<3.0	<20.2	<40.3	<19.2	<20.2
Bivalve	59	0.50	<1,172.5	<637.7	<492.4	<2,300.60	727.9	70.3	<42.4	<98.9	<40.4	<42.4	222.9	<6.1	<40.4	<80.7	<38.3	<40.4
Bivalve	59	0.44	<1,315.3	<716.2	<551.8	<2,567.57	<105.9	135.1	<47.3	<110.4	<45.0	<47.3	<40.5	<6.8	<45.0	<90.1	<42.8	<45.0
Bivalve	22	2.34	157.8	119.2	59.9	336.89	11.4	52.2	10.7	<5.1	<0.4	5.8	10.3	38.7	<0.4	27.2	28.6	<0.4
Sculpin	41	5.37	<108.7	<59.2	<45.6	<212.1	<8.77	13.8	<3.91	<9.19	7.40	<3.91	4.12	4.97	<3.70	93.8	15.2	6.9
Pollack	4	2.71	<215.8	296.7	136.5	541.20	23.5	53.6	11.3	<18.1	11.1	19.4	52.5	53.4	9.6	149.7	127.7	61.05
Shrimp	13	1.44	<405.8	<221.0	<170.3	<792.22	<32.7	58.4	23.3	<34.1	<13.9	<14.6	<12.5	4.5	<13.9	<27.8	<13.2	16.74
Zooplankton	57	0.05	3,906.7	3,980.0	<3,260.0	9,516.67	<620.0	376.7	<280.0	<480.0	<40.0	<280.0	150.0	195.0	<40.0	742.3	590.0	760.0
Zooplankton	32	2.27	224.9	160.0	93.8	478.62	13.7	84.2	18.1	30.3	<0.4	20.1	19.6	15.6	111.5	40.1	456.9	300.6
Zooplankton	11	1.63	148.6	442.0	523.7	1,114.31	27.7	58.4	19.6	24.8	NA	NA	NA	1.0	NA	69.8	NA	NA
Neuston	22	0.91	3,110.6	2,892.8	1,453.4	7,456.80	100.9	305.4	91.8	99.9	<4.4	100.2	123.1	143.0	62.6	621.1	503.0	440.4
Phytoplankton	108	0.76	418.6	394.1	258.6	1,071.26	<25.0	81.4	21.1	<18.4	<1.3	11.7	24.2	38.0	<1.3	75.3	51.5	74.1
Phytoplankton	86	0.06	5,812.5	5,387.5	<2,716.67	12,558.33	<516.67	<350.0	<233.33	<400.00	29.17	95.83	141.67	1,056.67	<16.67	379.17	<250.00	175.00
Phytoplankton	69	0.05	5,033.3	4,180.0	2,613.3	11,826.67	<320.0	<220.0	<140.0	<240.0	<20.0	230.0	340.0	999.0	<20.0	1,012.7	2,020.7	2,610.0
Urchins	41	0.67	<865.2	<471.1	<363.0	<1,688.89	<69.6	<47.4	<31.1	<72.6	<29.6	<31.1	<26.7	<4.4	<29.6	<59.3	<28.1	<29.6

HCB = hexachlorobenzene; α -HCH, γ -HCH & β -HCH = alpha, gamma, & beta hexachlorocyclohexane; DDE, DDD & DDT = p,p'-DDE, DDD & DDT; OXY = oxychlordan; cis-CHL = cis-chlordane; trans-CHL = trans-chlordane; trans-NON = trans-nonachlor; cis-NON = cis-nonachlor.

Subchapter 8.2:

Fate of Petroleum Hydrocarbons

8.2.1 Distribution and Sources of Sedimentary Hydrocarbons

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Introduction

The distribution, sources, and fate of natural and anthropogenic hydrocarbons in polar regions are poorly understood. As increased exploration and development of oil and gas reserves in polar regions continue, an understanding of the hydrocarbon geochemistry in these areas is essential. A preliminary study to assess baseline sediment hydrocarbon levels and distributions, sources (including biogenic, anthropogenic, and natural seepage), and potential pathways of hydrocarbon transport was undertaken by Venkatesan and Kaplan (1982) on the outer continental shelf of Alaska. Sediments from the Beaufort Sea, southeastern Bering Sea, Norton Sound, Navarin basin, Gulf of Alaska, Kodiak Shelf, and lower Cook Inlet were collected and analyzed. This study concluded that these areas exhibit little evidence of petroleum hydrocarbons except at a few isolated locations. The sediments contain mixed marine autochthonous and terrestrial allochthonous hydrocarbons. A complex mixture of polynuclear aromatic compounds (PAH), attributed to pyrolytic sources, were detected at all sites. One station in lower Cook Inlet and one in the southeastern Bering Sea had indications of the presence of weathered petroleum.

The present study is a continuation of a program designed to determine the concentrations, distributions, and sources of hydrocarbons in the Bering Sea. Sediment samples were obtained from grab sampler and gravity cores during the Third US-USSR Joint Bering & Chukchi Seas Expedition aboard the Soviet Research Vessel *Akademik Korolev* August 1988.

During a previous joint cruise in July 1984, aliphatic and aromatic hydrocarbons were detected in sediments at all locations sampled in the Bering Sea (Kennicutt *et al.*, 1990). The hydrocarbons were determined to be a mixture of marine biological debris (bacteria, algae, zooplankton, phytoplankton), terrestrial plant biowax (normal alkanes), "recycled" or exposed immature sediments, petroleum (natural seepage), and pyrolytic sources. The levels of hydrocarbons detected were similar to those reported for sediments on the Alaskan outer continental shelf. Unique biological olefins, previously identified in the area, were distributed over a wide area. The relative amounts and composition of hydrocarbons varied widely over the area sampled. The presence of a complete suite of normal alkanes and isoprenoids, an unresolved complex mixture, petroleum related PAH, mature biological markers (hopanes), and vertical distributions of hydrocarbons confirmed the presence of

petroleum at stations in the western and southern Bering Sea. This petroleum is most likely derived from natural seepage from much deeper source rocks and/or reservoir fluids. The petroleum seepage at one southern Bering Sea location is typical of a condensate and is significantly different from that observed at western Bering Sea locations.

Experiment

The analytical methods utilized in this study are described in detail elsewhere (Brooks *et al.*, 1986; Kennicutt *et al.*, 1988). Briefly, sediment samples were freeze-dried, Soxhlet extracted for 12 hours (hexane), and analyzed. Polynuclear aromatic hydrocarbons were detected by spectrofluorescence on a Perkin-Elmer 650-40 fluorometer. Extracts were then analyzed for aliphatic hydrocarbons by gas chromatography with flame ionization detection. Component separations were attained using fused silica capillary columns (DB-5) and temperature programming. Selected sediments were further analyzed by gas chromatography/mass spectrometry (HP 5890/HP5790 MSD) in both scanning and selected ion monitoring modes.

Results and Discussion

One hundred eighty-eight samples from 132 surficial sediment grab samples and gravity cores were taken over a large portion of the Bering and Chukchi Seas (Fig. 1).

Fluorescence

Total scanning fluorescence analysis of sediment extracts shows that varying amounts of petroleum-related hydrocarbons are present throughout the study area (Fig. 2). The majority of fluorescence intensities were less than 400 and represent low level background values. Fluorescence R ratios were highly variable and spanned the range for both condensates and oil (Fig. 2). The average fluorescence maximum excitation and emission wavelengths for the entire study were 340 nm and 380 nm, respectively, typical of petroleum (Fig. 2). The geographic distribution of fluorescence intensities is presented in Fig. 3. These maps, and all subsequent maps, show the highest 25% of the values for the parameter mapped as the dark, shaded areas. Significant geographic variations in both fluorescence intensity and fluorescence R ratios are apparent (Figs. 3,4). The southern portion of the study area had relatively high fluorescence intensities at several locations with a

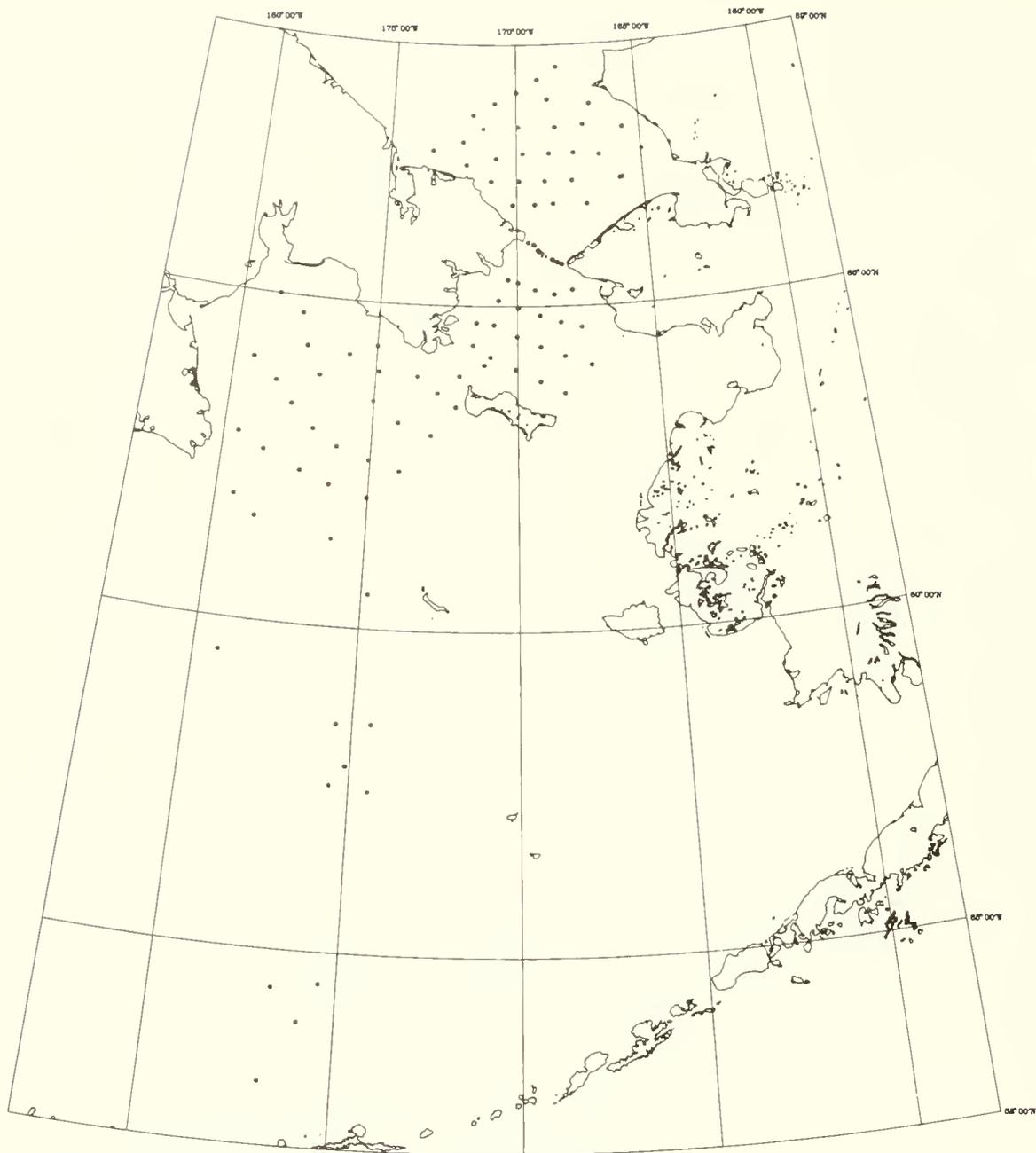


Fig. 1. Location of sediment samples collected in the Bering and Chukchi Seas.

correspondingly low R ratio typical of a condensate. The central and northern portions of the study area have significant relative highs in fluorescence intensity and high R values (>2.0) more typical of an oil signature (see the discussion below).

Gas Chromatography

Gas chromatographic analysis demonstrated that aliphatic hydrocarbons are ubiquitous in sediment extracts throughout the survey area. Normal alkanes were predominantly of terrestrial, biological origin as evidenced by the abundance of compounds with 23, 25, 27, 29, and 31 carbons (Fig. 5). The lower molecular weight alkanes were only a small percentage

of the total n-alkanes in most cases. In general, most alkanes appeared to be of a biological origin, including complex mixtures of normal and branched alkanes and alkenes with 15, 17, and 21 carbons. The presence of petroleum related n-alkanes and/or UCM's were observed in sediment extracts at Stations 22, 32, 33, 45, 67, 92, and 107. In gravity cores the highest concentrations were deep in the core suggesting an upward migration source. A low level unresolved complex mixture was observed at many locations. The geographic distribution of the total unresolved complex mixture is presented in Fig. 6. The co-occurrence of high fluorescence and R ratio values and GC derived indicators confirms the presence of microseepage at several locations.

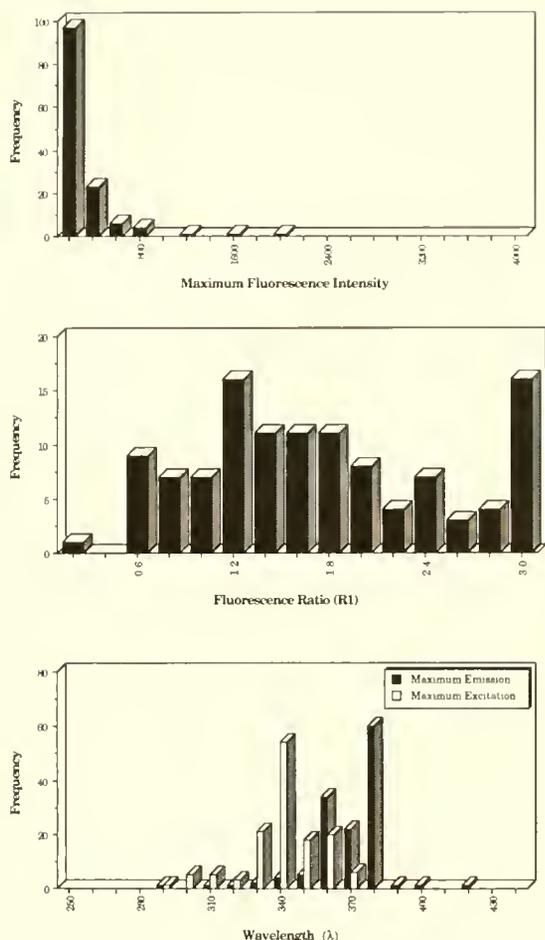


Fig. 2. Summary of fluorescence analysis of sediment extracts from the study area.

Polynuclear Aromatic Hydrocarbons (PAH's)

Quantitative PAH determinations revealed that low levels of PAH were detected throughout the study area. Generally total PAH concentrations were less than 100 ppb (Fig. 7). The highest PAH levels were detected in the deeper sections of gravity cores (averages for all samples at a site were used to produce regional maps)(Fig. 8). In general, relative regional anomalies in fluorescence intensity, UCM, and PAH coincide. Background PAH's, composed primarily of nonalkylated analogues, have been ascribed to pyrogenic sources (Kennicutt & Comet, 1990). This is consistent with much of the low level PAH and fluorescence intensities reported here. Polynuclear aromatic hydrocarbons compositions at locations with total PAH in excess of 100 ppb are more indicative of natural seepage. Macroseepage has been documented to the south and southwest of the present study area. Both oil and condensate seepage was detected and their general locations are consistent with the regional variations observed in the present study (Kennicutt *et al.*, 1990).

Biomarker Analysis

The previous reports of significant amounts of unique biologically-derived aliphatic hydrocarbons in the eastern Bering Sea was confirmed. Many of the sediment extracts contain compounds previously identified as olefins. A tetraene (Kovats Index [KI] = 2657), squalene (KI = 2895), and a C30

bicyclic tetraene (KI = 3027) are believed to be due to inputs from zooplankton and/or phytoplankton. These compounds were detected at most locations though concentrations varied widely. A suite of hopenes, moretanes, and $\beta\beta$ -hopanes were present at several locations and appear to represent a recent background biological marker mixture. This background may represent erosionally exposed, in place, sediments or materials from the surrounding land masses that have been transported to the site of deposition (i.e., recycled). The precursor functionalized hopanoids and steroids representative of unaltered biolipids were not determined by the analytical methods utilized in this study. The hopanoid compounds most likely represent early alteration products of biogenic lipids of bacterial and/or algal origin. In contrast to these immature markers, overprinting by 17α , 21β hopanes; diasteranes; and steranes ($\alpha\alpha\alpha$ and $\alpha\beta\beta$) are evident at sites suspected of containing mature, migrated petroleum (Table 1). These mature biomarkers, which are only produced when temperatures are substantially higher than in these near-surface sediments, are present in extracts from a few stations (Table 1). These mature petroleum hydrocarbons—derived from a much deeper, higher temperature source—overprint the *in situ* biological and “recycled” immature lipids.

Conclusions

Aliphatic and aromatic hydrocarbons were widely detected at locations sampled in the Bering and Chukchi Seas. The hydrocarbons are a mixture of marine biological debris (bacteria, algae, zooplankton, phytoplankton), terrestrial plant biowaxes

TABLE 1

Core #	Presence (+, ++, +++) or absence (-) of selected mature biomarkers in Bering Sea extracts.			
	Triterpanes (m/z = 191)	Steranes (m/z = 217)	Monoaromatic Steranes (m/z = 253)	Tiraromatic Steranes (m/z = 231)
3	-	+	-	-
7	-	+	-	-
19	-	-	-	-
22	++	+++	-	-
32	+++	+++	-	++
45	++	+	-	-
47	-	++	-	-
49	-	+	-	-
50	-	-	-	-
53	-	-	-	-
66	-	-	-	-
74	-	-	-	-
79	-	-	-	-
81	-	-	-	-
92	-	-	-	-
97	-	-	-	-
109	-	-	-	-
110	-	+	-	-
21	-	-	-	-

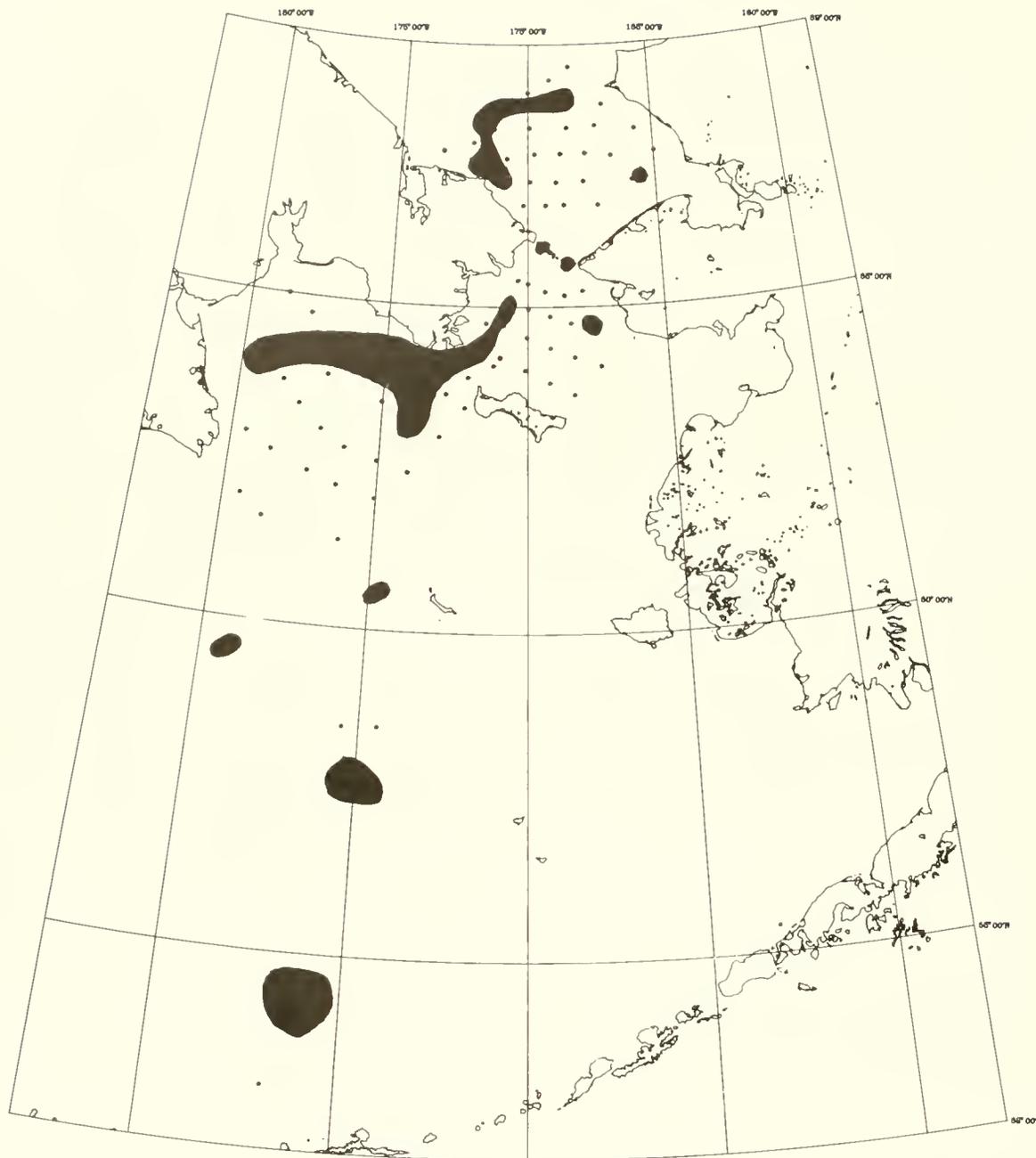


Fig. 3. Geographic distribution of sediment extract fluorescence intensity from the study area (contour indicates the highest 25% of the values, >300).

(normal alkanes), "recycled" or exposed immature sediments, petroleum (natural seepage), and pyrolytic sources. The relative amounts and composition of hydrocarbons varied widely over the area sampled. The presence of a complete suite of normal alkanes and isoprenoids, an unresolved complex mixture, petroleum related PAH's, mature biological markers (hopanes and steranes), and vertical distributions of hydrocarbons in cores confirm the presence of petroleum related hydrocarbons at several locations. This petroleum is most likely derived from natural seepage from much deeper source rocks and/or

reservoired fluids. Significant geographic variations were noted in all parameters measured and definable regional highs were apparent. The coincidence of fluorescence and GC derived petroleum indicators provides confirmatory information on the presence of mature petroleum hydrocarbons at several locations. These regional highs were lower than previously reported macroseepage to the south and southwest survey. When present, mature biological marker distributions were similar in general, suggesting a common source for the migrated hydrocarbons.



Fig. 4. Geographic distribution of sediment extract fluorescence ratios from the study area (contour indicates the highest 25% of the values, >0.21).

Average Alkane Concentration (ppb)

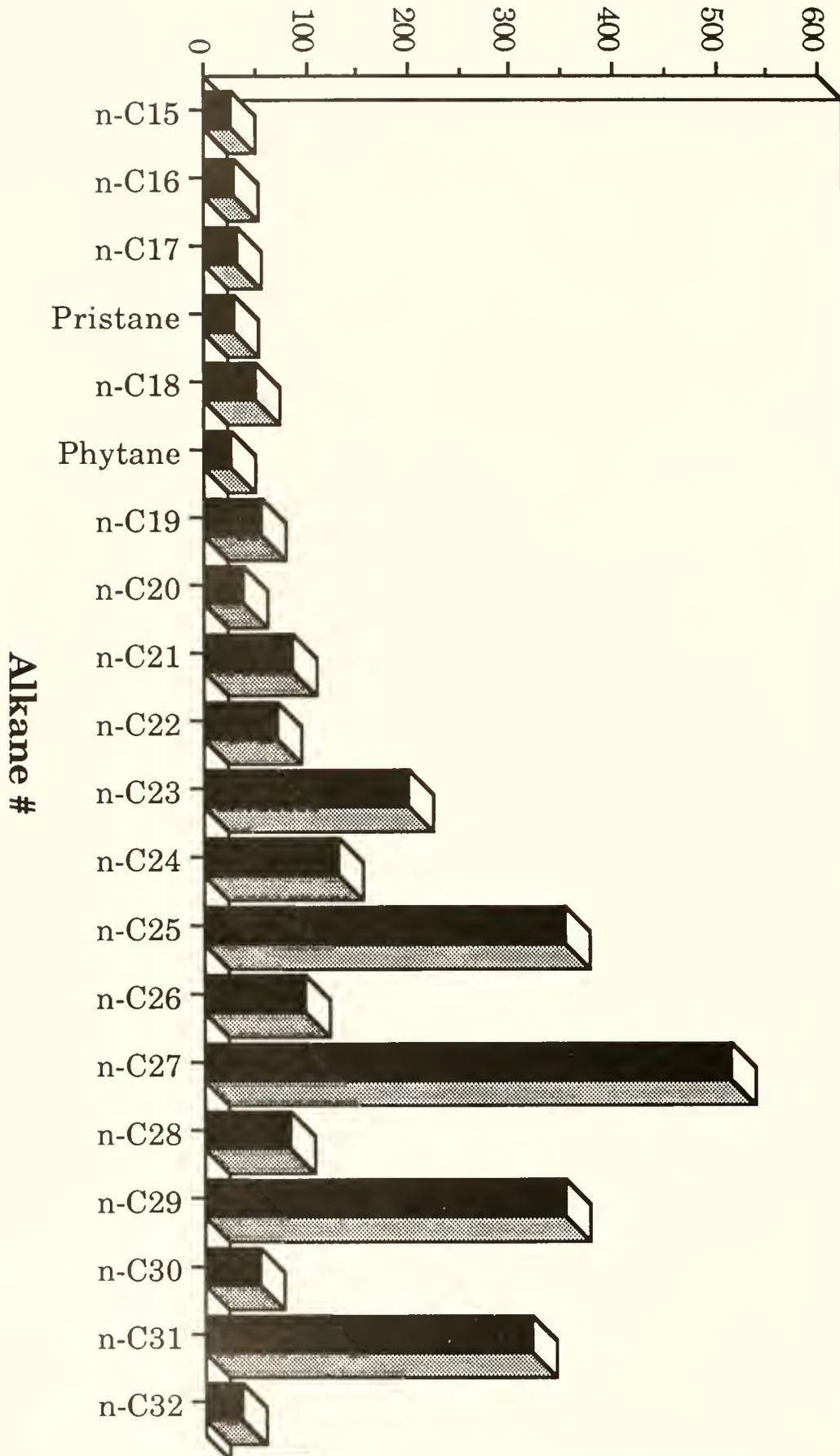


Fig. 5. Summary of the average n-alkane distribution and concentration for all sites sampled.



Fig. 6. Geographic distribution of sediment extract unresolved complex mixture (UCM) concentrations by GC/FID from the study area.

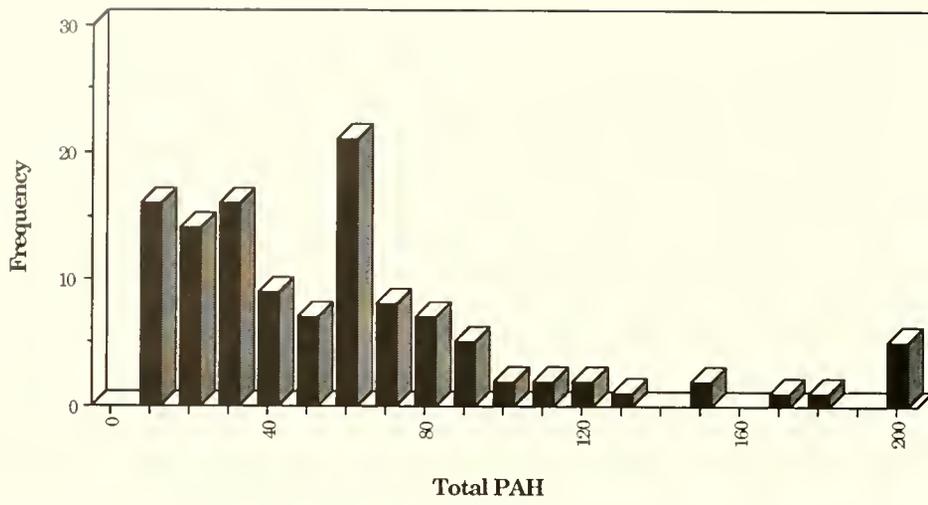


Fig. 7 Summary of sediment extract total polynuclear aromatic hydrocarbon (PAH) concentrations from the study area.

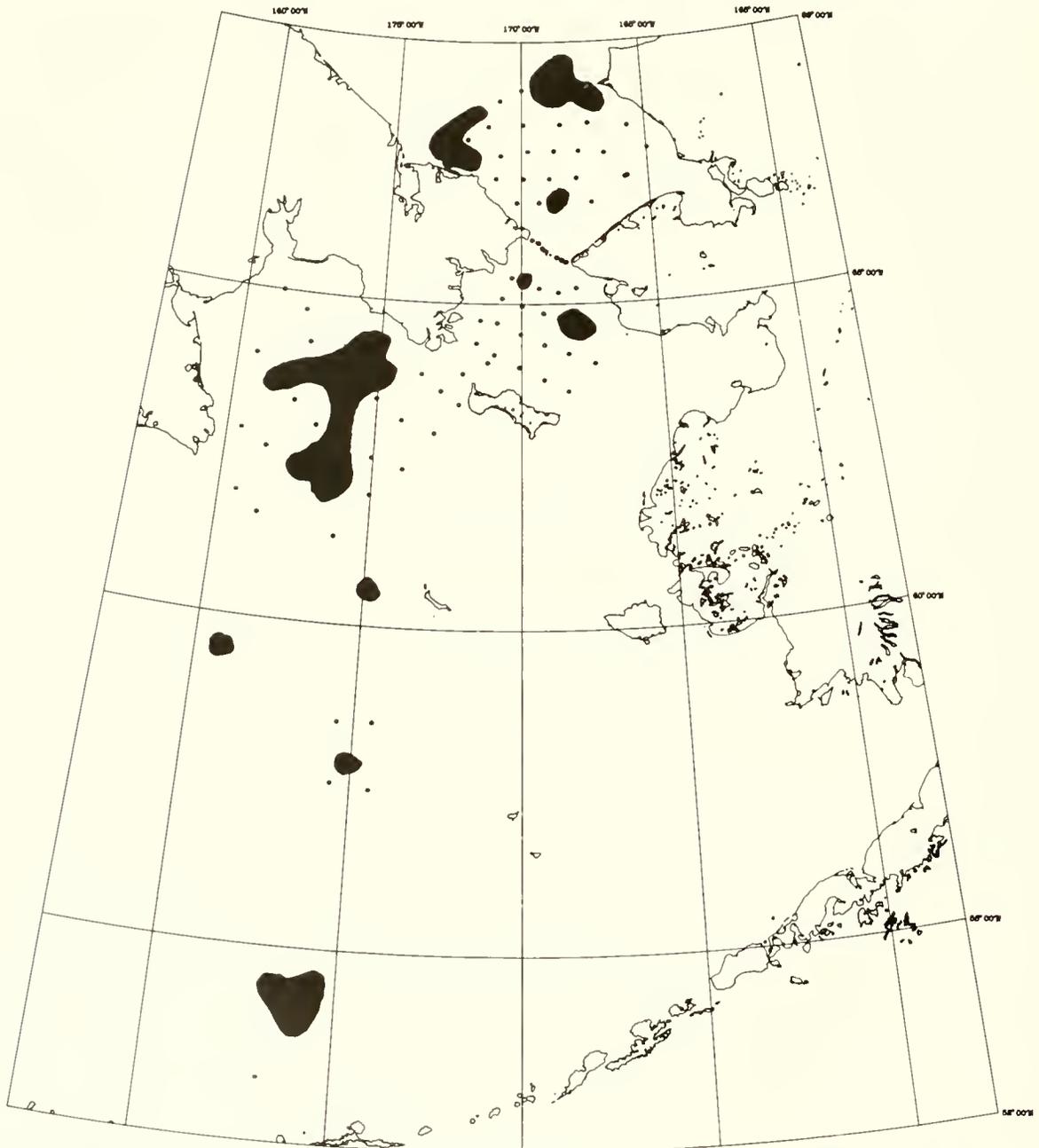


Fig. 8. Geographic distribution of sediment extract (PAH) concentrations for the study area (contour indicates the highest 25% of the values, >65 ppb).

8.2.2 Distribution of PAH's

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Introduction

Among the more than 50,000 known pollutants in the hydrosphere, the carcinogenic polycyclic aromatic hydrocarbons (PAH's) are detected in almost all compartments of marine ecosystems. The pathways for the movement of PAH's into seawater is still a subject of much discussion by the scientific community. Human activities (Kirso *et al.*, 1988) and natural processes (Lisitsyn, 1989) are considered two likeliest routes. A large amount of data has been obtained on the regularities of the distribution of a typical carcinogenic PAH—benzo(a)pyrene (BaP)—in the marine environment. In order to describe the modern distribution of PAH's, one must consider historical changes in man's culture (Izrael & Tsyban, 1985a). Due to their high hydrophobicity and low solubility, the investigation of PAH's in contact zones of the ocean (Vinogradov, 1990) (i.e., at the sediment-water and air-water interfaces, where so-called zones of 'condensed life' have been observed) are of interest (Fig. 1).

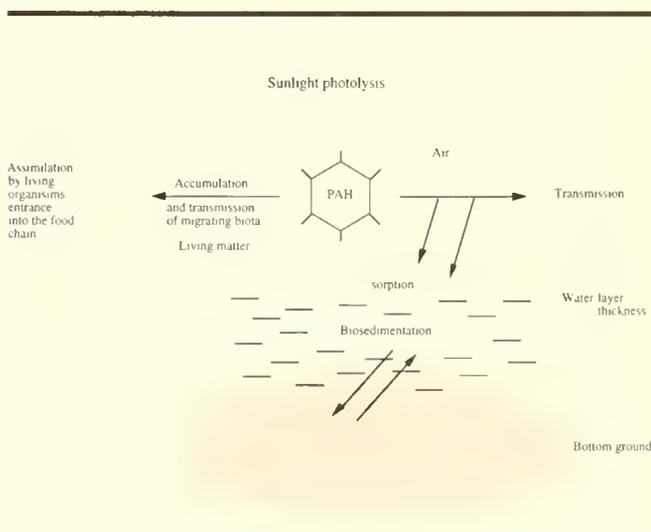


Fig. 1. Scheme of natural agents contributing to the transformation of PAH in marine ecosystems.

To obtain further information on the characteristics of the spatial and temporal variations in PAH pollution, a complex study of PAH concentration in the ecosystem of the Bering and Chukchi Seas (specifically the suspended matter, bottom sediments, and biota) during the cruise of the R/V *Akademik Korolev* was undertaken (47th cruise, July–November 1988).

Sampling, Processing, and Analysis of Samples

Sampling

Preparation and analysis of samples of water, bottom sediments, plankton, benthos, and hydrobionts were carried out using standard methods (Tsyban *et al.*, 1988). All the solvents used were preliminarily purified by passing them through activated carbon.

To take samples from the surface microlayer (SML), a metal screen (cells 2×2 mm) was pulled horizontally across the sea surface. Samples from the other horizons were taken using a standard water sampler. The bottom sediments were taken with a dredge. These samples were dried at 50–60°C and stored in polyethylene bags.

Suspended matter samples were taken from different horizons by means of a 'Midia' pump equipped with filters 0.5 μ m in pore diameter. The filters were previously purified with hexane. The filters with suspended matter were dried at room temperature and stored in polyethylene bags. Plankton and neuston samples were collected with plankton nets, and benthos were collected with a bottom trawl. Plankton and neuston samples were collected on filter paper and dried on foil in a drying oven.

Extraction

Water (2.5–5.0 l) was twice extracted with hexane (100 ml each) with a magnetic stirrer for 2 h. The combined extracts were dewatered with sodium sulphate, evaporated to 0.1 ml and dried at room temperature. Bottom sediment samples (10.0 g) were extracted with 50 ml benzene under static conditions at room temperature in the dark for 48 h. The solids were removed and the extract was evaporated to 1–2 ml. Air-dried samples of plankton, neuston, and benthos tissues were saponified with a 92% ethanol-KOH mixture (25 ml of ethanol and 1 g of KOH per g of sample) at 45°C in a water bath for 48 h. The hydrolysate was extracted with hexane (10 ml each); the extract was concentrated and dried.

Chromatographic fractionation of the extracts was carried out using thin layer chromatography plates, which were coated with aluminum oxide. The solvents for developing the plates were chosen as follows:

- for separation of total PAH fractions, used a benzene:acetone mixture (9:1).
- for separation of BaP, used a mixture of petroleum ether (fraction 40–70°) and chloroform (9:1).

The zones containing the PAH's on the plate was marked using fluorescence UV-irradiation ($\lambda_{\max} \sim 360$ nm).

For identifying BaP, a BaP standard was used (a BaP solution in benzene, concentration 5×10^{-4} g/ml). The zone containing PAH's was collected and washed off with a 1:1 mixture of benzene:acetone. The extract was evaporated and

dried at room temperature. A quantitative determination of BaP was performed using the spectral-luminescence methods based on the measurement of the relative intensity of the luminescence of the BaP solution in n-octane and using benzo(ghi)perylene (BPer) as an internal standard, which was frozen at -196°C. (Shpolshy effect-[Fedoseyeva and Khesina, 1968]).

A quantitative determination of the other PAH's was carried out using high-performance liquid chromatography (HPLC). A mixture of PAH's similar in composition to known environmental pollutants served as standards [US NIST Standard Reference Material, SRM-1647a]. The determination of the PAH's was carried out starting with pyrene, which was the first to elute from the column.

Conditions of Analysis

Dry samples were dissolved in 0.2 ml of acetonitrile and introduced into a "Knauer" liquid chromatograph equipped with a 'Kratos' fluorescence detector. The excitation and emissions wavelengths were 295 nm and 418 nm; the eluent solution was 95% methanol in water at a flow-rate of 0.5 ml/min through a (25 × 0.25-cm) 'Perkin Elmer' Sil ODS column. The absolute calibration method was used for the determination. The sensitivity was 10⁻⁹ g.

Results and Discussion

In the water, sediments, suspended matter, and biota of the Bering and Chukchi Seas, 10 PAH's were identified, of which eight are carcinogenic and three of these (viz., benzo(b)fluoranthene [BbF], benzo(k)fluoranthene [BkF] and BaP) are highly carcinogenic (Table 1).

PAH's in Water

In the Bering Sea and the Bering Strait, the PAH concentration in water was below the sensitivity of the HPLC method. In the northwestern Bering Sea and eastward from St. Lawrence Island, the surface and near-bottom water contained a high concentration of PAH's (from 0.5 to 149.2 ng/l) which were made up of seven representatives of four- and five-nucleated PAH's (Table 2). In the surface layer the following compounds prevailed (wt. %): benzo(e)pyrene [BeP] 40.3, pyrene [P] 35.14; the concentration of other PAH's was as follows: BbF, 17.6; BaP, 4.76; and BkF, 2.2%. In the near-bottom layer, the distribution of PAH's was the following: BeP, 47.43; benz(a)anthracene [BaA] and chrysene [Chr], 40.4; Py, 7.67; BbF, 2.7; BaP, 1.9; and BkF, 0.2.

Thus, the concentration of PAH's in surface and near-bottom layers differed. In the water of the central, southern, and partly northeastern areas of the Bering Sea and the Bering Strait, insignificant amounts of BaP were detected (Table 3), not exceeding the background level. In most cases, the PAH concentration in the surface water layer was twice as high as that in the near-bottom layer. While in the central part of the Bering Sea (Fig. 2), the BaP concentration increased 10-fold from the top to the bottom (e.g., Station 6 increased from 0.1 ng/l at the surface to 1.02 ng/l in the deepest sample).

Table 1

List of specific PAH's identified by displacement-elutonal liquid chromatography

Name	Symbol	Structural formula	Carcinogenicity (Lee <i>et al.</i> , 1981)
Pyrene	Py		0
Chrysene	Chr		+
Benz(a)anthracene	BaA		+
Benzo(e)pyrene	BeP		0/+
Benzo(b)fluoranthene	BbF		++
Benzo(k)fluoranthene	BkF		++
Benzo(a)pyrene	BaP		++
Benzo(g,h,i)perylene	BPer		+
Dibenz(a,h)anthracene	DBA		+
Indeno(1,2,3-cd)pyrene	IPy		+
			
Note			
Classification	Symbol		Criterion % of animals that developed lesions
noncarcinogenic	0		0
weakly carcinogenic	+		33
strongly carcinogenic	++		>33

According to our data the total concentration of PAH's in the SML in that same area was also below the sensitivity of HPLC, but the concentration of BaP (Fig. 3) is ×3 as high as that in the surface layer; however, they did not exceed the values established for SML in the other oceanic environments (Anikejev & Urbanovitch, 1989). The concentration of PAH's in the Chukchi Sea waters was also often below the sensitivity of HPLC method. In the water of the southeastern part of this sea, the same 4- to 5-nucleated PAH's were identified as in the Bering Sea (Table 2): Py, BaA, Chr, BeP, BkF, BaP. Their overall concentration in the surface water layers did not exceed 5.1 ng/l, but in the near-bottom layer it reached 24 ng/l, which is considerably lower than the respective values for the Bering Sea. Five-nucleated PAH's accounted for the major portion of the total concentration of PAH in the surface layer (wt %): BeP, 72; BbF, 28. Benzo(a)pyrene, BaA, and Chr were present in trace amounts and the near-bottom layer was characterized by the following pattern: BeP, BbF, and BaP which accounted for 72, 23, and 5%, respectively. Benzo(a)anthracene and BkF were present in trace amounts. The abundance of BaP in the surface water layers in the Chukchi Sea area, where the level of PAH was below the sensitivity of HPLC, was also insignificant being lower than for the Bering Sea (Table 3). However, in the near-bottom layers of both seas, its level was the same. It should be mentioned that the concentration of BaP in ice samples was somewhat higher than in the surface water layers (Fig. 4) and it increased with depth.

TABLE 2

PAH concentration (ng/l) in the Bering (1) and Chukchi (2) Sea waters (47th cruise of the R/V *Akademik Korolev*, July–November 1988).

Indices	Py		BaA+ Chr		BeP		BkF		BbF		BaP	
	1	2	1	2	1	2	1	2	1	2	1	2
surface layer (0–0.5 m) n*	2	-	5	1	3	1	3	1	4	1	6	15
minimum	3.4	-	traces	-	3.8	-	0.1	traces	0.1	-	0.07	0.01
maximum	4.1	-	q*	q	5.2	3.3	0.5	-	6.4	1.8	1.6	0.5
average	3.8	-	-	-	4.3	-	0.2	-	1.9	-	0.5	0.2
standard deviation	0.5	-	-	-	0.8	-	0.2	-	3.0	-	0.5	0.2
near-bottom layer n*	3	2	2	2	4	2	5	3	7	3	7	13
minimum	1.6	q	4.7	q	2.3	2.0	0.02	traces	0.2	1.2	0.2	0.01
maximum	7.0	15.0	56.0	3.7	88.4	10.0	0.3	0.1	4.3	3.2	2.4	0.6
average	4.5	-	30.3	-	28.0	6.2	0.1	-	1.6	2.3	0.8	0.2
standard deviation	2.72	-	36.3	-	40.6	5.3	0.1	-	1.4	1.0	0.8	0.2

n* - number of points

q* - qualitative

TABLE 3

Concentration of BaP (ng/l) in surface (1) and boundary bottom (2) water layers of the Bering Sea, the Bering Strait and the Chukchi Sea (August 1988).

Object	1			2		
	Number of Points	Limits	Average ± standard dev.	Number of Points	Limits	Average ± standard dev.
Bering Sea	19	up to 0.78	0.32 ± 0.24	12	up to 0.74	0.19 ± 0.20
Bering Strait	4	0.14–1.60	0.57 ± 0.69	4	0.10–0.31	0.23 ± 0.12
Chukchi Sea	15	up to 0.51	0.20 ± 0.19	13	up to 0.63	0.20 ± 0.17

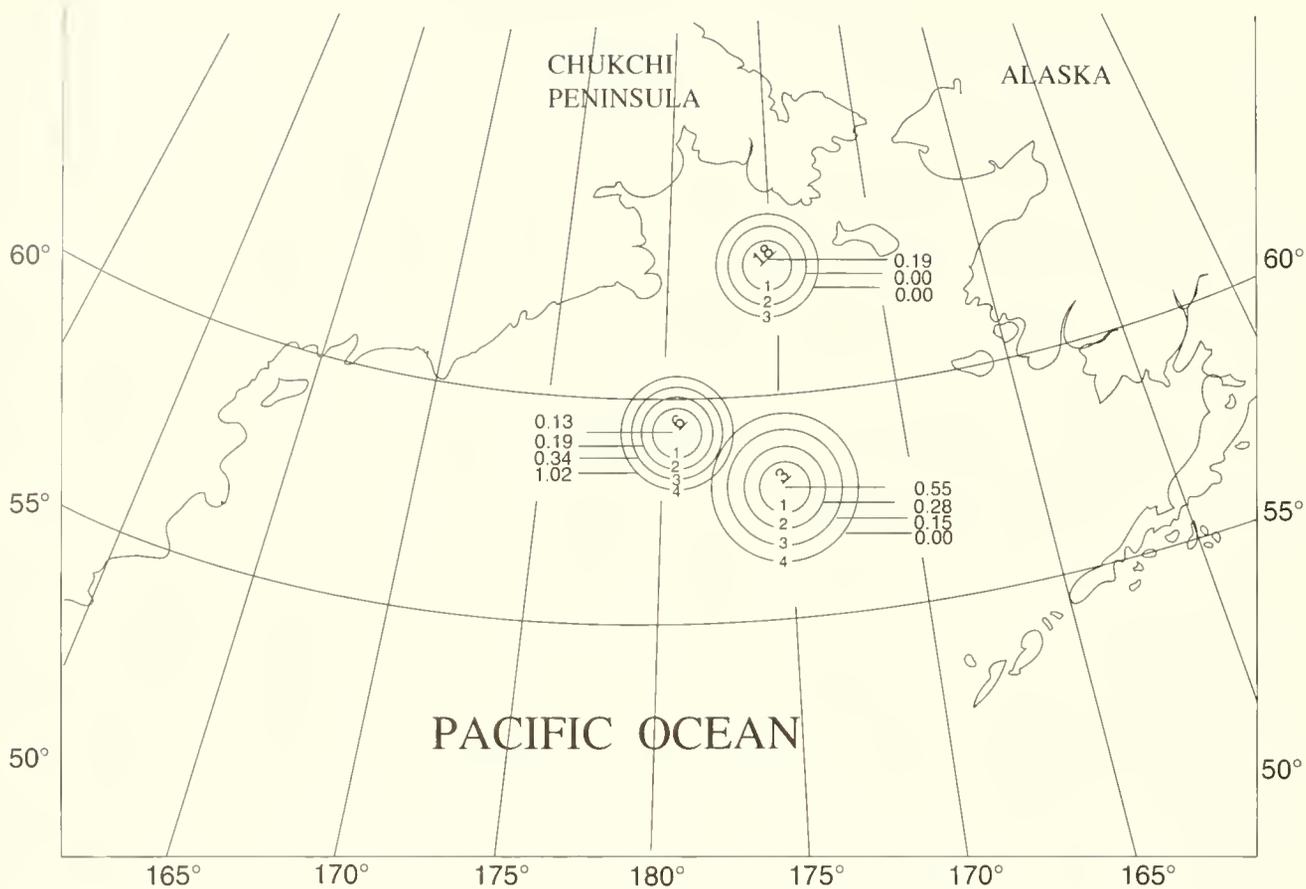


Fig. 2. BaP concentration (ng/l) in the Bering Sea waters depending on depth (m). Station 3: (1) 0-0.5; (2) 45; (3) 100; (4) near the bottom layer. Station 6: (1) 0-0.5; (2) 10; (3) 45; (4) 100. Station 18: (1) 0-0.5; (2) 45; (3) 70.

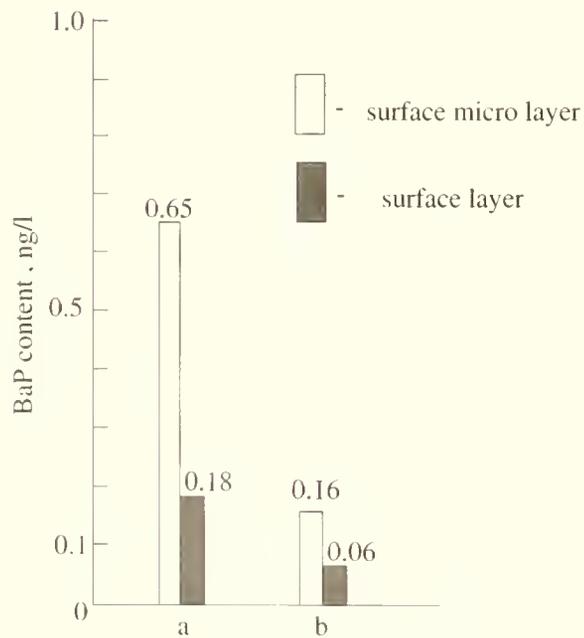


Fig. 3. BaP concentration (ng/l) in surface microlayer and surface water samples in the Bering Sea (a = Station 110, b = Station 24).

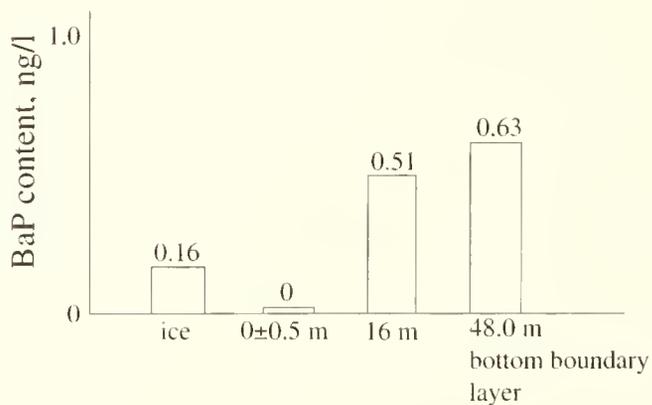


Fig. 4. BaP concentration (ng/l) in ice and water samples from different horizons of the Chukchi Sea (Station 15).

PAH's in Suspension

It is known that PAH's, being of poor water solubility, are readily sorbed onto suspended particulate matter, accumulated in bottom sediments and are sorbed by biota (Fig. 1). In the Bering Sea and the Bering Strait, five suspended matter samples were collected at depths of 70 and 170 m. The total concentration of PAH's in the suspended matter of the surface layer reached 1,620 ng/g, but in deeper horizons the maximum was only up to 1,018 ng/g (Station 110).

In the samples at the surface in the Bering Sea the following 4-6-nucleated PAH's (Table 4) were identified (wt %): BaA plus Chr, 19.8; Py, 44.8; BeP, 22.0; BbF, 14.8; BaP, 12.8; and BkF, 2.5. It should be noted that the weight composition of PAH's in these suspended sediment samples varied within a wide range depending on the regions sampled; for example, at some locations the concentration of BbF reached 48%, that of BaA plus Chr, 42%, and BeP, 22%. At the same time, at deeper horizons, BeP concentration increased up to 78% of the total PAH's concentration and, correspondingly, the percent composition of the above PAH's decreased. The BaP concentration in the suspended matter never exceeded 15% of total PAH concentration.

In the Chukchi Sea the concentration of total PAH's in suspended matter in the upper horizons, Station 45, was 3,544 ng/g, and at 40 m it was 89.0 ng/g. The PAH's in the suspended matter samples at the surface from the western part of this sea contained the same 4- to 6-nucleated PAH's as were identified in the Bering Sea (Table 2) (wt %): BaA plus Chr, 16.4; BkF, 1.6; BaP, 2.2; BeP, 8.5; BbF, 0.33; and P was qualitatively identified. However, among the PAH's, dibenz(a)anthracene [DBA] prevailed, whose concentration reached 71%. In the surface layer, BaA and Chr predominated, their concentration reaching 69% of the total PAH concentration, that of BbF was 20%. At deeper horizons, as a rule—BbF and BaP in the suspended matter averaged 30% of the total PAH's. Thus, the suspended matter of the Bering and Chukchi Seas contained a wide range of 4-6-nucleated PAH's. The composition and ratio of PAH's differed depending on depth and sampling area.

PAH's in Biota

The concentration of PAH's in the biota, as in the other elements of the ecosystem of the Bering and Chukchi Seas, is low, generally below the sensitivity of HPLC. The BaP

TABLE 4

PAH content in the suspension (ng/g) of the Bering (1) and Chukchi (2) Seas (47th cruise of the R/V Akademik Korolev, July–November 1988).

Indices	Py		BaA+Chr		BPer		BkF		BbF		BaP		BeP		DBA		
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	
0 m	n*	3	1	3	1	3	-	3	1	3	1	3	1	3	1	-	1
minimum	q*	-	-	tr.	-	-	-	6.0	-	19.8	-	tr.	-	-	-	-	-
maximum		1000	-	59.4	-	57.4	-	41.0	-	204	-	124	-	495	-	-	-
average		337	q*	19.8	581	19.1	-	19.0	5.8	111	8.1	80.8	79.1	165	302	-	2560
standard deviation		583	-	34.3	-	33.1	-	19.0	-	92.2	70.0	0.09	-	-	-	-	1.5
40, 70 m	n*	1	-	1	-	-	-	-	-	1	1	1	1	-	-	-	1
minimum		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
maximum		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.6
average	q*	-	-	q*	-	-	-	-	-	149	89.0	104	tr.	-	896	-	-
standard deviation		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
170 m	n*	1	-	-	-	-	-	1	-	1	-	1	-	1	-	-	-
minimum		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
maximum		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average	q*	-	-	-	-	-	-	18.5	-	259	-	148	-	593	-	-	-
standard deviation		-	-	-	-	-	-	-	-	-	0.1	-	0.07	0.06	-	-	-

n* - number of points

q* - qualitative

tr. - traces

TABLE 5

Concentration of BaP (ng/l) in surface (1) and boundary bottom (2) water layers of the Bering Sea, the Bering Strait and the Chukchi Sea (August 1988).

Object	1				2			
	Number of Points	min max	average	standard dev.	Number of Points	min max	average	standard dev.
Plankton	12	0.4-10.6	3.0	2.9	10	0.22-12.6	2.8	3.9
Zooplankton	9	0.5-8.4	2.2	2.4	-	-	-	-
Neuston	9	up to 10.0	2.6	3.0	7	0.6-1.9	2.0	2.6

concentration (Table 5) in the biota of these regions varied depending on where the samples were taken, as did its average concentration; however, they never exceeded 3.0 µg/kg dry wt. In the plankton and neuston of the Bering and Chukchi Seas seven 4- to 6-nucleated PAH's were detected (Table 6). The total PAH concentration in the plankton of the Bering Seas ranged from 40 to 480, but in the neuston from 26 to 114.8 µg/kg on a dry weight basis. As shown in Table 6, the major PAH's in the plankton of the Bering Sea were 4- to 5-nucleated compounds, (wt %): Chr, 40; BaA, 24.6; BbF, 22; BaP, 11.8; and BkF, 1.6. Also BPer, Indeno(123cd)pyrene [IP], and BeP were detected in the phytoneuston of the northwestern part of the Bering Sea.

The total PAH concentration in the neuston of the Bering Sea, as a rule, was somewhat lower than in the plankton and varied from 11 to 115 µg/kg on dry wt. basis. The total concentration of PAH's in the neuston from the northwestern part of the Bering Sea exceeded its concentration in the plankton by a factor of 15–20. However, the composition and ratio of PAH's were nearly identical for both the neuston and the plankton; BaA plus Chr, 41; BbF, 36; BkF, 38; and BaP, 18.2. In the biota of the Chukchi Sea, the composition and

distribution of PAH's was somewhat different from those in the Bering Sea.

The total concentration of PAH's in the plankton varied widely, viz., from 12 to 677. For the neuston, they ranged from 20 to 188 µg/kg on a dry weight basis. The percent weight of individual PAH's in the plankton samples was 41 for Chr, 26 for BbF, 21.9 for BeP, and 1.1 for BaP. In some cases, trace amounts of BPer and IP were detected in plankton, and in one case BeP was detected.

In the neuston, PAH's are represented mainly by 4- to 5-nucleated compounds with the distribution (wt%) being BbF (37.6%), BaA plus Chr (29%), BaP (25.8%), and BkF (75%). Thus, in the biota of the ecosystem of the Bering and Chukchi Seas, 4- to 5-nucleated carcinogenic PAH's are most common, with Chr, BaA, and BbF predominating (Fig. 5).

PAH's in Bottom Sediment

The concentration of PAH's in sediment of the Bering Sea varied from 0 to 1.7 µg/kg on a dry wt. basis. The maximum of 1.7 µg/kg was detected northwest of St. Lawrence Island (Station 32), which is considerably lower than for the Baltic Sea (Kirso *et al.*, 1985).

TABLE 6
PAH concentration in the biota (ng/l) of the Bering (1) and Chukchi (2) Seas (47th cruise of the R/V Akademik Korolev, July–November 1988).

Indices	BaA/ Chr		BPer		BkF		BbF		BaP		BeP		IP	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Plankton n*	5/4	-/4	1	-	3	4	6	4	5	4	1	1	1	1
minimum	0.1/2.7	-/1.0	-	-	0.1	0.6	1.7	0.5	0.6	0.01	-	-	-	-
maximum	118/189	-/178.0	71.0	-	10.0	2.4	116.0	136.0	48.0	91.0	27.0	272.0	80.0	2.9
average	51/83	-/47	-	-	3.4	1.3	46.0	41.0	24.4	24.7	-	-	-	-
standard deviation	57.0/94.0	-/87.0	-	-	5.7	0.9	50.0	64.0	31.0	44.2	-	-	-	-
Neuston n*	2	4	-	1	2	4	2	4	2	4	1	1	-	-
minimum	15.7	0.01	-	-	0.8	0.01	5.3	2.9	4.5	0.01	-	-	-	-
maximum	32.0	18.0	-	49.0	3.7	1.8	35.6	31.8	16.5	7.6	27.0	65.0	-	-
average	23.8	9.7	-	-	2.2	2.5	20.4	12.4	10.5	8.4	-	-	-	-
standard deviation	11.5	6.9	-	-	2.1	3.0	21.4	11.7	8.5	8.3	-	-	-	-

n* - number of points

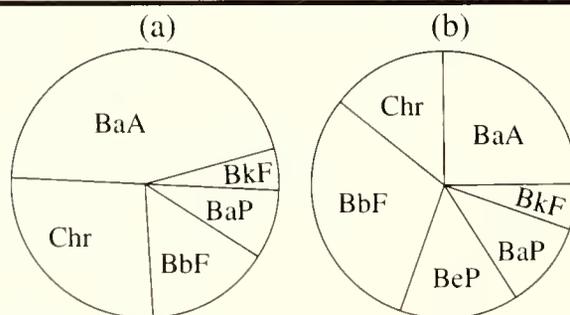


Fig. 5. Distribution of PAH's (wt%) in the biota of the Bering Strait (Station 83); plankton (a), neuston (b).

In sediments in the southwestern parts of the Bering Sea and the Bering Strait, the PAH concentration is primarily below the detection limits of the method. At the same time, seven PAH's were detected near St. Lawrence Island and northeast of there (Table 7). Their total concentration ranged from 0.87 to 4.8 $\mu\text{g}/\text{kg}$ on a dry wt. basis, while BbF accounted for the major part (up to 66.77%). In addition to the PAH's listed in Table 7, low amounts of BaA and IP were detected in the southeastern part of the Bering (up to 10 and 10.48 wt%, respectively). The total PAH concentration in the sediment of the Chukchi Sea varied from 8.3 to 76.4 $\mu\text{g}/\text{kg}$ on a dry wt. basis. These values were higher than for the Bering Sea, and BbF accounted for 56.4% of this total. Seven representatives of the 4- to 5-nucleated PAH's were identified.

Benzo(a)pyrene was present in nearly all of the sediment samples from the Chukchi Sea. The highest was 4.5 $\mu\text{g}/\text{kg}$ on a dry wt. basis (Station 40) which is about $\times 3$ higher than was measured in the sediment samples from the Bering Sea.

Published data (Malins *et al.*, 1985; Israel & Tsyban, 1987; Kirso *et al.*, 1988) and those obtained by us show a relatively low level of PAH pollution of water, biota, and sediments in the Bering and Chukchi Seas. Of more concern, however, is the accumulation of the dangerous carcinogen BbF (Fig. 6) which was observed in these ecosystems both in the process of circulation and in biosedimentation.

Apparently entering into the marine environment as part of oil pollution, BbF appears to have become concentrated in the neuston, suspended matter, and bottom sediments of these regions. Minor portions also seem to reenter the surface layer. Finally, this carcinogen enters the food chain making it a possible risk to man under the right conditions.

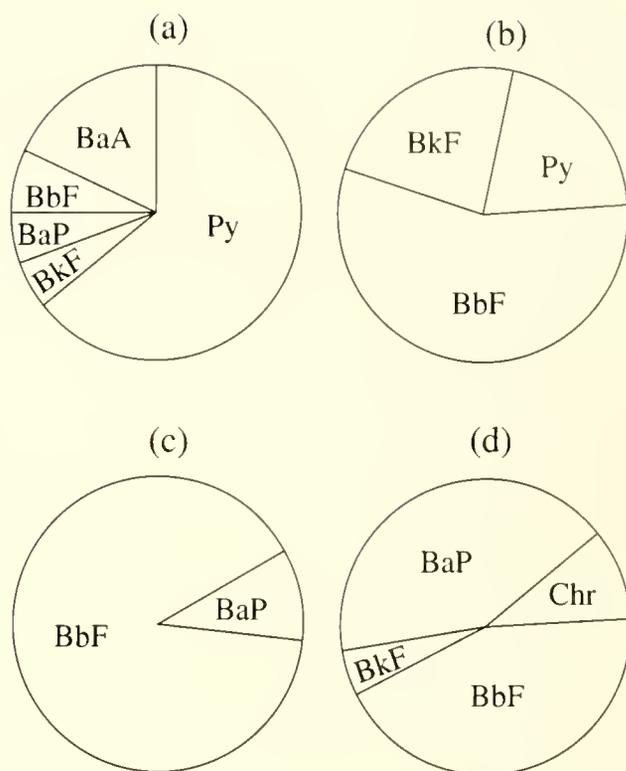


Fig. 6. Distribution of PAH's (wt%) in compartments of the ecosystem of the Chukchi Sea (Station 74): near bottom layer (a); sediment (b); suspended matter (c); neuston (d).

TABLE 7

Concentration (%) of individual compounds of total PAH concentration in the bottom sediments of the Bering Sea, the Bering Strait and the Chukchi Sea.

Station No.	Total PAH concentration ($\mu\text{g}/\text{kg}$ dry wt.)	Py	BbF	BkF	BaP	BeP	BPer	DBA
49	3.56	-	37.35	8.43	54.21	-	-	-
52	13.20	78.79	21.21	-	-	-	-	-
53	3.20	-	56.25	5.62	6.88	-	-	31.25
64	25.35	22.09	33.14	1.45	0.71	31.56	11.04	-
67	76.40	17.02	31.41	2.62	-	18.06	10.73	-
69	24.83	39.47	56.39	1.03	3.14	-	-	-
77	3.56	-	50.56	5.06	16.29	-	-	28.08
96	0.87	-	41.38	19.54	39.00	-	-	-
100	1.16	-	45.69	18.96	35.35	-	-	-
104	4.34	-	-	43.78	3.22	-	53.00	-
106	4.80	-	66.66	-	33.34	-	-	-

8.2.3 Distribution of Benzo(a)pyrene and other Polycyclic Aromatic Hydrocarbons

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Introduction

In the recent decade, the impact of various social and economic factors on the environment has caused certain negative consequences, including changes in the natural chemical background caused by growing entrainment of pollutants in natural ecosystems. Pollutants, first propagating on the land and in the atmosphere, come by various routes to the world oceans and, in the long run, circulate within them (Izrael & Tsyban, 1989). Coastal regions rapidly accumulate pollutants to critical levels producing irreversible changes in the functioning of marine ecosystems. In open regions of the oceans, aquatic organisms and ecosystems as a whole begin to suffer from a constant impact of low intensity factors such as low doses of toxicants.

Among numerous organic pollutants causing dangerous changes in the chemistry and biology of the marine environment, a unique role is played by polycyclic aromatic hydrocarbons (PAH's), including both the natural and anthropogenic-derived materials. With a significant molecular stability as well as pronounced carcinogenic and mutagenic effect, these chemicals present a great danger to the existence of marine organisms.

The most characteristic and widely spread chemical of this series is benzo(a)pyrene (BaP), which is widely accepted as an indicator of environmental pollution by carcinogenic PAH's (Izrael & Tsyban, 1989).

Benzo(a)pyrene and PAH's are found in many compartments of sea ecosystems from Arctic (Mallet *et al.*, 1979) to Antarctic latitudes (Clark *et al.*, 1981). Entrainment of PAH's in the currents of these systems causes their further circulation throughout the seas. One of the consequences of these processes is accumulation of carcinogenic PAH's in traditional marine products: plants and animals sold in commerce (Corner, 1975; Mix *et al.*, 1983), which ultimately threaten the health of human beings.

There are many publications on the distribution of these dangerous chemicals in hydrosystems; however, there is an obvious shortage of systematic information on the patterns and origins of biogeochemical cycles in the ocean ecosystems.

This paper considers individual results from investigating biogeochemical cycles in the ecosystems of the Bering and Chukchi Seas. Distribution and accumulation of these toxic chemicals in components of marine ecosystems (in the water, surface layers, sediments, plankton, and neuston) was studied using benzo(a)pyrene as a model compound for explaining PAH processes in general.

Considering that the increase in PAH's in a particular marine environment depends greatly on the proximity of the sources of these pollutants, it is noteworthy that there have been recent increases in sources of PAH's in the southeast marginal polar seas. These areas have been noted as only recently being affected by any pollutants at all, which therefore makes it important to study what other pollutants may also be of concern in these regions.

Investigations performed in 1988 by the research vessel *Akademik Korolev* are a continuation of comprehensive work begun in the Bering Sea basin in 1981 and 1984 (Roscigno, 1990).

Methods

Sampling

Polycyclic aromatic hydrocarbons circulation in ecosystem components of the Bering Sea and southern part of the Chukchi Sea, specifically, circulation of benzo(a)pyrene, was studied by the Third Joint US-USSR Bering & Chukchi Seas Expedition on the *Akademik Korolev* in August 1988. Samples were collected at 54 stations, which include four specific test polygons, the North (Stations 34-37), East (Stations 1-5) and South Polygons (Stations 108-112) in these waters. These polygons are sites of continuous sampling, which were visited in 1977, 1981, and 1984 by scientists from the joint US-USSR expeditions.

The goals of the sampling program were as follows:

- collect seawater from surface to deep horizons, including a near-bottom horizon;
- collect samples of floating ice;
- collect bottom sediments (the upper 5 cm of the surface);
- collect samples of plankton organisms taken in 45-100 m layers;
- collect samples of neuston organisms taken from the top 10 cm of the sea surface; and
- continue long-term monitoring at sites occupied previously in 1977, 1981, and 1984.

Water was sampled using a Niskin water sampler, 5-10 l per sample. Samples were obtained from 5-8 equally spaced horizons from the surface to the sea floor. Surface microlayer water (0.2 mm) was sampled by a stainless steel mesh (0.26 m²) screen. In order to prove that the vessel was not a source of contamination, some of the surface microlayer samples were obtained from a tender boat at a considerable distance

from the ship. Benzo(a)pyrene was extracted from 11 samples by triple extraction with benzene. Final processing of the benzene extracts (100 ml volumes) were carried out in the laboratory in Moscow.

Bottom sediments were collected using an OKEAN dredge, which removed a 0.25 m² area of the bottom without disturbing its stratification. A 5-cm depth was removed from these grab samples (50 to 100 g). These were then dried at 60°C, wrapped in aluminum foil, placed in a plastic bag, and stored for later analysis.

Plankton samples were collected using a Gedy net, which was allowed to drift behind the ship at 45- to 70-m depths for 1 h. The collected biomass was dried at 60°C to a constant weight and stored until analyzed at the laboratory in Moscow.

Samples of neuston organisms were obtained using a surface neuston net "ПНС-2" (see Subchapter 5.2.5, this volume). The samples were dried and prepared for subsequent analysis as described above.

Chemical Analysis

Quantitative Determination of Benzo(a)pyrene in Seawater

The benzene extracts of the samples that contained the benzo(a)pyrene (BaP) were concentrated to 1 ml volumes and chromatographed using thin layer chromatography using alumina coated plates. The running solvent was heptane:benzene:acetone (100:60:6.7). The BaP-containing spot on the plate was scraped off and eluted with acetone. The acetone solvent was then exchanged with n-octane.

Quantitative determinations of the BaP dissolved in the n-octane solutions were carried out by fluorescence analysis using the Shpolsky effect (Shpolsky *et al.*, 1952; Fedoseyeva *et al.*, 1968) at 196°C on a ΔΦC-12 spectrograph using appropriate standards, BaP and others.

Sensitivity of the method allowed quantitation of BaP down to 1x10⁻¹⁰ g/ml, with an error of less than 10%.

Determination of Benzo(a)pyrene in Sediment and Biota

Bottom sediments, plankton, and neuston were crushed to a powder. Portions of 3 to 5 g were extracted using 200 ml of benzene in a Soxhlet unit for 12- to 18-h periods. After concentration and chromatographic separation by thin layer chromatography on alumina plates using a (9:1) benzene:acetone developing solution, the BaP spots were scraped off and quantitatively analyzed using the fluorescence technique discussed earlier.

Results and Discussion

The Third Joint US-USSR Bering & Chukchi Seas Expedition (August to September 1988) studied biogeochemical cycling of PAH's in marine ecosystems of the northern oceans using benzo(a)pyrene as a model compound. The expedition was a continuation of previous investigations in the Bering Sea (Izrael *et al.*, 1987), and also was expanded to include the Gulf of Anadyr, the Chirikov basin and the Chukchi Sea, where this work was carried out for the first time.

By positioning the sampling locations where work began in 1981 and 1984, as well as positioning them at new stations in the Gulf of Anadyr, we were able to cover both the deep-water areas of the Bering Sea (the East and South Polygons) and the northern shallow-water areas of the continental shelf.

At the high latitude stations, BaP concentrations exceeded 10 ng/l in 28 of the 45 surface water samples. The highest concentration values that were measured in these regions are shown in Fig. 1 for the water.

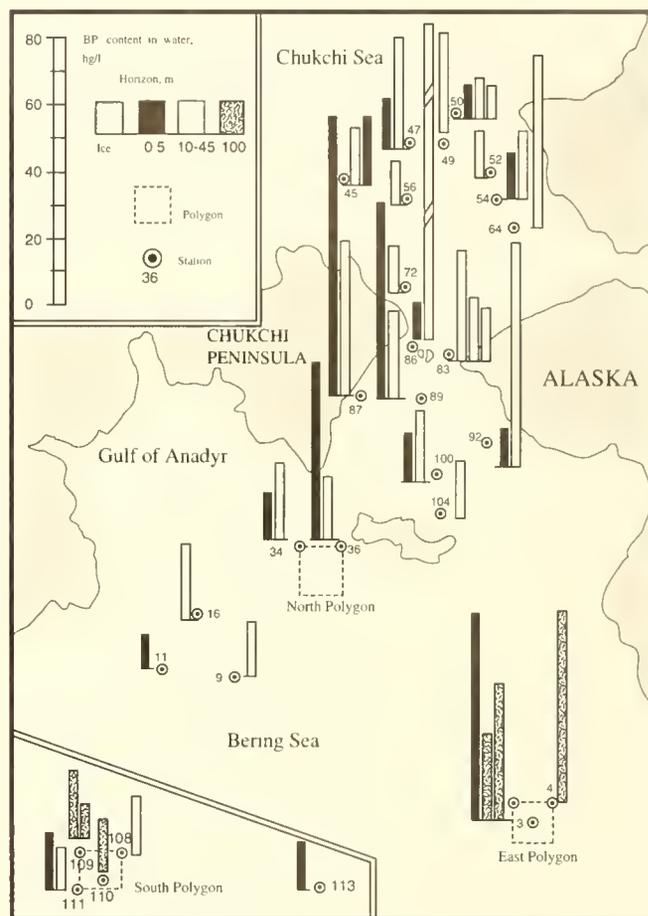


Fig. 1. Distribution of the the highest benzo(a)pyrene concentrations (those >5 ng/l) measured in waters of the Bering and Chukchi Seas (August 1988).

The BaP spatial distribution in water of the southern Bering Sea and East, South, and North Polygons was generally homogeneous, without the spottiness characteristic of the previous expeditions (Tsyban *et al.*, 1986; Volodkovich *et al.*, 1987). The average concentration in the seawater was 3.5±0.48 ng/l. Notice that even taking into account all of the values, including the highest ones (up to 80 ng/l), the average BaP concentration did not exceed 9.3 ng/l, which is much below the levels recorded on the previous expedition in 1984.

The majority of the BaP concentrations in the Bering Sea in August 1988 fell between 2 and 5 ng/l, which corresponded to the natural low levels of BaP in seawater reported by other investigators. In many cases, the maximum values found were only 0.4 to 0.6 ng/l. The highest BaP concentrations were

64 to 85 ng/l (the East Polygon and the Chirikov basin) and 185 ng/l in the Bering Strait. These high levels were found in photic layers of the water column (0.5 to 25 m). At the same time, BaP concentrations up to 40 ng/l were recorded in deep water 1,000 to 3,000 m, the East Polygon, Station 3; and 20 ng/l at the South Polygon, Stations 109 and 110.

The BaP vertical distribution was also relatively homogeneous and, unlike the 1984 samples, did not tend to accumulate in the surface samples. However, 14 maxima out of the 42 that were measured (18% of the total number) corresponded to the 0.5 and to the 11 to 25 m horizons.

The most homogeneous vertical distribution of low BaP levels was found in samples from the southern area of the Gulf of Anadyr (Station 6—0.6 to 1.6 ng/l), in the central part of the Gulf of Anadyr (Stations 22, 24, and 27—0.8 to 4.0 ng/l) and in the 10 to 500 m water layer at the East Polygon where it was 1 to 6 ng/l.

The South Polygon contained BaP concentrations in the water between 1 to 21 ng/l, with those samples in the 0.5 m surface layer at 4.15 ng/l. The average for this entire station was 4.15 ± 0.37 ng/l. The highest BaP concentrations were found in deep water (1,000 to 3,000 m) in the western part of this polygon at Stations 109, 110, and 111. The southwest Station 111 showed relatively high concentrations at 0.5 and 45 m depths; this area also produced higher levels in 1984.

At Station 113, which was east of the South Polygon, the BaP concentrations at the depth range of 25 to 2,000 m were characterized by considerable homogeneity, 1.2 to 3 ng/l, and only in surface water (0 to 10 m) were the levels higher, ranging from 8 to 13 ng/l.

At the East Polygon, the BaP concentrations at the depth of 1,000 m was also relatively homogenous and low, 1 to 3 ng/l, which was the same in 1984. However, some individual horizons showed BaP concentrations that were among the highest concentrations found in 1988 (i.e., 25 to 67 ng/l). Also, some of the highest values recorded in 1988 were at the 0.5 m layer (up to 59 ng/l) and at the depths of 100 to 1,000 m (see Fig. 1). Note that the highest BaP concentration recorded in 1984 in the southeast part of this sampling area was 46.6 ng/l. The average BaP value in the East Polygon water was among some of the lowest compared with the other areas tested this year (i.e., 3.34 ± 0.54 ng/l).

The Gulf of Anadyr was investigated for the first time. It showed a pronounced BaP homogeneity and was uniformly characterized by low levels of 0.5 to 5.8 ng/l (93% of the determinations). At a number of stations, the BaP concentration throughout the whole water depth varied over even a smaller range (i.e., 1 to 3 ng/l). The exceptions were the 3 stations in the southern part of the gulf where the concentrations in the surface horizons (10 to 25 m) ranged from 16.5 to 23.9 ng/l (see Fig. 1). The average BaP value for the entire area of the Gulf of Anadyr was 2.22 ± 0.22 ng/l, the lowest among all the investigated northern regions.

On the shelf near St. Lawrence Island, in the water of the larger part of the investigated horizons of the North Polygon, low BaP concentrations of 1 to 6 ng/l dominated, with the average value being 3.68 ± 0.65 ng/l. The most homogeneous BaP distribution with depth was observed in the southern part

of this polygon. Higher concentrations, up to 25 ng/l in the 10 to 25 m horizon and 34 to 52 ng/l in the 0.5 meter surface layer were confined to the northern part of this region nearest to St. Lawrence Island (see Fig. 1). However, these recorded maxima were lower than in 1984.

At higher latitudes the BaP distribution was characterized by generally higher concentrations.

The water of the shallow Chirikov basin, the area between St. Lawrence Island and the Bering Strait, contained an average BaP level of 4.63 ± 0.54 ng/l, with the maximum values for individual samples being 2 to 4 ng/l. However, most stations (see Fig. 1) at the 0 to 25 m depths showed increased BaP levels up to 68 to 85 ng/l. The highest BaP concentrations, both for this area and other areas in the north, were recorded at the 45 m depth in the western part of the Bering Strait that had a value of 185 ng/l.

Of considerable interest are the samples that were collected for the first time from the southern part of the Chukchi Sea (Stations 44 to 81). In the southern region of this investigated area, the BaP concentration over the water depth profile, including the surface layer, was within 0.8 to 3 ng/l; however, in the northern part of this area, BaP concentrations up to 15–56 ng/l were measured, with maxima near the Alaska coastline (Station 64). The distribution of the high BaP water plume covered quite a pronounced area interacting in the north with the floating sea ice boundary (see Frontispiece station map). The vertical BaP distribution in this relatively shallow area (50–60 m) did not have any pronounced stable maxima since the higher BaP levels were found throughout the whole water depth from the surface to near-bottom horizons.

Special note should be taken of the BaP concentrations in the samples of sea ice and the water collected from the surface microlayer (0 to 200 μ) that were taken at 68°N latitude. (Station 45). These values were 13 to 18 ng/l and 20 ng/l, respectively. There was significant BaP concentration in the ice. With considerable ice areas occurring in the Chukchi Sea even in summertime, this would indicate that there is a potential danger from PAH accumulation in this substrate and the levels are reaching those that might pose a real threat to this vulnerable northern sea ecosystem.

The results of this investigation show a wide distribution of BaP in the water and even ice cover of this subpolar region. The most frequently occurring concentrations were low levels, near the natural levels of 5 ng/l, with the BaP concentrations slightly higher at the northern latitudes (65°N latitude and higher). It was at these latitudes that most of the higher BaP concentrations (60–80 ng/l) were found. These areas include the East Polygon (deep water horizons) and the North Polygon (northern stations), as well as several locations in the Chirikov basin and the northern part of the investigated regions of the Chukchi Sea.

Not only is BaP present in the waters of the Bering Sea and the Chukchi Sea, it is also found in the bottom sediments of these regions. In 1988, BaP was recorded in sediment at most of the 43 investigated stations. The exceptions were only 6 of the 43 locations that were in the southern part of the Gulf of Anadyr (Station 6 and 7), to the north from St. Lawrence Island (Station 102), and along the Alaska coast (Stations 66,

67, and 52). It should be noted that the BaP concentration in the near-bottom water at these stations also had the low values (0.6 to 1.0 ng/l).

In other regions the BaP concentrations in the upper 5 cm layers of the sediment, which are the primary areas of PAH accumulation (Bourcart *et al.*, 1961; Larsen *et al.*, 1983), were within 0.11 to 1.7 $\mu\text{g}/\text{kg}$ of dry mass. The maximum BaP concentration (4.5 $\mu\text{g}/\text{kg}$) was measured in the shallow water of the northern section in the Chukchi Sea (Station 49). A high BaP concentration (0.87 $\mu\text{g}/\text{kg}$) was also measured in the Gulf of Anadyr at Stations 12 and 13 near the Chukchi coast, and (1.7 $\mu\text{g}/\text{kg}$) Station 43, and also in the center of the North Polygon where it was 0.87 $\mu\text{g}/\text{kg}$.

The general character of BaP distribution in bottom sediments may be represented by the contours presented in Fig. 2. It is evident that the spatial BaP distribution in bottom sediments has quite a sophisticated structure with pronounced concentration maxima regions. The position of areas with maximum BaP concentrations in the sediment correspond to the central portions of the northern section of the Gulf of Anadyr, St. Lawrence Island, the central part of the Chirikov basin, and the Central part of the investigated area of the Chukchi Sea.

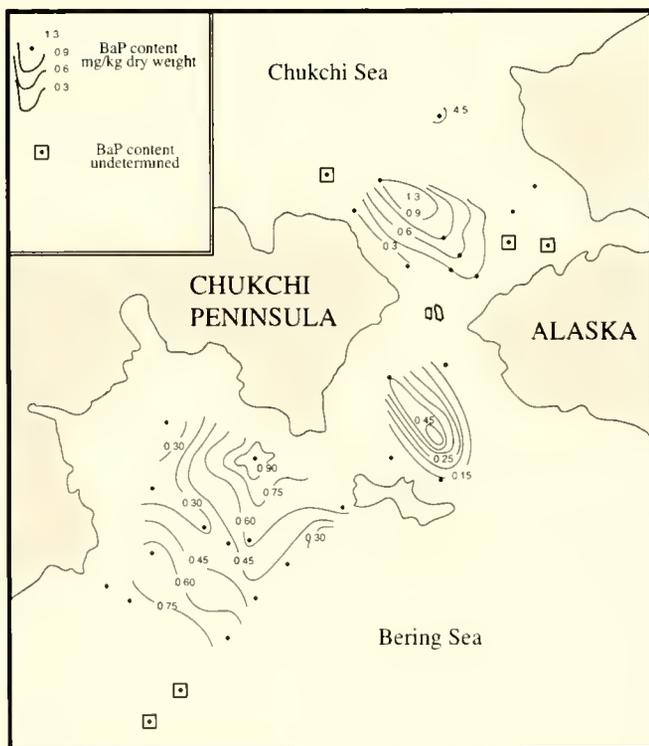


Fig. 2. Concentration contours for BaP measured in the top 5 cm-layers of sediment in the Bering and Chukchi Seas (August 1988).

BaP accumulation was recorded in bottom sediments (Tsyban *et al.*, 1987) in previous studies as well (1981 and 1984). Incidentally, BaP levels at a number of sampled stations showed no significant change over this time (Fig. 3), indicating

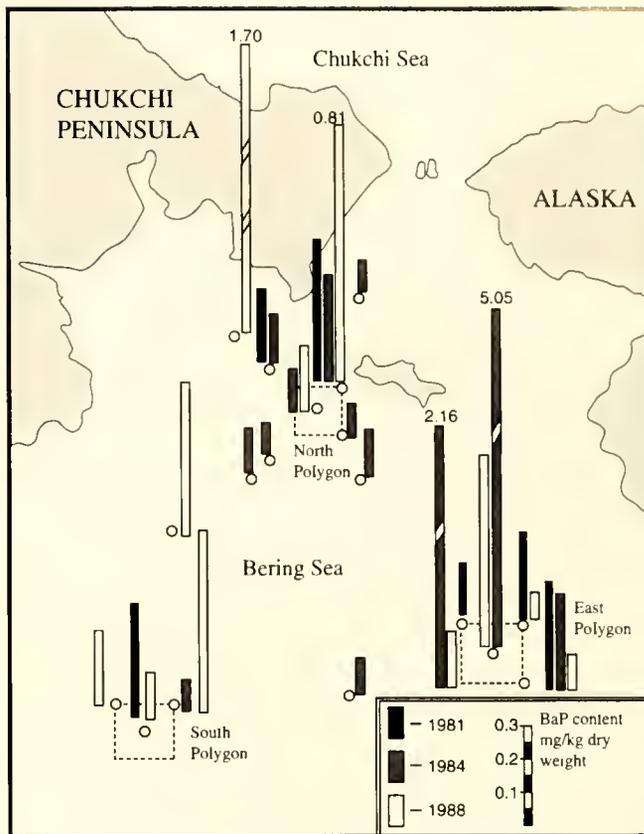


Fig. 3. Comparisons of the concentrations of BaP measured over time in surface sediments collected in 1981, 1984 and 1988 from similar locations in the Bering Sea.

a relatively constant processing of this constituent at these locations. However, in general the total BaP accumulation in bottom sediment of the Bering Sea and the Chukchi Sea is 1 to 2 orders of magnitude lower than in impacted sea systems (Tsyban *et al.*, 1985) and corresponds to the levels characteristic of relatively clean regions such as the western coast of Greenland (Mallet *et al.*, 1979).

Benzo(a)pyrene distribution in the seawater showed a significant impact on the biotic component of this system, which was expressed, in particular, in the accumulation of this toxic compound in aquatic biota, especially in the phytoplankton. Earlier, in the investigated periods of 1981 and 1984, we showed their presence in all of the samples of plankton taken in the Bering Sea (phytoplankton and zooplankton). Its content in plankton organisms was at the level of 10^1 to 10^3 $\mu\text{g}/\text{kg}$ dry wt.

In 1988, BaP was recorded in all 26 samples of plankton organisms taken at 22 stations in the Bering Sea and the Chukchi Sea, and in most cases, BaP content in plankton was within 0.2 to 0.9 $\mu\text{g}/\text{kg}$ (46% of the samples) and 2.0 to 2.6 $\mu\text{g}/\text{kg}$ (23% of the samples).

As one can see from Fig. 4, the highest BaP accumulation in plankton in the Bering Sea, 10.2 to 10.6 $\mu\text{g}/\text{kg}$, was in the areas in the northern part of this area near the shallow water of the St. Lawrence Island, the North Polygon, and Station 100 in the Chirikov basin.

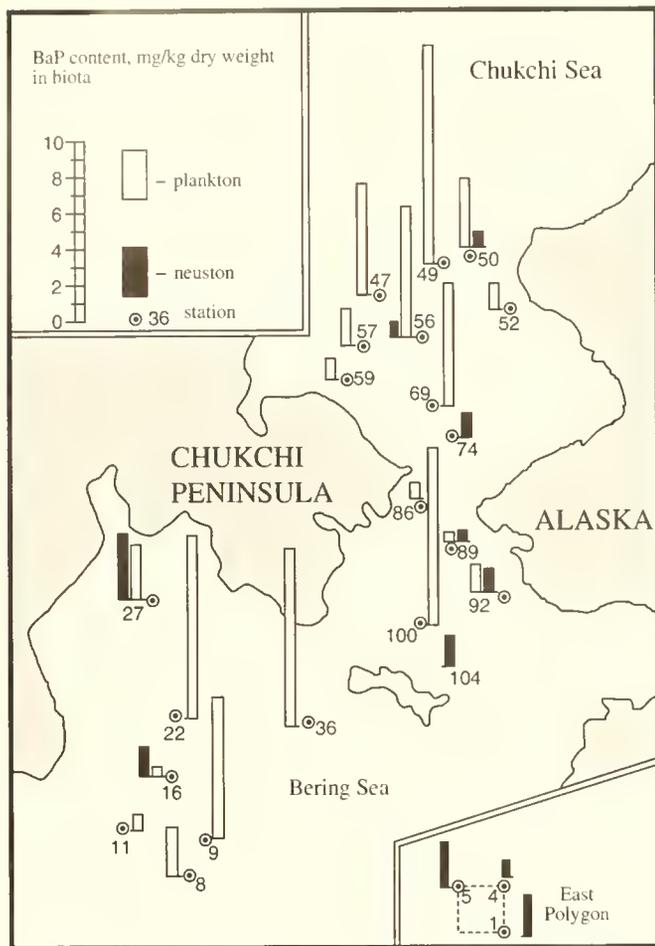


Fig. 4. Distribution of the highest concentrations of BaP measured in plankton and neuston collected in the Bering and Chukchi Seas (August 1988).

In the Chukchi Sea, the area of the highest BaP accumulation by plankton was located along the highest latitudes, with the maximum $12.6 \mu\text{g}/\text{kg}$ occurring at Station 49.

It should be especially noted that the maxima for BaP accumulation in plankton were found at those stations (35, 100, and 49) that were also characterized by the maximum BaP levels found in bottom sediments. This fact is most pronounced at the northern section of the Chukchi Sea (Station 49): 12.6 and $4.5 \mu\text{g}/\text{kg}$, respectively. These facts may indicate the

primary role of biosedimentation processes in deposition of pollutants to bottom sediments—in particular, in highly productive shelf regions of the arctic seas.

Plankton communities are particularly sensitive to changes of the hydrochemical background. Due to some physical and biochemical processes, PAH accumulation in plankton often exceeds the concentration in their habitat by 15 to 165 times. This process can be indicated by the coefficient of BaP accumulation by plankton organisms or the biomagnification coefficient (ratio of BaP concentration in plankton to that in the water, $C_p:C_w$).

In 1988, the most significant BaP accumulation was recorded at the East and North Polygons as well as in the Chirikov basin (Station 100), where accumulation coefficients were 3.9×10^2 , 3.8×10^2 , and 2.0×10^2 . In the other investigated regions, these values were within 0.2×10^1 to 8.8×10^1 (Table 1), which is comparable with the data obtained for these regions in 1984.

Note that in 1981 the accumulation coefficients were higher than observed here with some as high as 10^4 and 10^5 . A reason for these differences could be that in 1981 there was a higher BaP content in every element of the Bering Sea ecosystem than was present during the 1988 cruise.

Benzo(a)pyrene accumulation was also discovered in the neuston community populating the surface layer of the seawater. Benzo(a)pyrene accumulation in neuston was comparable with that in plankton and had the values of 0.6 to $10.0 \mu\text{g}/\text{kg}$ dry wt. (Table 2 and Fig. 4).

Eleven investigated samples show relatively high BaP concentrations for neuston organisms from the Bering Sea—in particular, in the Gulf of Anadyr and the East Polygon (Fig. 4). These facts are evidence for a selective trend towards higher PAH accumulation in the biotic component of these ecological systems.

Comprehensive investigations of PAH biogeochemical cycles carried out in this region of the world's oceans showed a widespread BaP distribution in the Bering and the Chukchi Sea ecosystems. The general character of BaP distribution and their accumulation in components of marine ecosystems testifies to the fact that even though the degree of pollution of these aquatic systems is not high, carcinogenic PAH's constitute a constant and characteristic feature for most regions of the Bering Sea and Chukchi Sea.

TABLE 1

Concentration of benzo(a)pyrene in plankton in the
Bering and Chukchi Seas, August 1988.

Area of Investigation	Station No.	Concentration of Benzo(a)pyrene		Accumulation Factor for Plankton (C_2/C_1)
		In water, at collect site ng/l (C_1)	In plankton ng/kg wet wt. (C_2)	
East Polygon Test Area	5	1.3	52	4.0×10^1
Gulf of Anadyr	9	2.1	835	39×10^1
	13	0.8	70	8.8×10^1
	16	3.1	40	1.3×10^1
North Polygon	36	2.7	1,020	38×10^1
Chukchi Sea	47	8.4	560	6.7×10^1
	49	12.5	1,260	10×10^1
	50	7.2	378	5.8×10^1
			459	6.3×10^1
	52	6.4	90	1.4×10^1
	56	0.9	22	2.4×10^1
	57	1.7	200	12×10^1
Chirikov basin	72	1.4	86	6.1×10^1
	89	4.3	63	1.5×10^1
	92	6.8	137	0.2×10^1
	100	5.2	1,063	20×10^1

TABLE 2

Concentration of benzo(a)pyrene in neuston of the Bering and
Chukchi Seas, August 1988.

Sampling Area	Station Number	Concentration of Benzo(a)pyrene ($\mu\text{g/kg wet wt.}$)
East Polygon Test Area	1	2.5
	4	1.2
	5	1.94
Gulf of Anadyr	16	2.43
	22	10.0
	27	3.0
Chukchi Sea	50	0.7
	53	0.6
	56	0.7; 0.8
	69	7.8
	74	1.9

Subchapter 8.3:

Fate of Heavy Metals

8.3.1 Heavy Metals in Water and Sediment

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Introduction

Among numerous pollutants coming to the World Ocean, the greatest potential threat is posed by chemicals that have global distribution, continuous input, and pronounced adverse effect on living creatures. These substances include heavy metals. These and other substances may cause serious ecological changes on a global scale. Therefore, studying their occurrence and distribution may help us avoid their damaging effects.

Pollution of the World Ocean by toxic metals is a most telling example of a global anthropogenic effect. Today there are practically no regions in the world oceans that do not contain increased levels of trace metals. Analysis of the modern data (Izrael & Tsyban, 1981) shows that millions of tons of toxic metals come to the world oceans every year. It is established (Izrael & Tsyban, 1981; Sapozhnikov, 1982) that in recent years the anthropogenic components of some pollutants (including lead, mercury, arsenic) is comparable to and even exceeds natural flows of these elements to the world oceans. The present concentrations of toxic metals in the world oceans varies from single digit to hundreds of ng/l, which considerably exceeds (5 to 10 times) their natural concentration in seawater.

Being intrinsic constituents in the habitat, metals, when exceeding their natural concentrations in these habitats, can render an adverse effect on living creatures (Florence, 1983; Yablokov & Ostroumov, 1983).

In view of the above, investigation of toxic metal behavior, as well as processes of their accumulation and distribution in sea ecological systems, takes an important place among environmental pollution problems. However, their concentration is usually lower than those of such widely spread pollutants as oil products and chlorinated hydrocarbons.

At the same time, one has to note that, regardless of several serious studies aimed at evaluation of the World Ocean pollution by toxic metals performed in the last decades, individual seas, specifically those in the so-called background regions of the ocean, are still insufficiently studied. The present state of knowledge does not provide any complete concept of the processes of metal accumulation and distribution in ecological systems of these seas. Meanwhile, some of these seas—in particular, the Bering Sea and the Chukchi Sea—belong to the most productive and more used regions of the world oceans. That is why a study of toxic metal accumulation and distribution processes in such ecological systems, as well as their interaction with the environment, is of special interest.

Materials and Methods

This paper discusses distribution of trace metals in water and bottom sediments of the Bering Sea and the Chukchi Sea on the basis of studies performed by the Third Joint US–USSR Bering & Chukchi Seas Expedition. The cruise track covered the larger part of the sea regions in this area, including shallow water and coastal areas as well as deep-water regions.

Water was sampled using Niskin plastic bathometers. Preliminary treatment of samples was done using standard procedure described in detail in the *Methodological Foundations of Integrated Ecological Monitoring of the Ocean* (Tsyban *et al.*, 1988).

The top layers of the bottom sediments were sampled without disturbance of the stratification, using an OKEAN-50 dredger with 0.25 m² coverage area. After the samples were air dried at 20 to 25°C, they were sealed in plastic bags for storage. Further treatment of sediment samples was performed in the permanent coastal laboratory using the procedure described by Prokofyev and associates (Prokofyev *et al.*, 1981).

Solutions, resulting from acid digestion of the samples, were tested for metal concentrations using flame atomic absorption spectroscopy.

Results and Discussion

Tables 1 and 2 show the trace metal concentration in water and bottom sediments of the Bering Sea and the Chukchi Sea.

Comparison of the data shows inhomogeneity of metal distribution in the water of the regions in question. For instance, concentrations of copper varied from 0.01 µg/l (in the Gulf of Anadyr) to 0.46 µg/l in the open areas of the Bering Sea (Station 109), with an average value of 0.08 µg/l. Shallow-water stations (up to 100 m deep) demonstrated a direct relation between copper concentration in water and bottom sediments: a larger copper concentration in water is accompanied by its larger concentration in bottom sediments. Such a correlation was not found at the deep-water stations. In general, copper concentration in bottom sediments of the Bering Sea varied from 9.32 µg/g dry wt. in the open areas of the Bering Sea up to 38.32 µg/g dry wt. in the Gulf of Anadyr with the average value 17.0 µg/g.

Sediments of the Chukchi Sea contained a significantly smaller copper concentration—found near the Alaska coastline (Station 64) and the smallest one (4.6 µg/g) near the arctic coast

of Chukchi (Station 59)—than in the other areas that were sampled. For the Bering Strait, in this shallow-water area, the copper concentration in bottom sediments only reached a maximum of 3.56 µg/g.

Cadmium showed a similar heterogeneity of distribution. In general, cadmium concentration in water varied from 0.01 to 0.13 µg/l in the Chukchi Sea. Cadmium concentration in the Bering Strait water was below the level of detection. The highest cadmium concentration (3.69 µg/l) was found at Station 24 in the surface water layer, which is probably related to local geographic conditions.

Cadmium distribution in bottom sediment showed little variation in its concentration and was generally low and of little significance, with average concentrations being 0.6 µg/g dry mass in the Bering Sea, 0.4 µg/g in the Chukchi Sea, and 0.2 µg/g in the Bering Strait.

TABLE 1

Metal concentrations in the water of the Bering Sea and the Chukchi Sea.

Station	Horizon (meters)	Concentration, µg/l				
		Cu	Cd	Mn	Zn	Pb
1	0	-*	0.65	-	-	-
	25	0.06	0.06	0.04	0.30	2.05
2	30	-	-	-	0.46	0.02
	100	-	-	0.01	-	0.09
5	130	0.46	-	0.01	3.67	-
7	20	0.07	0.06	0.04	0.15	1.03
	100	0.10	0.11	0.06	2.85	0.41
9	20	-	-	-	-	-
	60	-	-	-	0.39	-
13	5	-	-	-	-	-
15	5	0.01	-	-	-	-
	75	-	-	-	-	-
24	HMC	0.09	3.69	3.6	0.12	-
	75	0.09	-	0.01	-	-
32	50	0.06	-	-	-	-
50	10	-	-	-	0.01	-
57	10	0.08	0.03	0.02	-	0.57
59	10	0.07	0.13	0.02	0.29	2.34
64	10	0.03	-	-	-	-
69	10	-	0.01	0.02	-	1.29
72	10	0.17	-	0.04	2.13	0.07
74	10	0.016	-	0.01	-	-
83	10	0.68	-	0.03	-	-
86	10	0.08	-	-	3.30	-
96	10	0.01	-	-	-	1.23
100	10	-	0.02	0.02	-	0.10
108	10	-	0.11	-	0.76	1.87
109	1000	0.49	0.29	0.40	-	-
113		0.03	-	-	-	-

* Metal concentration is below sensitivity of the method.

TABLE 2

Metal concentration in the bottom sediments of the Bering Sea and the Chukchi Sea (µg/g dry weight).

Station	Cu	Cd	Mn	Station	Cu	Cd	Mn
2	15.40	0.36	208.00	32	10.5	-	166.00
3	18.90	0.56	236.40	47	11.2	0.42	238.00
5	33.50	0.21	758.40	52	10.8	0.87	241.60
6	17.50	-	592.40	55	11.4	-	259.40
7	10.50	0.09	189.20	59	4.6	-	88.40
8	21.50	0.92	290.40	63	9.56	0.35	193.62
8 (0.3)	18.90	0.54	258.40	64	12.52	0.77	209.02
8 (1.2)	20.10	0.70	281.20	74	4.58	0.17	89.62
8 (2.0)	20.10	0.68	271.40	92	2.24	0.03	83.82
8 (5.0)	20.30	0.76	176.80	69	7.72	0.46	148.22
9	16.78	0.95	216.60	76	9.84	0.59	186.42
18	9.32	0.57	182.20	89	3.56	0.22	98.62
19	8.76	0.59	146.00	96	6.32	0.15	144.22
27	11.42	0.61	141.20	100	2.68	0.15	83.82
22	15.16	0.88	189.00	104	2.72	0.19	85.22
29	38.32	1.58	860.42	110	65.92	3.10	5,996.42

Note: Metal concentration is below sensitivity of method.
(0.3) - depth of bottom sediment sampling, m.

The study of manganese distribution in the investigated ecological systems showed an extremely low concentration in seawater, except for Station 109. The concentration of manganese did not exceed 0.04 µg/l (see Table 1). The average manganese concentration in bottom sediments was 220 µg/g dry wt. These data are consistent with the results of Loring (1984) obtained for bottom sediment samples (340 µg/g) taken near the Arctic coast.

The high concentration of manganese (5,996.4 µg/g) observed at Station 29 is, probably, related to manganese remobilization processes in this region of the bottom.

Concentrations of zinc and lead were determined only in samples of seawater. The concentration of zinc in the Bering Sea varied from 0.15 µg/l (central part) to 3.67 µg/l (eastern part), and the concentration of lead varied from 0.02 µg/l (eastern part) to 1.03 µg/l (central part).

The concentration of zinc and lead ranged from 0.01 to 2.13 µg/l and 0.07 to 2.34 µg/l, respectively.

In conclusion, it should be noted that our results for metal concentrations in water and bottom sediments of the Bering Sea and the Chukchi Sea are close to the values obtained by other investigators (Hegge, 1982; Maeda, 1986; Hegge *et al.*, 1987).

Thus, studies from the Third US-USSR Joint Bering & Chukchi Seas Expedition verify that metal concentrations in water and bottom sediments of the Bering Sea and the Chukchi Sea are still at background levels.

8.3.2 Baseline Levels of Certain Trace Metals in Sediment and Biota

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Introduction

The Bering and Chukchi Seas are believed to be relatively free from pollutants due to sparse human coastal populations and limited industrial development. Increased industrial activity, especially in petroleum exploration and production, is proposed for the future and thus preliminary studies in determining baseline concentrations of environmental contaminants are necessary. Up to now, there have been no comprehensive studies in determining baseline concentrations of trace metals in sediment and biota in the Bering and Chukchi Seas by the US or USSR.

The US Fish and Wildlife Service was concerned that tissues collected from Pacific walrus (*Odobenus rosmarus divergens*) in the Bering Sea were high in cadmium (Taylor *et al.*, 1989). For example, the maximum concentrations of cadmium were 50 ppm (wet weight) in the liver and 99 ppm (wet weight) in the kidney. Cadmium residues in vertebrate kidney or liver that exceed 10 ppm (wet weight) or 2 ppm whole body (wet weight) should be viewed as evidence of probable cadmium contamination (Eisler, 1985). Taylor *et al.* (1989) recommended that additional studies be conducted on cadmium contamination since levels exceed the safe levels of human consumption.

Under the auspices of a cooperative program between the US and USSR, we conducted this study in order to help address the above issues. During the Third Joint US-USSR Bering & Chukchi Seas Expedition our purpose was to determine baseline concentrations of arsenic, cadmium, cobalt, copper, lead, manganese, and mercury in the sediment. Cadmium, arsenic, lead, and mercury were determined in biota. Trace metal results obtained by sediment analysis, unlike seawater analysis, are generally well above the analytical detection limit and contamination risks of the sediments from sample handling are insignificant (Szefer, 1988). Sediment data are, therefore, utilized as a tool for assessing sources and distribution of some elements in aquatic environments. We investigated trace metals in biota to determine if lower trophic organisms bioaccumulate these metals. This may explain high concentrations of cadmium in walrus further up the food chain. On this expedition we collected bivalves (Nuculoidae), hermit crabs (Paguridae), sea urchins (Strongylocentrotidae), shrimp (Pandalidae), neuston, zooplankton, and phytoplankton.

Materials and Methods

Samples were collected from the Bering and Chukchi Seas while aboard the research vessel *Akademik Korolev* from 26 July to 2 September 1988. The stations were determined by the chief scientists from both the US and Soviet sides and the samples were collected opportunistically from each station. The stations sampled are shown in the preface to this book and the numbering corresponds to that shown in this figure. The zooplankton and phytoplankton were collected by net tows performed by the Russian scientists and described in Chapter 5 (this volume). The neuston samples were collected by Soviet scientists using a special surface trawl also described elsewhere in this text. Samples were placed in chemically cleaned I-Chem jars (I-Chem Research Inc., New Castle, Delaware). The excess water was decanted and the samples stored frozen until they were prepared for trace metal analyses.

A bottom trawl, designed and operated by Soviet scientists, was used to obtain the benthos samples (shrimp, crabs, bivalves, and urchins). These samples were either placed in I-Chem jars or, for larger samples, placed in plastic Whirl-pak bags, and frozen for storage.

The sediment samples were obtained using a 30 cm² box corer provided by Texas A&M University. Surface layers (0-2 cm) of each sediment sample from the box corer were scooped with a teflon spatula and placed directly into precleaned I-Chem jars. The samples were frozen until trace metal analysis.

Analysis

Sediment

Sediment samples for arsenic, cadmium, cobalt, copper, lead, and manganese were digested as described by Krynitsky (1987), with modifications for the above metals. A 2.0 g (wet weight) aliquot was placed into a 50 ml polypropylene centrifuge tube and 5.0 ml of nitric acid and 0.5 ml of 30% hydrogen peroxide were added. The Krynitsky method was modified in that 5 ml of hydrofluoric acid were added in order to free the analytes from the silicates contained in sediments. The samples were allowed to digest for 2 h in a hot water bath at 90°C (Krynitsky, 1987). After digestion, the samples were diluted, shaken, and centrifuged prior to analysis.

A Perkin-Elmer Model 5000 flame atomic absorption spectrometer was used to analyze for copper, cobalt, and manganese. The parameters are described in the instrument's operations manual (Perkin-Elmer Corp., 1976).

A Perkin-Elmer Zeeman Model 3030 graphite furnace atomic absorption spectrometer (GFAAS) was used to analyze for arsenic, cadmium, and lead. The GFAAS conditions for arsenic are described by Krynitisky (1987). The GFAAS conditions for cadmium and lead are described by Hinderberger (1981).

Separate 5.0 g (wet weight) aliquots of sediment were digested for mercury analysis under reflux in sulfuric and nitric acids (Monk, 1961). The determinations were performed by cold vapor atomic absorption spectroscopy (CVAAS) using a Coleman MAS-50B-Mercury analyzer.

The detection limit for arsenic, lead, and cadmium was 0.05 ppm based on a 2.0 g sediment sample. The detection limit for mercury was 0.01 ppm based on a 5.0 g sediment sample. The detection limit for copper and cobalt was 0.2 ppm and that for manganese was 1.0 ppm, based on a 5.0 g sample. All sediment analysis was based on wet weight.

Biota

After each station, samples were combined by family name for analysis. The digestion procedure for cadmium, lead, and arsenic was described by Krynitisky (1987). The entire sample (including shell in the benthos) was homogenized in a Virtis Model 45 blender. A 0.5 g wet weight aliquot of tissue was digested in 5 ml of nitric acid and 0.5 ml of 30% hydrogen peroxide as described above. Determinations for lead and cadmium were performed using the instrument parameters described by Hinderberger (1981) and arsenic as described by Krynitisky (1987). The detection limit for lead and cadmium was 0.05 ppm and that for arsenic was 0.1 ppm, based on a 0.5 g sample wet weight. For mercury 1.25 g were digested and analyzed according to the procedure described by Monk (1961). The mercury determinations were performed using a Spectro Products mercury analyzer equipped with a Varian VGA-76 vapor generation accessory. The detection limit for mercury was 0.05 ppm based on a 1.25 g sample wet weight.

Moisture Determinations

Moisture determinations were performed by weighing out a separate 1.0 g of aliquot of biota or sediment into a tared aluminum pan. The sample was allowed to dry for 24 h at 110°C and the percent of moisture was calculated.

Quality Assurance/Quality Control

The samples were processed in batches of 10 to 20 samples with one matrix spike, one procedural blank, one duplicate sample, and one standard reference material (SRM) for each batch. The SRM used for sediments was provided by the National Institute of Standards and Technology (NIST), formerly National Bureau of Standards. The SRM used was NIST 1646 Estuarine Sediment, which contained the following certified values (ppm dry weight) for the metals of interest: arsenic 11.6 ± 1.3 , cadmium 0.36 ± 0.07 , and cobalt 10.5 ± 1.3 . The SRM used for biota was provided by the

National Research Council of Canada, Ottawa, Ontario, Canada. The SRM used was TORT-1, which is a freeze-dried sample of a partially defatted lobster. TORT-1 contained the following certified values (ppm dry weight) for the metals of interest: arsenic 24.6 ± 2.2 , cadmium 26.3 ± 2.1 , lead 10.4 ± 2.0 , and mercury 0.33 ± 0.06 . The matrix spike for the sediment consisted of: 300 µg manganese; 10 µg each of lead, copper, cobalt, and cadmium; 20 µg arsenic; 0.5 µg mercury. The matrix spike for the biota consisted of (6.0 µg arsenic and 5.0 µg each of cadmium, lead, and mercury).

Recoveries were monitored in both the standard reference materials and matrix spikes. The average recoveries ranged from 87–108% for the metals we investigated. The relative percent differences between duplicate results averaged less than 10%.

Results and Discussion

Trace metals, with the exception of mercury at a few stations, were present in all sediment samples collected in the Bering and Chukchi Seas (Table 1). The one deep-water station (Station 3) differed from the shallow-water stations in that manganese and copper were much higher. This was probably due to the remobilization of these metals within the sediment core as a primary mechanism. Other investigators during the Second Joint US-USSR Expedition to the Bering Sea (Summer 1984), who sampled more deep-water stations in the Bering Sea than were sampled during this cruise, observed the same phenomenon with these two metals (Iricanin & Trefry, 1991).

When comparing the concentrations of trace metals obtained in sediments during the 1988 cruise to those obtained during the 1984 cruise (Table 2), the concentrations of lead and cadmium are generally higher for the 1988 cruise. During the 1988 cruise the stations sampled were primarily shallow-water stations (<200 m) where the primary productivity was high (Zeeman, Subchapter 6.2, this volume), and during the 1984 cruise the stations sampled were the deep-water stations (>600 m). These higher concentrations were most likely due to a downward vertical flux of planktonic organisms and other biogenic debris (Iricanin & Trefry, 1991). In general, the values for trace metal residues obtained from both the 1984 and 1988 cruises appear to be less than value for trace metals in sediments from some other parts of the world (Table 2), which suggests that the Bering and Chukchi Seas are relatively pristine.

Only arsenic, cadmium, and lead had reportable values in the biota (Tables 3,4). The values of mercury in the biota are less than the detection limit. The benthos samples might be expected to have residue patterns similar to the sediments they reside in except in cases where bioavailability plays an important role. Even though the lead values in the sediment were 30 to 40 times higher than those for cadmium, the cadmium values in the benthos were in most cases higher than the corresponding lead values. This indicates that the benthos investigated bioaccumulated cadmium better than lead. Lead values were also comparable to the arsenic values in the sediment. As with cadmium, we found that the arsenic values in the benthos were

TABLE 1

Trace metal concentrations, ppm dry weight,
for surficial sediments (0–2 cm).

A. Trace metal concentrations in sediments from the Bering Sea.

Station No.	Depth (meters)	Pb	Cu	Mn	Co	Cd	Hg	As
3	3,092	8.5	31.	910.	7.4	0.35	0.06	3.5
7	140	7.9	13.	390.	8.5	0.24	<0.02	8.3
9	107	9.7	16.	360.	10.	0.46	0.033	14.

B. Trace metal concentrations in sediment from the Gulf of Anadyr.

Station No.	Depth (meters)	Pb	Cu	Mn	Co	Cd	Hg	As
13	148	7.4	6.5	290.	7.6	0.24	<0.02	9.8
18	75	9.5	13.	410.	8.4	0.17	0.026	19.
22	88	17.	14.	390.	6.9	0.46	0.063	14.
35	63	16.	13.	370.	10.	0.47	0.045	13.

C. Trace metal concentrations in sediment from the Chukchi Sea.

Station No.	Depth (meters)	Pb	Cu	Mn	Co	Cd	Hg	As
45	45	17.	16.	340.	9.2	0.39	0.036	20.
47	49	15.	11.	350.	8.9	0.29	<0.02	12.
50	48	16.	10.	490.	11.	0.16	<0.02	12.
55	46	5.2	6.7	220.	5.5	<0.10	<0.02	6.2
59	38	11.	7.8	210.	5.6	0.13	<0.02	10.
61	49	7.4	8.4	190.	5.7	0.32	0.025	7.2
64	45	4.7	6.3	220.	4.7	<0.10	<0.02	6.0
67	35	6.5	6.1	250.	5.3	0.13	<0.02	6.8
69	41	7.8	8.2	300.	6.7	0.13	0.022	6.8

TABLE 2

Comparison of the average values of trace metals in sediment obtained during the 1988 Joint US–USSR Expedition to other values of trace metals in surficial sediments from different parts of the world.

	ppm Dry Weight						
	Pb	Cu	Mn	Co	Cd	Hg	As
Bering Sea 1988	8.7 ± 0.075	20 ± 7.9	553 ± 252	8.6 ± 1.1	.35 ± .09	.03 ± .02	8.6 ± 4.3
Gulf of Anadyr 1988	13 ± 4.1	12 ± 3.0	365 ± 46	8.2 ± 1.2	.34 ± .13	.03 ± .02	14 ± 3.3
Chukchi Sea 1988	10 ± 4.6	8.9 ± 2.9	285 ± 90	7.0 ± 2.1	.17 ± .13	<0.02	9.6 ± 4.3
Bering Sea 1984 ^a	3.5 ± 1.9	22 ± 12	362 ± 46	NA ¹	.14 ± .13	.04 ± .03	NA
Southern Baltic ^b	330.	52.	540.	21.	2.9	NA	NA
Ivory Coast West Africa ^c	93.	55.	190.	NA	NA	280	NA

¹NA - Not analyzed.

^aData from the Second Joint US–USSR Expedition to the Bering Sea, Summer 1984 (Iricanin & Trefry, 1991).

^bData obtained from Szefer *et al.*, 1988.

^cData obtained from Kouadio *et al.*, 1987.

TABLE 3

Trace metal residues in bivalves, hermit crabs, shrimp,
sea urchin, and sculpin from the Bering and Chukchi Seas.

Station Number	Common Name	Family Name	Hg	ppm Dry Weight		
				As	Pb	Cd
22	Bivalve	Nuculidae	<0.25	7.8	<0.25	3.2
35	Bivalve	Nuculidae	<0.25	11.	2.2	1.2
45	Bivalve	Nuculidae	<0.25	5.1	0.97	1.3
59	Bivalve	Nuculidae	<0.25	5.1	<0.25	5.2
59	Bivalve	Nuculidae	<0.25	5.9	.031	1.9
100	Hermit Crab	Paguridae	<0.25	7.6	0.49	2.4
53	Hermit Crab	Paguridae	<0.25	11.	0.33	3.1
41	Shrimp	Pandalidae	<0.25	13.	0.75	3.5
41	Sea Urchin	Strongylocentrotidae	<0.25	<0.5	1.3	8.1

TABLE 4

Trace metal residues in zooplankton, phytoplankton,
and neuston from the Bering and Chukchi Seas.

Station No.	Specimen	Hg	ppm Dry Weight		
			As	Pb	Cd
11	Zooplankton	<0.25	4.5	215.	6.9
13	Zooplankton	NA ¹	1.5	97.	1.7
15	Zooplankton	NA	2.8	17.	1.3
50	Zooplankton	NA	1.7	17.	0.75
55	Zooplankton	NA	0.99	21.	0.85
57	Zooplankton	<0.25	3.8	17.	1.4
52	Phytoplankton	NA	1.4	31.	0.90
53	Phytoplankton	NA	<0.5	11.	0.51
61	Phytoplankton	NA	0.59	47.	0.55
64	Phytoplankton	NA	0.80	8.1	0.33
69	Phytoplankton	<0.25	<0.5	103.	1.3
72	Phytoplankton	NA	1.3	118.	1.7
83	Neuston	NA	2.0	11.	1.0
86	Neuston	<0.25	2.8	33.	2.1

¹ NA - Not analyzed.

higher than the corresponding lead values. For most marine species, arsenic exists as arsenobetaine, a water soluble organoarsenical compound that poses little threat to human consumption or to the organism (Eisler, 1988). The data indicates that a direct correlation cannot always be made between the residues found in the sediment to those found in the biota residing in that particular sediment.

Arsenic values were comparable to the cadmium values in zooplankton and phytoplankton (Table 4). The lead values were probably unrealistically high (8.1–215 ppm, dry weight), based on work of other investigators (Flegal, 1985). Flegal found that phytoplankton residues, collected from the central Pacific Ocean, contained 0.04 ppm lead (fresh weight) and zooplankton contained 0.05 ppm lead (fresh weight). We suspect that these high values may have been due to contamination from the ship's hull since the paint and rust chips from the ship were known to contain lead. The plankton tows were made only 15 to 20 m below the surface of the water and lead in the plankton and the neuston may have been contaminated by the rust or paint chips. These data should be cautiously interpreted.

Cadmium and arsenic concentrations in the plankton and neuston may not have been as severely affected by the ship's contamination, but these findings should be viewed with caution because we do not definitely know the chemical contents of the paint and rust chips from the ship. For example, our values for cadmium (Table 4) were lower than those collected in the northeast Pacific Ocean where Martin *et al.* (1975) found cadmium concentrations ranging from 2.0 to 5.0 ppm (dry weight) except 10 to 20 ppm (dry weight) off Baja, California. To avoid problems with contamination from the ship, these

investigators collected their samples from an inflatable dinghy rowed several hundred meters away from the ship. However, they found their cadmium data to be comparable to their data on the previous cruise when they performed their plankton tows directly off the research vessel.

Both arsenic and cadmium tended to be elevated in these marine biota because of their ability to accumulate these contaminants from the seawater or food sources and not due to localized pollution (Eisler, 1985, 1988). We have no reason to suspect that the water column was severely contaminated, even though we did not analyze the water column for arsenic and cadmium. There are, however, cadmium values for water that were collected from the Bering Sea during the Second (1984) Joint US-USSR Expedition (Montgomery & McKim, personal communication). During the 1984 expedition, they found cadmium in the water column ranging from <5.0 to 100 ng l. They used differential pulse anodic stripping voltametry and a rotating disk electrode to make these measurements.

Cadmium especially tends to accumulate in a marine organism with the age of the organism (Eisler, 1985). In view of these facts, a likely explanation for the high cadmium concentrations found in walrus by Taylor and coworkers could be linked to longevity and not to pollution sources. To further explain the high concentrations of cadmium in walrus, more research is also needed to determine how much cadmium is bioaccumulated in the food chain.

We wish to thank Mark Abramovitz, Steven Boateng, and Brenda Cheek for their able assistance in preparing these samples for analyses. The patience and expert assistance of the crew of the *Akademik Korolev* are deeply appreciated. We also wish to thank Texas A&M University for the use of their box corer and other coring equipment that was provided to us.

Subchapter 8.4:

Distribution of Radionuclides

8.4.1 Investigation of Cesium-137 Distribution in Seawater

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Introduction

Nuclear exercises during the last 30 years and modern development of nuclear energy are the main sources of global and regional nuclear pollution of the biosphere, especially the world oceans. The main potential hazard is the accumulation of long-lived radionuclides of anthropogenic origin, such as Sr⁹⁰, Cs¹³⁷, and Pt²²⁹, in various natural objects.

The stable level of nuclear pollution in the environment (after the banning of nuclear exercises in the atmosphere) was disturbed in 1986 by the accident at the Chernobyl nuclear power station, which led to a massive input of radioactive substances. As a result of this accident, very high concentrations of radionuclides were found in the environment of Europe and the whole of the Northern Hemisphere (Uematsu & Duce, 1986; Buessler, 1987; Kusakabe *et al.*, 1988; Nikitin *et al.*, 1988).

During the 47th cruise of the Soviet research vessel *Akademik Korolev*, we investigated the present state of radionuclide contamination in the waters of the Chukchi and Bering Seas based on the distribution of the long-lived radionuclide Cs¹³⁷.

Methods

Sampling of large volumes of water (0.8–1.1 m³) was carried out at depths of 0 to 170 m with immersion pumps, models 'NIVA' and 'MALYSH.' To selectively concentrate the Cs¹³⁷ from the sea water, we used fibrous sorbents, 'MILTON-T,' impregnated with copper ferrocyanide (Vakulovsky, 1986). After sampling, the sorbent was ashed in an oven at temperatures not exceeding 450°C. The ash (10–15 g) was packed hermetically in polyethylene film. Later these samples were transported to the special laboratory of the State Oceanographic Institute (Odessa Branch), where analyses were carried out using the following gamma-spectrometer:

- scintilatic (firm LKL WALLAC type COMPU-GAMMA 1282)
- semiconductor (analyzer AMA-0202 with detector DGDK-100B)

The accuracy was in the range of 10%, and the detection limit was 0.1 Becquerel (Bq).

The concentration of Cs¹³⁴ (the natural radioactive form of cesium) in every sample was less than the detection limit. Therefore, we suggest that the maximum possible concentration

of Cs¹³⁴ in the investigated samples could not be any higher than 0.015 Bq/ m³.

Results and Discussion

The concentrations of Cs¹³⁷ that were measured during this investigation of the Bering and Chukchi Seas are given in Table 1.

Assuming that the detection limit of Cs¹³⁴ was the maximum possible concentration of this radionuclide in the investigated areas, and basing this concentration on the initial correlation of Cs¹³⁷/Cs¹³⁴ activities during the Chernobyl accident, we estimated its influence on the radioactive pollution of the

TABLE 1

Concentration of Cs¹³⁷ in the Bering and Chukchi Seas, summer, 1988.

Date	Location lat. long.	Layer, (m)	Average concentration, (Bq/m ³)
27.07	57°30' N, 174°30' W	0–80	1.6
29.07	57 56 175 04	0–80	2.0
01.08	60 28 177 50	0–120	2.4
03.08	62 10 179 50	0–60	2.0
04.08	63 00 176 00	0–80	2.3
06.08	64 43 177 50	0–20	1.9
07.08	63 25 172 10	0–60	3.7
09.08	67 44 172 50	0–40	2.4
10.08	68 40 168 20	0–40	2.2
11.08	67 46 167 19	0–30	2.9
11.08	67 45 168 26	0–40	2.8
14.08	66 55 168 50	0–30	3.2
15.08	66 33 168 30	0–40	2.8
"	65 58 168 36	0–3	1.8
"	65 55 169 22	0–3	1.7
"	65 50 169 10	0–3	1.6
"	65 42 169 40	0–3	2.6
"	65 40 168 30	0–3	2.3
"	65 38 168 21	0–3	3.3
20.08	65 14 169 21	0–40	2.6
22.08	64 23 169 29	0–30	2.1
27.08	53 59 176 00	0–170	2.2
29.08	53 11 177 18	0–90	2.4

Bering and Chukchi Seas. These estimations showed that the maximum of "Chernobyl's" concentration could not exceed 0.07–0.09 Bq/m³.

Taking into consideration that the real concentrations of Cs¹³⁷ in the Chukchi and the Bering Seas are 1.6 Bq/m³ (Table 1), then the maximum contribution of "Chernobyl's" Cs¹³⁷ could not have been more than 6%.

The results of the vertical distribution of Cs¹³⁷ in the Chukchi and Bering Seas and the Gulf of Anadyr are given in Figs. 1, 2, and 3. The concentration of Cs¹³⁷, which is the average value along the whole investigated area, was estimated as 2.4 Bq/m³ (a range of 1.6 to 3.7 Bq/m³), 2.4 Bq/m³ for the Chukchi Sea and the Gulf of Anadyr, and 2.3 Bq/m³ for the Bering Sea. The maximum concentration, 3.7 Bq/m³, was determined in the 0 to 40 m layer to the southwest of St. Lawrence Island.

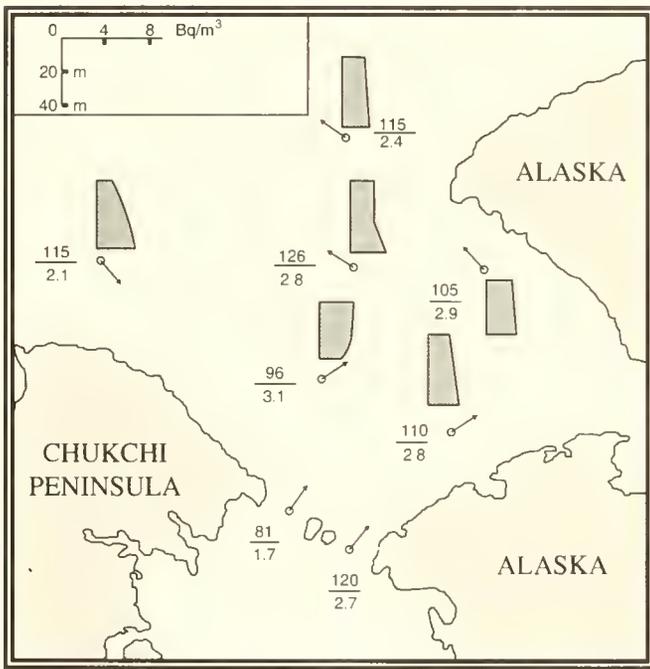


Fig. 1. Vertical profiles of Cs¹³⁷ concentrations in the Chukchi Sea (the main direction of the currents are shown by the arrows). Numerator = Cs¹³⁷ budget (Bq/m²), denominator = the average concentration of Cs¹³⁷ (Bq/m³) at that station from the surface to the bottom.

It is important to note that the vertical distribution of Cs¹³⁷ in the Bering Sea was homogeneous. The vertical distribution in the Chukchi Sea, however, was characterized by an elevated concentration in the bottom layers (ranging from 2.5 to 5.5 Bq/m³ and an overall average of 3.1 Bq/m³).

The maximum gradients for vertical distribution were observed in the western Chukchi Sea—that is, 1.1 Bq/m³ in the surface layer (0–3 m) and 3.5 Bq/m³ at a depth of 40 m. Simultaneously, a correlation in spatial distribution of Cs¹³⁷ and salinity was observed such that in a direction from the west to the east there was a decrease in the vertical gradients of these parameters and an increase of Cs¹³⁷ concentrations with an increase in salinity in the upper layers.

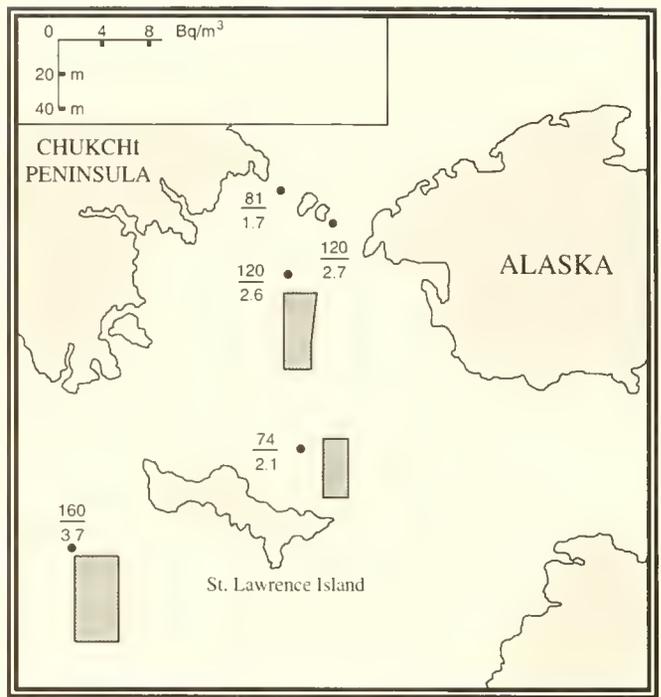


Fig. 2. Vertical profiles of Cs¹³⁷ concentrations in the Northern Bering Sea.

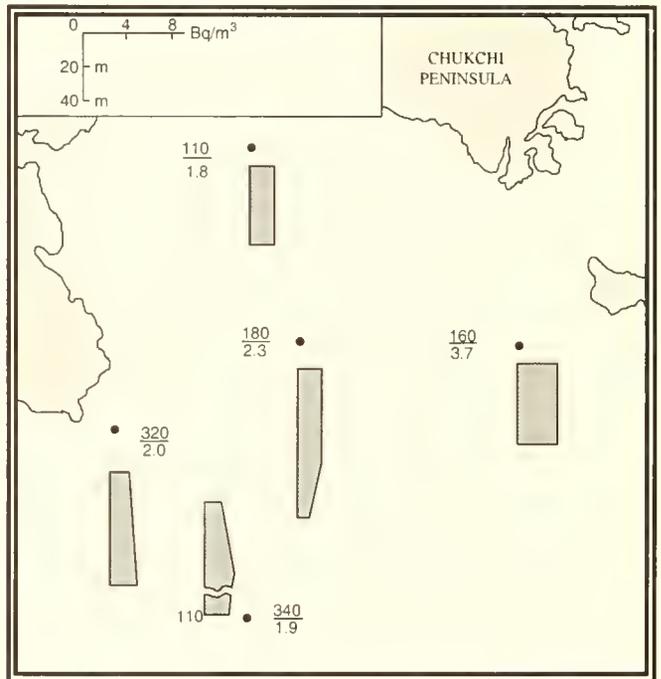


Fig. 3. Vertical profiles of Cs¹³⁷ concentrations in the Gulf of Anadyr.

Obviously, the flow of surface waters from the west into the Chukchi Sea significantly influenced the distribution of Cs¹³⁷, especially in the western part of the Chukchi.

The observed homogeneity of the Cs¹³⁷ over these areas demonstrated the lack of local inputs of this material. The concentration level was typical for the world oceans and was indicative of global input of Cs¹³⁷ from the atmosphere over a long period of time.

We calculated a concentration budget for Cs¹³⁷, using its vertical distribution in different areas (Figs. 1,2,3). For the period from the beginning of nuclear exercises and extending up to 1978, the total input of Cs¹³⁷ on the Earth's surface was estimated as 1,740 and 1,150 Bq/m² for the latitudes 60–70°N and 70–80°N, respectively (Vakulovsky *et al.*, 1985).

Accounting for radioactive disintegration, the concentration of Cs¹³⁷ could decrease by no less than twice; therefore, the maximum estimated amount of Cs¹³⁷ on the Earth's surface in

the above-mentioned areas should not exceed 1,370 and 575 Bq/m³. Amounts of Cs¹³⁷ in the seawater, calculated on the basis of this investigation, are 210 Bq/m³ for the Gulf of Anadyr and 120 Bq/m³ for the Chukchi Sea and the northern Bering Sea.

The average concentrations of Cs¹³⁷ in the Chukchi and the Bering Seas are 10–50 times lower than in the Black Sea (Buessler, 1987; Nikitin *et al.*, 1988) and in the Barents, the Greenland, and the Kara Seas, where local sources of radioactive pollution are situated.

Subchapter 8.5:

Distribution of Organic Matter

8.5.1 Characterization of Sediment Organic Matter

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Introduction

Carbon isotopic compositions are effective indicators of the source of sedimentary organic matter (Craig, 1953). For example, Sackett and Thompson (1963), Hunt (1970), and Hedges and Parker (1976) used stable carbon isotopes as a tracer of the incursion of terrestrial organic matter into the estuaries bordering the Gulf of Mexico and the Atlantic Ocean. A depletion in carbon of the heavier isotope (¹³C) is generally associated with terrestrially derived organic matter, while an enrichment suggests incorporation of marine derived material (Fry & Sherr, 1984).

Nitrogen isotope variations are less associated with the environment of their origin (Sweeney & Kaplan, 1980) but rather reflect the trophic level from which the organic matter has been derived (Miyake & Wada, 1967; Wada & Hattori, 1976; Macko *et al.*, 1982; Minigawa & Wada, 1986). Primary producers of organic nitrogen are isotopically like their source, atmospheric nitrogen, while consumers of organic matter become enriched in the heavier isotope (¹⁵N) with each step up the trophic ladder. The isotopic composition of nitrogen incorporated into marine sediments may indicate not only the trophic shift but also the degree of cycling and recycling of the organic matter in the water column and in the sediments. Remineralization of organic nitrogen may not be accompanied by significant isotopic fractionation; however, many reactions of nitrogenous compounds in natural and cultured systems may lead to considerable nitrogen isotope fractionation (Cifuentes *et al.*, 1988; Hoch *et al.*, 1989).

Carbon and nitrogen elemental content, and more specifically the C/N ratio, are also useful for indicating the sources of organic matter. Terrestrial plants with high carbon to nitrogen ratios are contrasted with marine organisms rich in organic nitrogen. The relative contributions of these two sources can be estimated by their C/N ratios (Faganeli *et al.*, 1988). Of course, the picture is complicated in nature because there are more than two end members in most ecologic systems.

This report summarizes the results and conclusions of a four year effort to study the isotopic and elemental distribution of organic carbon and nitrogen of sediments within the Chukchi-Bering-Anadyr system. Included in the repertoire of samples are those recovered in the Third Joint US-USSR Bering & Chukchi Seas Expedition in August 1988.

The present distribution of carbon and nitrogen throughout the arctic marine ecosystem can result from several well known but, perhaps, inadequately studied processes: 1. primary production through fixing atmospheric carbon dioxide and nitrogen by phytoplankton; 2. transport of nutrients into the system from upwelling of deep Pacific waters; 3. transportation of primary production of terrestrial origin by rivers and streams; and 4. recycling of these elements by remineralization of organic matter both in the sediments and in the water column. In this report we are primarily concerned with the sources and sinks of these elements within the sediments.

Methods

Sediment samples were collected on eight different cruises from 487 stations at approximately 280 separate locations. Table 1 lists the cruise identifications, dates, and number of samples, plus replicates of sediments taken for each cruise. Sample station locations are shown on the map of Fig. 1. Because of strong bottom currents, some samples (particularly those recovered from the area of Anadyr Strait west of St. Lawrence Island) were mainly cobbles and boulders with very little fine-grained sediments at the surface. Samples from this locale are largely muds that were found adhering to cobbles or the van Veen grab.

Samples were frozen at the time of collection and maintained frozen until prepared for analysis in the laboratory. Samples were thawed, acidified, diluted, and picked free of any visible macro-organic materials such as worms, amphipods, hydroids, bivalves, etc. The residues were filtered, washed, air-dried at 60°C, and very gently disaggregated by passing through a screen of opening size equal to 150 μ meter. Any material not passing this mesh was discarded.

The nitrogen isotope measurements were made on a Nuclide model RMS-6 mass spectrometer. For carbon isotopes a VG Micromass model 602-E instrument was used. The data are expressed by the conventional del notation:

$$\delta^{13}C = \left[\frac{(^{13}C/^{12}C)_{\text{sample}}}{(^{13}C/^{12}C)_{\text{std}}} - 1 \right] * 10^3 \text{ ‰}$$

as the parts per thousand difference in the isotope ratio of the sample and an arbitrary standard, the carbon dioxide generated from the Peedee Belemnite (Craig, 1957). A similar expression,

TABLE 1

Cruises on which sediment samples were collected.

Cruise ID	Vessel	Dates	Number of samples
HX-72	α - Helix	12-23 July 1985	96
HX-74	α - Helix	27 August-10 September 1985	29
HX-84	α - Helix	30 June-10 July 1986	33
HX-85	α - Helix	11-26 July 1986	25
HX-88	α - Helix	24 August-9 September 1986	74
TT-213	T.G. Thompson	20 July-10 August 1987	61
TT-222	T.G. Thompson	2-25 July 1988	59
AK-47	<i>Akademik Korolev</i>	26 July-24 August 1988	110

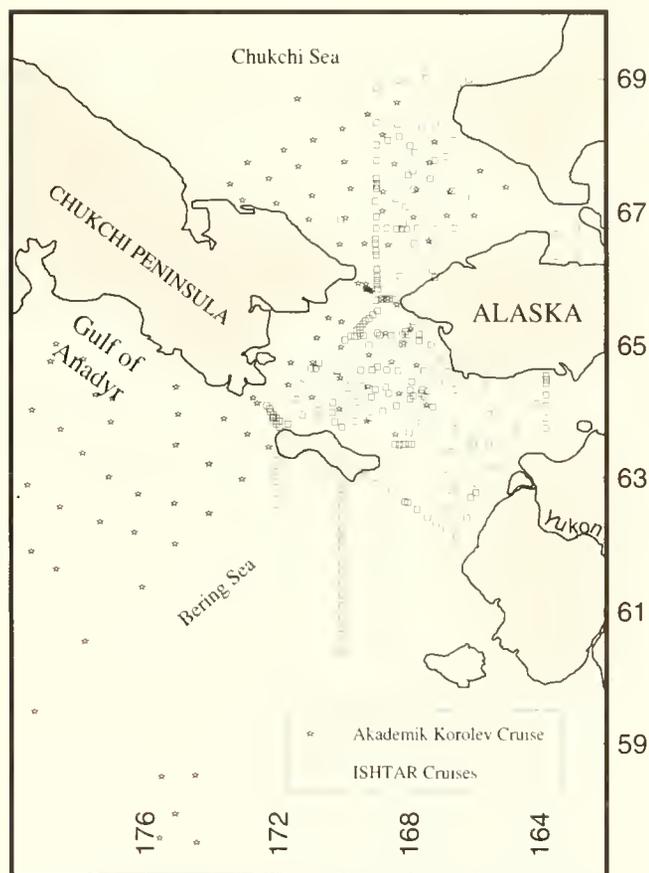


Fig. 1. Location of stations from which sediment samples were recovered.

$\delta^{15}\text{N}$, is used for $^{15}\text{N}/^{14}\text{N}$ data where atmospheric nitrogen is taken as the standard. Based on repeated analysis of samples and standards, the $\delta^{13}\text{C}$ values have an error of less than 0.1 per mil (‰) and $\delta^{15}\text{N}$ of less than 0.3 per mil. Sealed tube oxidations were used to prepare CO_2 suitable for isotopic analysis (adapted from Sofer, 1980). A sealed tube reduction

of organic nitrogen (adapted from Macko, 1981) in Pyrex tubes at 590°C combined with a postreduction purification, provided N_2 suitable for nitrogen isotope analysis.

Carbon and nitrogen elemental compositions of the dried sediments were measured using a Perkin-Elmer CHN-Analyzer, model 240 B. Sufficient numbers of blanks, standards, and replicated samples were determined to allow an estimated standard deviation of $\pm 2\%$ of the amount present.

Perhaps one of the more readily assimilated means of representing large amounts of data is by contour plotting on a map of the study area. While an attempt has been made to be completely objective in the selection of contour lines, some subjectivity is probably inherent in the "canned" computer program used in these presentations ("SURFER Ver. 4, 1989," Golden Software, Inc.).

Results and Discussion

Because only the clay-silt fraction size was used for analysis, the C and N quantitative data do not represent values for the total sediment and thus cannot be used as direct indicators of total sediment organic carbon or nitrogen. This organic fraction probably represents, for the most part, material added to the sediments either directly or through incorporation into fecal pellets and other small particles. It includes material reworked or produced by bacterial or other nano-organisms. By restricting the analyte to the fine-grained fraction, it was hoped that the carbon and nitrogen analyzed would represent an integrated value uninfluenced by inclusion of even a small quantity of macro-organisms.

Results of isotopic and elemental analyses of the sediments are summarized in Table 2 and are incorporated into graphical representations in the isopleths for $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, weight percent C, weight percent N, and C/N ratios of Figs. 2 through 6. Although not all of the samples collected have been analyzed and results for some stations are incomplete, all of the contour

TABLE 2

Summary of Analyses of Sediment Samples

Attribute	δ^{13}	C	δ^{15}	N	C/N
Average	-21.5	0.88	8.0	0.12	8.66
Std. Dev. (± 1)	1.24	0.52	2.27	0.07	2.39
No. of Samples	234	299	167	299	299
Maximum Value	-16.0	4.30	19.4	0.43	38.2
Minimum Value	-27.3	0.12	0.2	0.0008	2.4

figures show a common trait for the measured parameters; viz., organic matter generated or deposited in the sediments of the eastern part of the study area is readily distinguished from that of the western part.

Carbon

In Fig. 2, six general locations show enrichment in organic carbon: southern Bering Sea, central and northern Gulf of Anadyr, western Anadyr Strait, just north of the Bering Strait, and western Chukchi Sea. Though other parts of the study area are less organic-rich than these "hot spots," the entire Bering-Chukchi locale is abundant in carbon comparable to many other shelf environments. The average (0.88, Table 2), for instance, is not unlike that found for the Gulf of Mexico and other shelf environments of the world (Plucker, 1970; Newman *et al.*, 1973; Gearing *et al.*, 1977).

The distribution of the carbon isotope values (Fig. 3) shows lighter (more negative) values east and north of St. Lawrence Island as compared with those of the southern Bering Sea, Gulf of Anadyr, or the western Chukchi Sea. Presumably there is a considerable contribution of terrestrial organic carbon from the Kvichak, Kuskokwim, and Yukon Rivers and other minor drainage systems of Alaska. No such sources are apparent in the western part of the study area due to drainage from the Chukchi Peninsula.

The $\delta^{13}\text{C}$ values grade "lighter" away from the Yukon River toward the Seward Peninsula, suggesting either greater deposition of the terrestrially derived organic matter at some distance from the river delta (Dean, 1986, personal communication) or a contribution from the Seward Peninsula, perhaps from older mining operations on shore or more recent pollution from anthropogenic sources at Nome, Alaska. Values of the Gulf of Anadyr and the western Chukchi Sea resemble those of the open ocean. They show no contribution of terrestrial organic matter from the Chukchi Peninsula or from the Anadyr River.

Nitrogen

Del ^{15}N values of the sediment fines are shown graphically in Fig. 4. Values of 8 to 9 per mil are common throughout the study area. They become somewhat lighter in the Gulf of Anadyr (7 per mil) in the southern Bering Sea (4.5 per mil) and in the eastern Chukchi Sea (4.5 per mil). Three isotopic "lows"

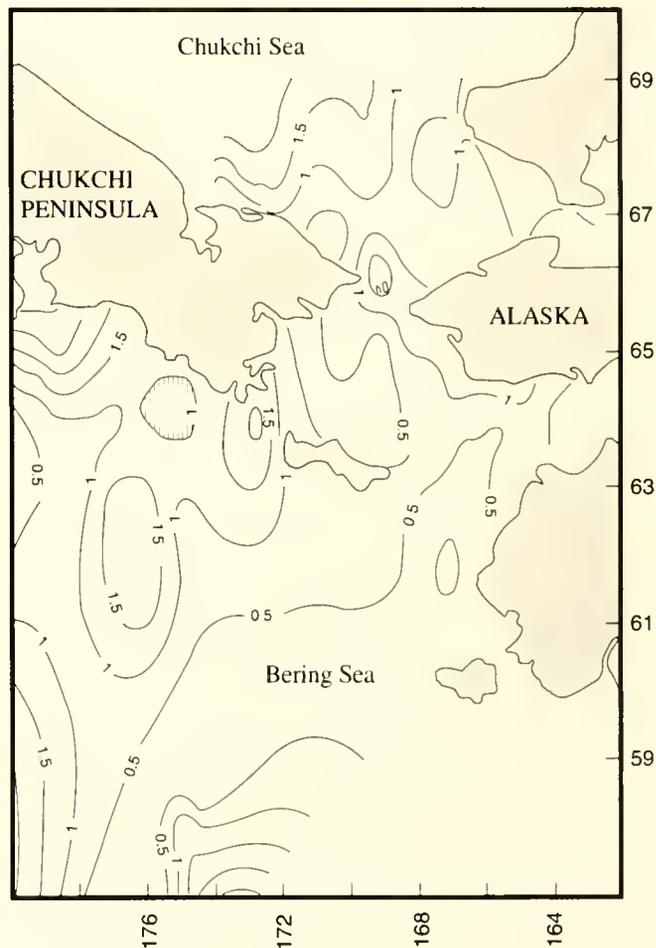


Fig. 2. Areal distribution of carbon concentrations in sediments.

occur at the biological "hot spots" north of St. Lawrence Island and two locations just north of the Bering Strait in the central Chukchi Sea. An isotopic "high" is associated with the output of the Yukon River.

Organic nitrogen content of sediment fines, shown in Fig. 5, is fairly consistent with the organic carbon content. Figure 6 shows the relationship between the two components. The relatively high correlation is not unusual and merely reflects the similarities of all biological tissues. The scatter about the regression line illustrates the relative variations of the C/N ratios. The slope of the regression line in Fig. 6 corresponds

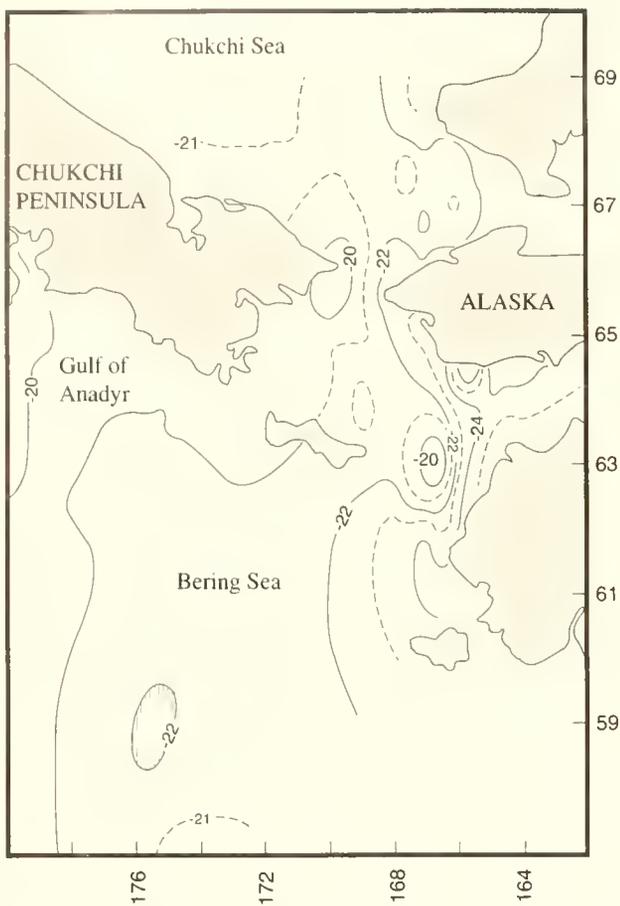


Fig. 3. Areal distribution of carbon isotope values of sediments.

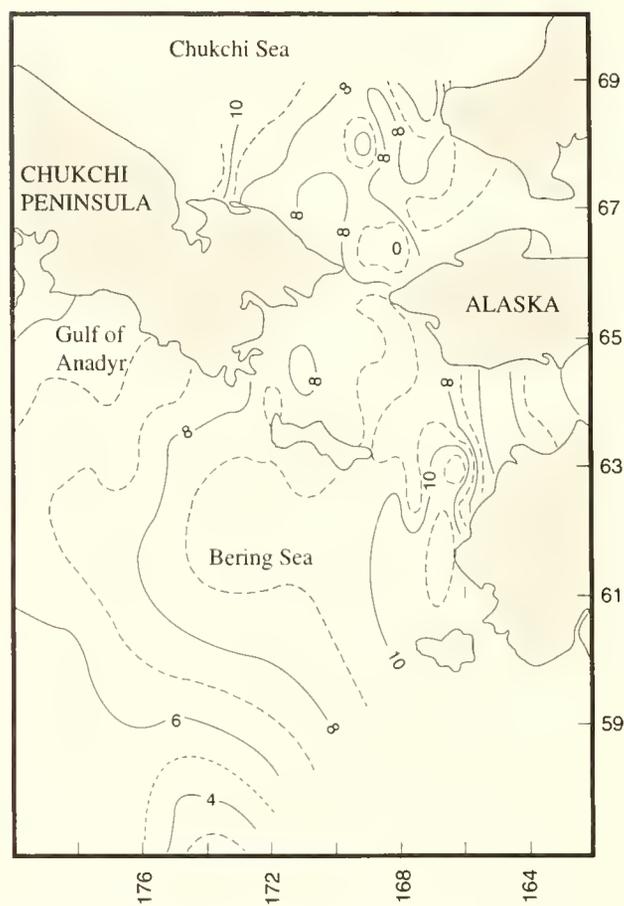


Fig. 4. Areal distribution of nitrogen isotope values of sediments.

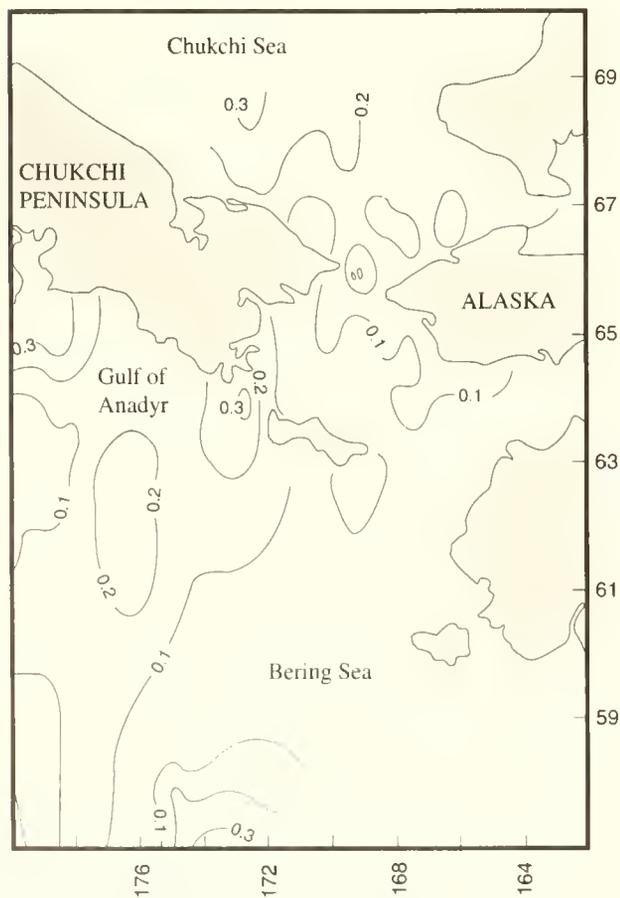


Fig. 5. Areal distribution of nitrogen concentrations in sediments.

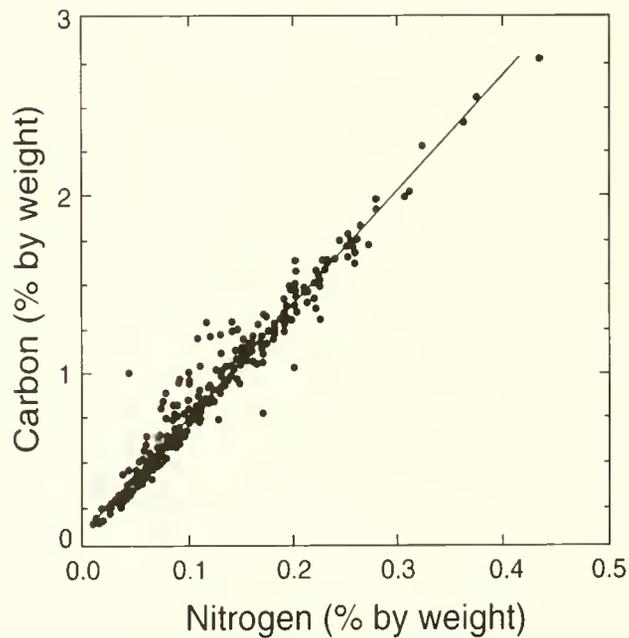


Fig. 6. Relationship between carbon and nitrogen concentrations in sediments.

to a C/N ratio (at/at) of 7.7, slightly higher than the commonly accepted "Redfield Ratio" of 6.6 for marine organic matter (Froelich *et al.*, 1979). Most likely, this indicates a contribution of terrestrially derived organic matter to these sediments. There is a possibility that recycling of sedimentary organic matter could lead to a selective reduction in nitrogen content, thus raising the C/N ratio.

The distributions of C/N ratios in sediment fines of the study area are shown in Fig. 7. A strong influence of the contribution of terrestrial organic matter is readily apparent at the mouth of the Yukon River. This is the same relationship as observed for the carbon isotopic composition distribution. Thus, much of the organic matter in these sediments must be derived from terrestrial sources transported to the Bering Sea by the Yukon River. The relationship between the two parameters is shown in Fig. 8. There is a complete overlap of samples from the area of the mouth of the Yukon River and Norton Sound with those from the rest of the study area. All of the samples having $\delta^{13}\text{C} < -24$ per mil or C/N ratio > 11 are from the Yukon area.

Figure 9 shows isopleths of a devised "environment of deposition" parameter formed from the normalized (0.0 to 1.0), unweighted product of $\delta^{13}\text{C}$ and the C/N ratio values used for Figs. 3 and 7, respectively. Both of these parameters are dependent, at least in part, on their terrestrial organic contribution. Thus, their product would tend to emphasize this

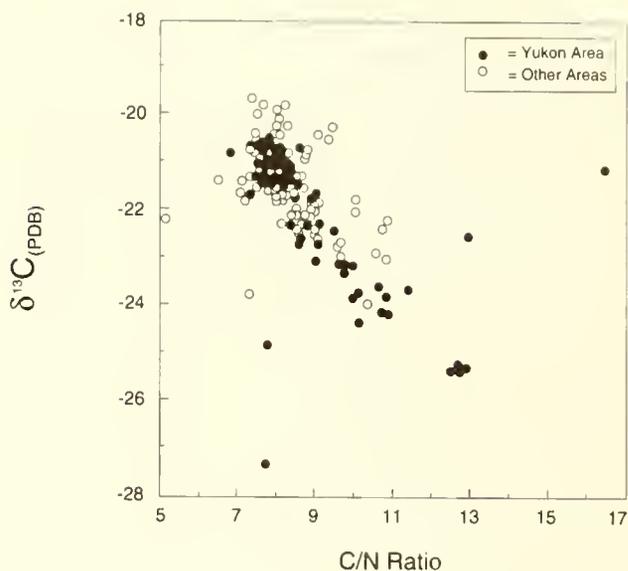


Fig. 8. Relationship between carbon isotope values and C/N ratios for sediments.

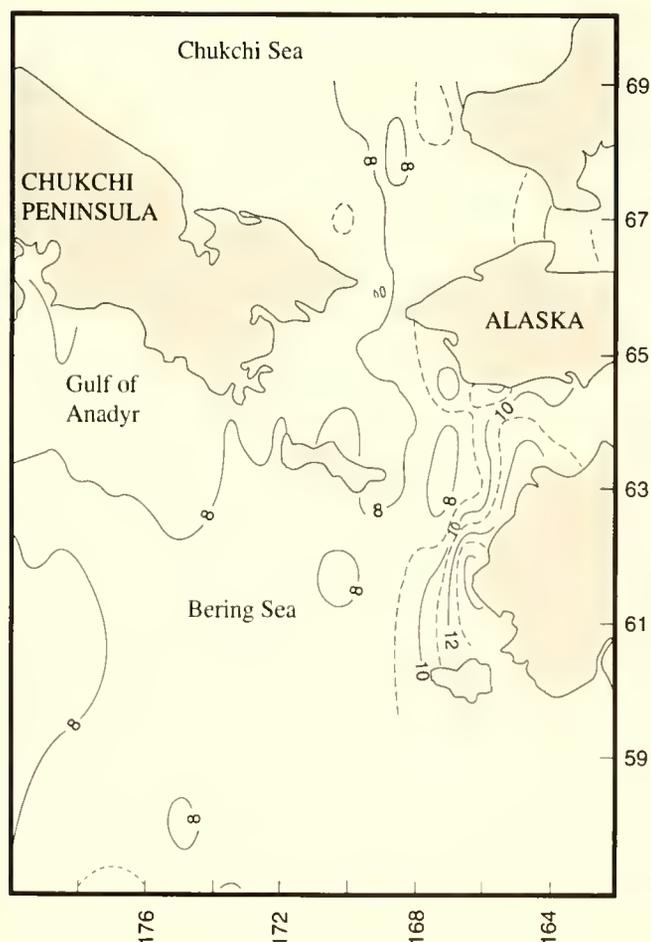


Fig. 7. Areal distribution of C/N ratios in sediments.

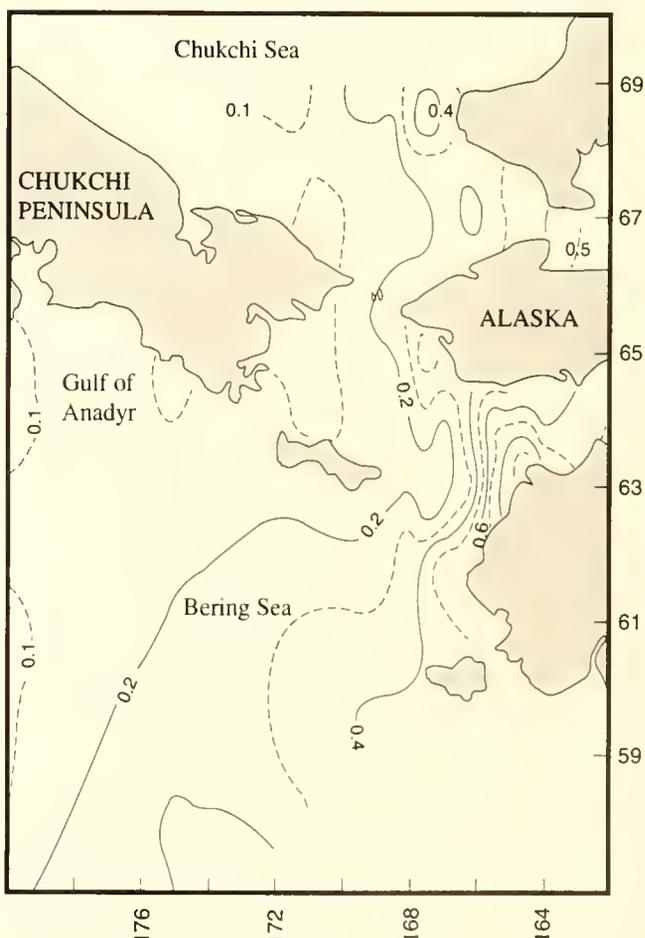


Fig. 9. Contours of a relative parameter of "environment of origin" of sediment organic matter.

aspect and minimize the influence of those samples for which one or the other value was more influenced by a factor other than the environment of origin. The influence of Yukon derived organic matter is quite evident.

A similarly derived parameter is shown by the isopleths of Fig. 10. In this case, contours of a normalized unweighted product of the carbon and nitrogen elemental content of Figs. 2 and 5 are plotted. Such a parameter would only tend to emphasize locations of concentrations of sediment organic matter in the fine-grained fraction (not biomass). Organic "hot spots" are evident in the southern Bering Sea, the Anadyr River, the Gulf of Anadyr, Anadyr Strait, Bering Strait, and the western Chukchi Sea. No excessive sediment organic concentrations are apparent at the Yukon River Delta nor at the site of high biological activity reported by Grebmeier and McRoy (1989) northeast of St. Lawrence Island.

Support for this study was provided, in part, by the ISHTAR project of the National Science Foundation (DPP-8405286, DPP-8605659) and by The University of Texas at Austin, Marine Science Institute. A major contribution to the overall sediment study was the participation of one of us (E.W.B.) in the Third Joint US-USSR Bering & Chukchi Seas Expedition aboard the Soviet research vessel *Akademik Korolev*. We express appreciation to the USSR State Committee for Hydrometeorology and the US Fish and Wildlife Service, USA, who made this sampling effort and our participation possible.

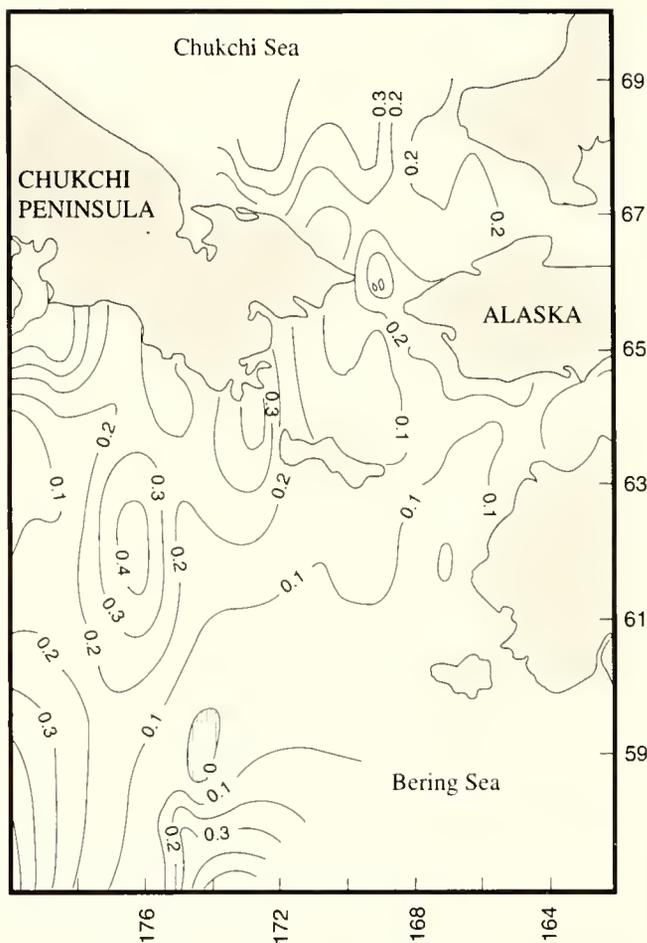


Fig. 10. Contours of a relative concentration parameter of sediment organic matter.

Subchapter 8.6:

Abiotic Processes of Decomposition of Some Organic Contaminants

8.6.1 Solar Oxidation of Benzo(a)pyrene

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Introduction

The extent of photochemical processes and their contribution to self-purification of the marine environment from carcinogenic PAH's are determined by both the value and distribution of solar irradiation energy (Rabek, 1985; Mill *et al.*, 1981) and the level of pollution of seawater, as well as the concentration and composition of pollutants. The latter may have an influence upon the pattern and intensity of the degradation processes of PAH's (Kirso & Gubergrits, 1971; Gubergrits *et al.*, 1975). Although systematic studies have been carried out on the photooxidation of individual PAH's in water (Kirso & Gubergrits, 1971; Gubergrits *et al.*, 1975; Paalme *et al.*, 1976, 1983b), there are few data on these processes under natural conditions. Therefore, during the cruise of the R/V *Akademik Korolev* (July–November 1988) a study was undertaken on the kinetics of the oxidative photolysis of a typical carcinogenic PAH—benzo(a)pyrene [BaP] (Clar, 1971) in the Bering Sea (Table 1).

It is known that the Bering Sea is almost wholly in the subarctic zone, excluding its northern parts, which are in the arctic temperature zones (Izrael & Tsyban, 1987). The main body of its waters is characterized by a subarctic structure whose specific feature is the existence of cold and warm intermediate layers. The upper layer thickness average 25–50 m, the salinity being 32.8–33.4 and the temperature

about 5 to 7°C. According to Izrael and Tsyban (1987), PAH's are permanent and typical components of these ecosystems.

Taking into account the low influence of this area from human activities, the physicochemical parameters of the atmosphere above these waters, and characteristics of the surface water layer, a study of sunlight photolysis of PAH's in seawater at lower temperatures and low intensity of solar irradiation was of interest.

Methods and Materials

Detailed descriptions of the techniques used in carrying out these experiments are described in Subchapter 2.6 of *Results of the First Joint US–USSR Central Pacific Expedition (BERPAC), Autumn 1988* (Nagel, 1992). Experimental conditions are described in Table 1.

Results and Discussion

From kinetic data (Table 2; Figs. 1, 2) it follows that during the first hour of exposure, a decrease in the BaP concentrations in seawater is described by a formal-kinetic equation for the first-order reaction, where c_0 and c_t are the initial BaP concentration at zero time, and that at a certain time t , k is the constant of the first-order reaction, the dimensions for this constant are per second (s^{-1}).

TABLE 1

Exposure of BaP solution in seawater
(the 47th cruise of the R/V *Akademik Korolev*).

Month (1988)	Experiment Number	Coordinates	Water Temp. $t = ^\circ\text{C}$	Average dose of solar radiation Q MJ/m ² during the first 3 hours
August	1	53°58'N/176°28'W	14.1	1.48
	2	53°58'N/176°28'W	15.7	1.09

TABLE 2

Kinetic characteristics of photochemical transformation of BaP in sea water under solar irradiation in the Bering Sea (47th cruise of the R/V *Akademik Korolev*, July–November 1988).

Experiment No. (see Table 1)	Initial BaP concentration	Rate constant 10^{-4}s^{-1} ($k \pm$)	Number of data points	Correlation coefficient r (first-order)	Sterility of media
1	1.47	1.69 ± 0.13	5	0.99	-
2	4.20	1.60 ± 0.08	7	0.99	+
	4.44	1.20 ± 0.16	6	0.97	-

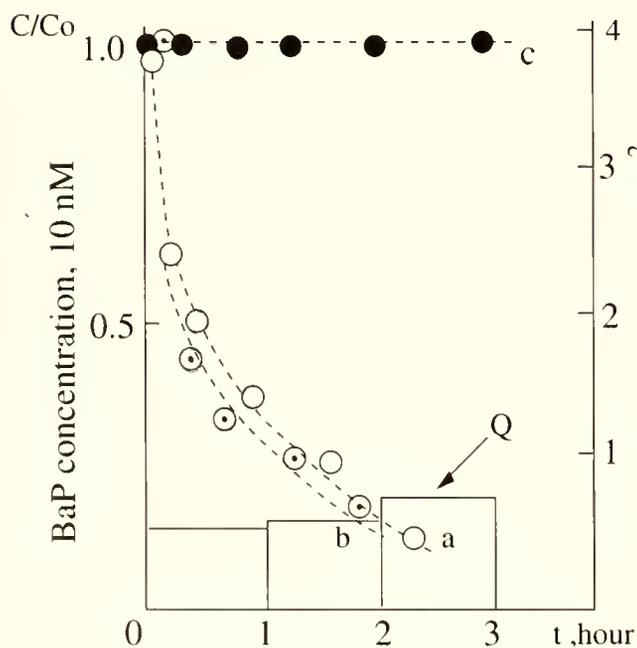


Fig. 1. Kinetics of BaP degradation under sunlight irradiation on the surface of the Bering Sea (coordinates: 67°42' N/115°43' W): a) in sterilized sea water; b) in sea water; and c) by autooxidation.

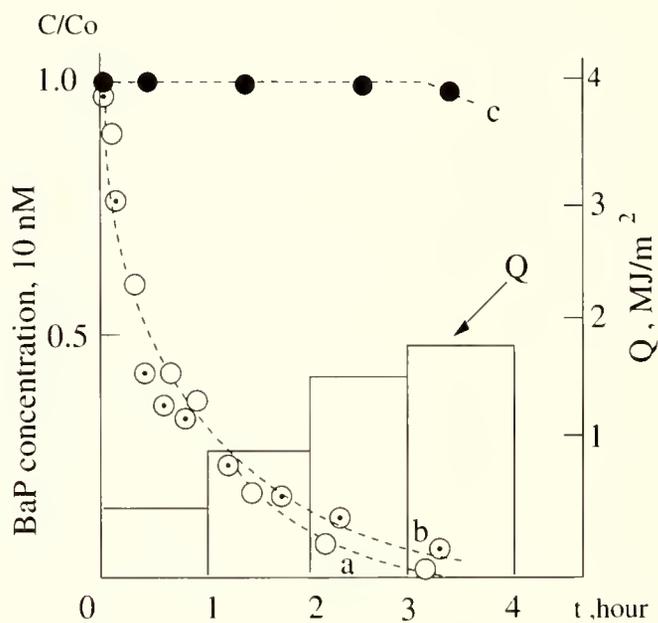


Fig. 2. Kinetics of BaP degradation under sunlight irradiation on the surface of the Bering Sea (coordinates: 53°58' N/175°28' W): a) in sterilized sea water; b) in sea water; and c) by autooxidation.

8.6.2 Influence of Ultraviolet Radiation on the Fate of PCB's

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Introduction

Chloroorganic compounds are considered to be the most environmentally resistant of organic compounds. The only abiotic process resulting in PCB destruction is photochemical decomposition (Brown *et al.*, 1984), which leads to dechlorination of the higher halogenated molecules. Studies on the photochemical degradation of PCB's showed that the most active destruction of PCB's at low concentrations occurs at the level of 1 ng/l and that the PCB half-life values were about 1 to 2 years, depending on solar radiation rates (Bunce *et al.*, 1978).

It is important to note that PCB transformation by sunlight occurs both as a result of direct light absorption by these compounds and also due to the interaction between reagents formed by the sunlight and subsequent reaction with the PCB molecules—for example, by irradiation of an organic solute that the PCB's might be associated with (Van Noort *et al.*, 1988).

New data on photochemical PCB decomposition processes were obtained during the Third Joint US-USSR Bering & Chukchi Seas Expedition on board the research vessel *Akademik Korolev* in 1988.

Materials and Methods

In order to make an assessment of the impact of photochemical processes on the behavior of chlorinated hydrocarbons in marine ecosystems, scale-model experiments on the decomposition of standard Aroclor 1232 were carried out in the aquatic environment of the Chukchi Sea and the Bering Sea by exposing this Aroclor to natural sunlight.

The experiments were conducted in 5-l reactors with a surface area of 400 cm². The side walls of the reactors were screened with dark foil. The Aroclor 1232 mixture was added in acetone to give a concentration of 100 ng/l in the sterilized seawater that was placed in the reactors. Control flasks were prepared identically and screened from the sunlight. Every hour, three 0.5-l samples were removed from each reactor. The samples were extracted by shaking with n-hexane (twice with 50 ml). The extracts were concentrated using a rotary evaporator to a volume of 2 ml, whereupon they were purified by shaking them with concentrated sulfuric acid. Tests for PCB microbial decomposition were carried out at the same time as the photochemical tests and under similar conditions. These results are described in Subchapter 4.4 of this volume.

The PCB content in the solutions was determined using a Hewlett-Packard model 5840A gas chromatograph. The chromatography conditions were as follows: a 30-m fused quartz capillary column with an internal diameter of 0.32 mm and coated with a 0.25- μ m layer of DB-1 chromatography phase. The analysis was carried out using column thermostat temperature programming as follows: the initial temperature was 120°C, and the temperature was raised at 5°C/min up to 250°C and held there for 14 min; thus, the chromatography time was 40 min. The injector temperature was 225°C, the electron capture detector temperature was 300°C.

Results and Discussion

Table 1 shows the findings of the photochemical PCB decomposition in Bering Sea water. The data demonstrates that after 6 h of exposure, up to 50% of 2,2',3,4-tetrachlorobiphenyl component (BZ#41 - Ballschmitter & Zell, 1980) and 30 to 40% of certain tri- and tetrachlorobiphenyls were decomposed. In the microbial tests, however, 75% of the added 2,2',3,4-tetrachlorobiphenyl and up to 50–60% of some of the low-chlorinated components underwent a reaction of oxidation in 12 h (Fig. 1).

In the photolysis tests, only seven components of pentachlorobiphenyls exhibited some minor degradation. Hexachlorobiphenyls and higher-chlorinated compounds did not undergo any reaction under the experimental conditions.

Therefore, only 16 main components of the Aroclor 1232 technical mixture were significantly altered in the photochemical degradation tests.

The experimental data showed that in the seawater under the influence of photochemical PCB degradation, only direct dechlorination proceeded, and this was accompanied by isomerization and condensation. The rate of the reaction appeared to depend more on the molecular configuration than the number of chlorine substituents. The availability of chlorine atoms in locations 2,2' or 4,4' of biphenyl molecules appears to be a necessary requirement for PCB's to undergo a reaction of photochemical degradation.

Schematically, the process of photochemical PCB degradation (hexachlorobiphenyl) in seawater can be shown in the schematic (Fig. 2)

As the reaction scheme demonstrates, the photochemical PCB degradation in the seawater proceeds in a very regular pattern. Direct dechlorination takes place without the rupture of the bonds between the benzene rings and without biphenyl

TABLE 1

Photochemical degradation of different PCB components in sea water.

BZ' Cl No.	Position	Time of Exposure																			
		1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	5d	10d	15d	20d
		PCB Decomposed as Percent of Total Added (%)																			
7	2,4	1	5	8	10	12	14	16	17	17	18	18	19	20	20	20	20	21	21	22	23
16	2,2',3	3	8	11	13	16	18	19	21	22	23	24	24	25	26	27	27	31	31	32	32
52	2,2',5,5'	1	3	5	6	8	10	12	13	15	17	19	22	24	27	28	29	29	31	31	31
49	2,2',4,5'	6	9	13	16	18	20	22	23	24	26	27	27	28	28	28	29	30	30	30	30
42	2,2',3,4'	7	12	16	18	21	23	25	27	28	29	30	31	32	33	34	35	40	41	41	41
47	2,2',4,4'	4	7	9	10	11	11	12	12	13	13	14	14	15	15	16	16	19	20	20	20
84	2,2',3,3',6	4	6	8	9	10	10	10	10	11	11	11	12	12	12	13	13	14	14	14	14
119	2,3',4,4',6	2	5	6	7	8	8	9	9	9	10	10	10	10	10	11	11	15	15	15	15
36	3,3',5	3	4	6	7	8	8	9	9	9	10	10	10	10	11	11	11	11	11	11	11
91	2,2',3,4',6	3	3	5	6	6	7	7	7	8	8	8	8	9	9	9	9	9	9	9	9
102	2,2',4,5,6'	2	3	5	5	5	5	6	6	6	7	7	7	7	8	8	8	8	8	8	8
70	2,3',4',5	2	3	3	3	4	4	4	5	5	6	6	6	7	7	7	7	7	7	7	7
66	2,3',4,4'	2	2	3	3	4	4	4	5	5	5	6	6	7	7	7	7	7	7	7	7
85	2,2',3,4,4'	2	2	2	3	3	4	4	4	5	5	5	6	6	7	7	7	7	7	7	7
90	2,2',3,4',5	2	2	3	3	3	3	4	4	4	4	5	5	5	6	6	6	6	6	6	6
99	2,2',4,4',5	2	2	3	3	3	3	4	4	4	4	5	5	5	5	6	6	6	6	6	6

*Numbering corresponds to the convention of Ballschmitter and Zell (1980).

h = hours d = days

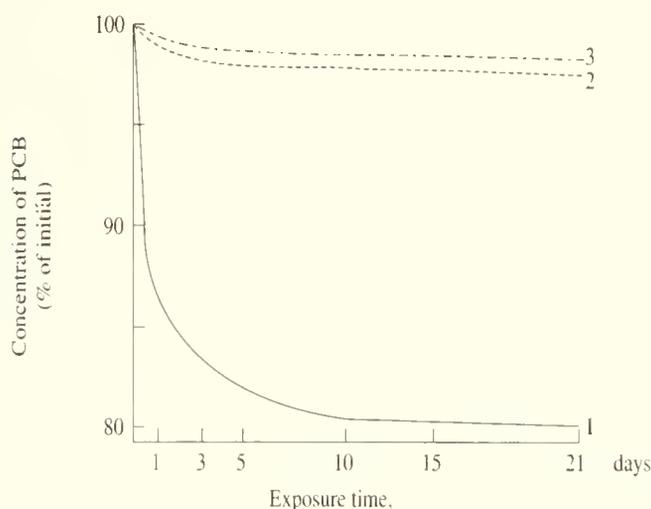


Fig. 1. Decomposition of PCB (Dichlorobiphenyls) under microbial and Photochemical transformation. Bering Sea, 53°58' N, 175°28' W.

- 1- microbial decomposition
- 2- photochemical decomposition
- 3- photochemical decomposition in presence of PAH.

structure decay. These reactions are accompanied by isomerization condensation processes, resulting in the formation of terphenols, tetraphenyls, and dibenzofurans (Bunce *et al.*, 1978). These dechlorination products are now more susceptible to subsequent microbial degradation.

When comparing the data on the scale-model experiments on photochemical breakdown with microbial PCB degradation in the seawater, it was determined that many of the PCB congeners that underwent photochemical degradation were not the ones undergoing decay from exposure to microflora. Of all the components of the technical Aroclor 1232 product, only 2,3',4,4'-tetrachlorobiphenyl and 2,3',4',5-tetrachlorobiphenyl responded to both microbial and photochemical degradation. However, the rate of photochemical reactions is 10 to 15 times slower than the rate of microbial degradation (see Subchapter 4.4 of this volume).

It was also determined that other contaminants (for example, PAH's) inhibited the photochemical degradation of PCB's by 10%. Furthermore, it was found that PCB's were inhibitory toward the photochemical oxidation of benzo(a)pyrene by 20% (Fig. 3). (These experiments were carried out jointly with N. Irha and E. Urbas from the Estonian Academy of Sciences and the final results will be published in the future.)

Therefore, the processes of photochemical PCB degradation were studied for the first time in the marine environment in the arctic regions of the oceans during the Third Joint US-USSR Bering & Chukchi Seas Expedition. The data allowed definition of photochemical PCB oxidation in seawater, and gave a quantitative assessment of this process, which is very important to know when studying biochemical cycles and predicting ecological situations in marine ecosystems.

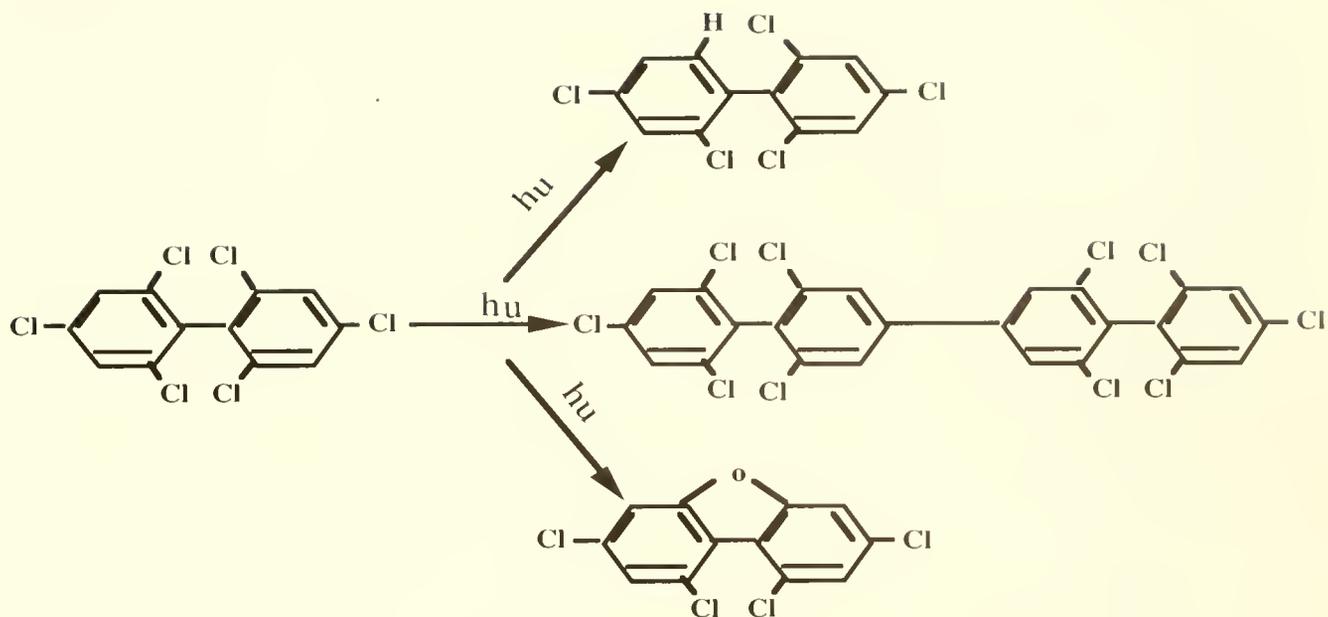


Fig.2. Schematic representation of the photochemical degradation of PCB(hexachlorobenzene) according to Bunce *et al.* (1978).

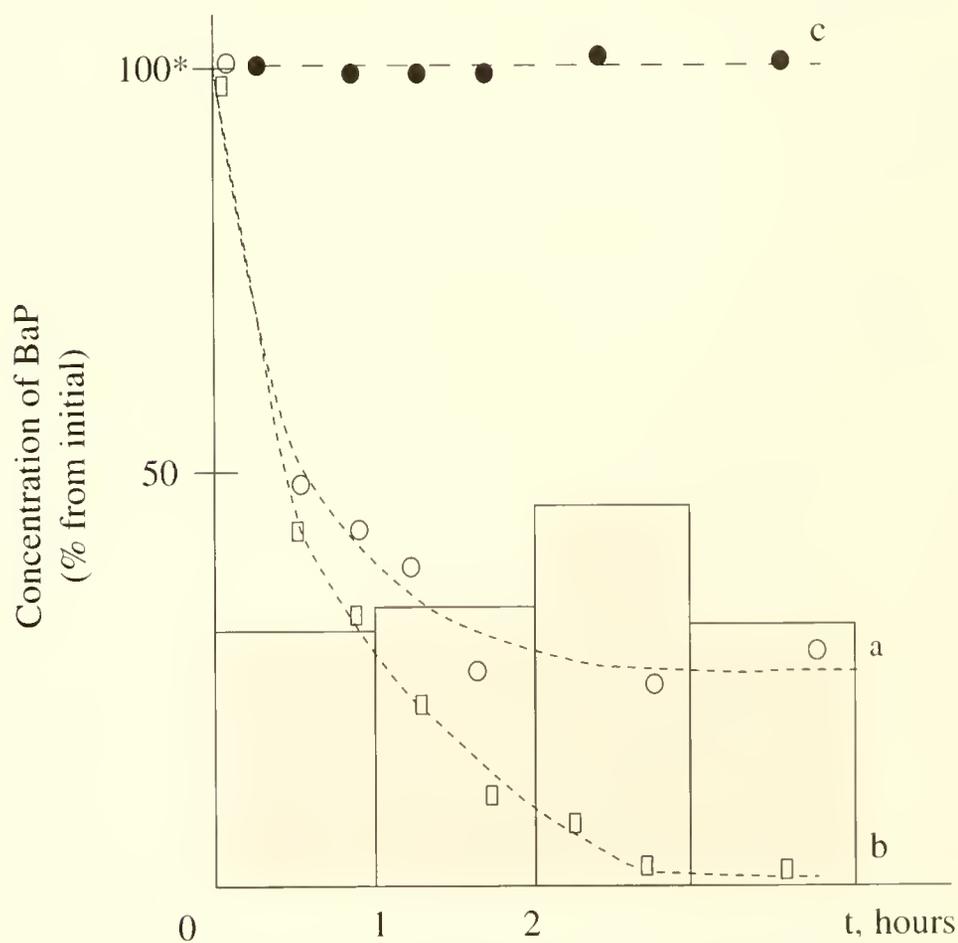


Fig. 3. Change of the benzo(a)pyrene in time a) with addition; b) without addition of PCB in sterilized sea-water; and c) by autooxidation with sunlight irradiation on the surface of the Bering Sea, 53°58' N, 175°28' W.

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Chapter 9:
ECOTOXICOLOGY

Editors:

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Subchapter 9.1:

Effects of Pollutants on Plankton Communities

9.1.1 Investigation of Negative Effects and Critical Concentrations of Some Toxic Substances on the Plankton Community

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Introduction

In recent decades anthropogenic effects have contributed to pollution in the World Ocean and have decreased the natural ability of marine ecological systems for continued reproduction and regulation, especially in those regions where continuous pollution inputs occur (Izrael, 1979; Izrael & Tsyban, 1989). Since marine environmental pollution continues to occur, it is necessary to conduct ecotoxicological research on the effects on plankton. In order to predict the ecological consequences of marine pollution, it is necessary to understand the oceanographic and biological processes controlling the values and the limits of critical concentrations of different pollutants (Izrael & Tsyban, 1989). The critical concentration concept means that the content of the pollutants in the aqueous medium will not initiate nonreversible changes in the ecosystem being considered. If pollutant concentrations are larger, then the value of critical concentration will lead to degradation and nonreversible changes of the plankton (Nosov & Syrotkina, 1981; Egorov *et al.*, 1984; Korsak & Egorov, 1985; Lifshits & Korsak, 1988; Izrael & Tsyban, 1989; Maximov *et al.*, 1989; Korsak & Timoshenkova, 1990).

The results of ecotoxicological research has shown that the influence of low concentrations of pollutants on a plankton community causes individual physiological effects in sensitive marine organisms. However, there may be no significant changes in the ecosystem that are expressed in the form of structural and functional changes of the main ecosystem characteristics such as primary production/destruction (P/D) coefficients, for example. The increase of a toxic contaminant influence in an ecosystem first results in a decrease of the number and biomass of the most sensitive plankton organisms. If a toxicant concentration increases further the most sensitive organisms will be completely replaced by more resistant planktonic species that occupy the nearest ecological niche (Odum, 1975; Nosov & Syrotkina, 1981). In the final stage there will be a few species, but total biomass will possibly increase.

During the Third Joint US–USSR Bering & Chukchi Seas Expedition, ecotoxicological experiments were performed on the basis of a “dose-effect” scheme (Lifshits & Korsak, 1988; Korsak & Timoshenkova, 1990). They were conducted with

the purpose of determining the limits of natural variation of critical concentrations of a plankton community to benzo(a)pyrene (BaP), polychlorinated biphenyls (PCB's), cadmium (Cd), and copper (Cu) pollutants. The biological responses measured were primary production (P), bacterial production (B_p), and the total number of microzooplankton.

Experimental Procedure

Water samples for the experiments were collected from the surface with 5-l plastic Niskin samplers. Nutrient samples were analyzed in the initial water for nitrate, ammonium, and phosphate using standard techniques. The experimental additions of 0.1, 1.0, 5.0, and 10 μg of BaP/l; 1.0, 10, 20, and 50 μg of PCB/l; 2, 4, 10, and 20 μg of Cu/l; 10, 20, 40, and 60 μg of Cd/l were made within 30 min after collection. The experimental bottles (150 ml) were placed in a shipboard deck incubator with flowing seawater under natural illumination. At the end of incubation unpreserved subsamples were used for the determination of the total number of microzooplankton as well as primary production and bacterial destruction using previous ¹⁴C-methods (Egorov *et al.*, 1984). The data were then used for calculations of LC₅₀ values (Lifshits & Korsak, 1988).

Results

The ecotoxicological data and critical concentrations of BaP, PCB's, Cu and Cd from experiments performed in the Bering and Chukchi Seas are presented in Tables 1–8 and Figs. 1–8. Those data show the range of toxicity of the investigated pollutants in the following decreasing toxicity: BaP, Cu, PCB's, Cd (Table 7, 8; Figs. 1–8).

The LC₅₀ values, which approximate critical concentration values for BaP during its influence on phyto- and microzooplankton in the Bering Sea, vary from 0.1 to 10 μg /l in relation to primary production (Table 7). When microzooplankton are used as a biological target, the critical concentration values range from 0.05 to 7 μg /l (Table 7). For the Bering Sea, the average critical concentrations for BaP on phyto- and microzooplankton were 3.6 and 1.0 μg /l, respectively (Table 7). The most sensitive phytoplankton communities to

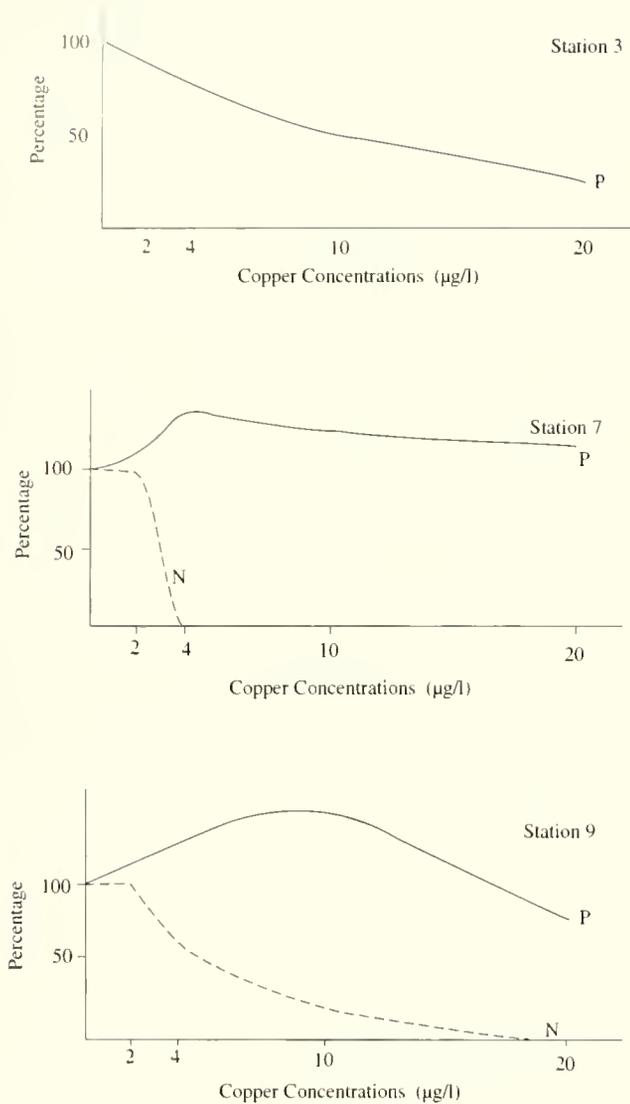


Fig. 1. Negative effects of Cu concentrations on primary production (P) and the total number of infusoria (N) on Stations 3, 7, and 9.

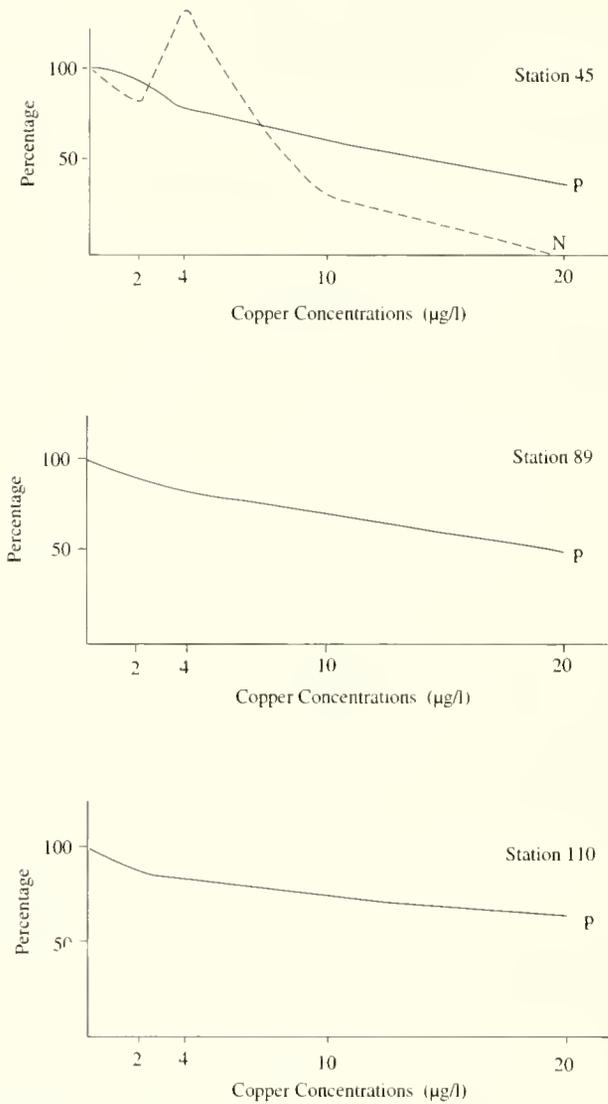


Fig. 2. Negative effects of Cu concentrations on primary production (P) and the total number of infusoria (N) on Stations 45, 89, and 110.

BaP additions were located in the Bering Sea on Station 3, and microzooplankton on Stations 7 and 9 (Tables 1,5; Figs. 6,7). It should be noted that toxicity tolerance of BaP increased from Station 3 to Station 7 (from 0.1 to 10 µg/l, Figs. 6,7; Table 1) when primary production is used as a biological target.

A toxicity tolerance of the bacterioplankton community to BaP was higher than for phytoplankton and the bacterial production rates in ecotoxicological experiments were much larger than in control bottles (Tables 1,5). This stimulation effect can probably be explained by the influence of released organic matter from dead plankton organisms. The data of primary and bacterial production obtained in ecotoxicological experiments can be used to calculate P/D coefficient changes under different additions of pollutants (Table 5; Fig. 8). The P/B_p coefficients were calculated and found to be in good correlation with P/D coefficients, which we believe depend upon the stability of the whole plankton community (Odum, 1975; Izrael & Tsyban, 1989). The critical concentration of BaP to the plankton community (target P/B_p) was calculated to

be about 0.05 µg/l (Table 8). It should be mentioned that the critical concentrations of BaP to the phytoplankton and microzooplankton population were the same order but higher than for the whole plankton community (Table 8).

The critical concentration values of Cu (2–20 µg/l) to phytoplankton had the same order of variation as BaP (Tables 1,2,7). The Bering Sea microzooplankton were found to have critical concentrations of Cu, about 2–15 µg/l (Table 7; Figs. 1,2). The average critical concentrations of Cu for phyto- and microzooplankton in the Bering Sea were, correspondingly, 10 and 6 µg/l (Table 7). The phytoplankton populations most sensitive to Cu additions were located on Stations 3 and 89, and for microzooplankton, correspondingly, on Stations 7 and 9 (Figs. 1,2).

It is necessary to mention that bacterial production increased in ecotoxicological experiments on Stations 3 and 4 with larger Cu concentrations, but in other areas on Stations 7 and 35, the values of bacterial production decreased significantly (Table 4). The critical concentration of Cu (target bacterial

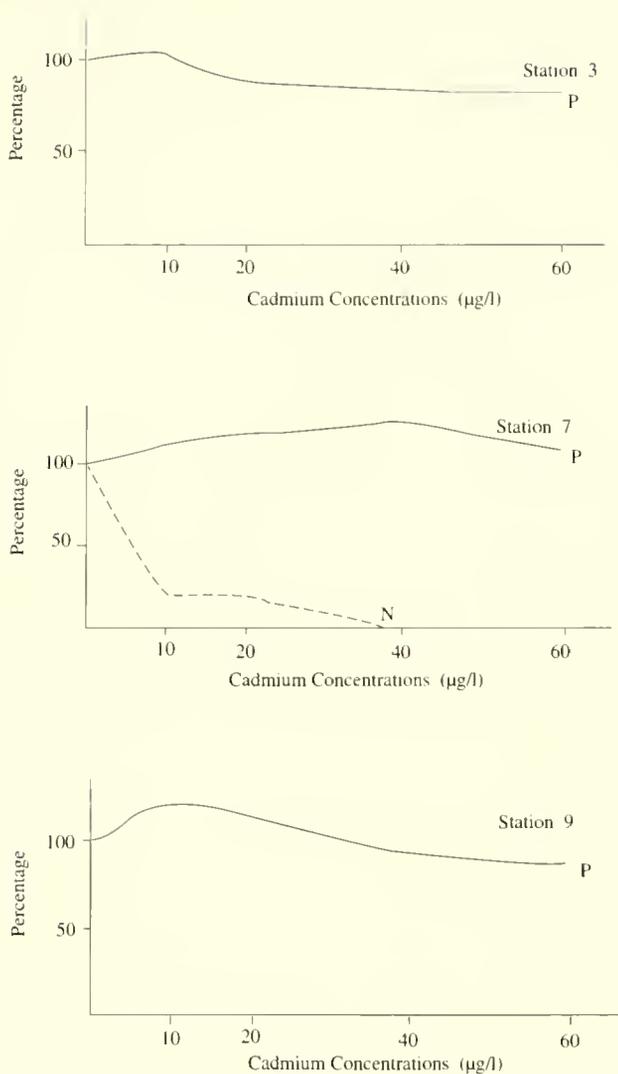


Fig. 3. Negative effects of Cd concentrations on primary production (P) and the total number of infusoria (N) on Stations 3, 7, and 9.

production) for bacterioplankton in Anadyr Bay, on Stations 35 and 7, were very close to critical concentrations for phyto- and microzooplankton in the same area (3–20 $\mu\text{g/l}$). The value of P/B_p coefficient increased together with Cu concentrations on Station 7, and we think that 3 $\mu\text{g/l}$ Cu was very close to the critical concentration for the whole plankton community because this toxic effect disturbs the balance of organic matter significantly (Table 6; Fig. 8). Low bacterioplankton tolerance on Station 35 to Cd and Cu additions probably depends upon the high level of primary production and biomass of phytoplankton, which can suppress bacterioplankton (Tables 4,6). The phytoplankton populations most sensitive to Cd additions were located on Stations 3 and 9, and the most sensitive microzooplankton populations were at Station 7 (Table 2; Fig. 3). The average Cd critical concentrations for phyto- and microzooplankton in the Bering Sea ecosystem were 40 and 28 $\mu\text{g/l}$, respectively (Table 7). The critical concentration of Cd to the whole plankton community (P/B_p -target) on Station 3 was nearly 8 $\mu\text{g/l}$ (Tables 6,8). It was noticed that the sensitivity of plankton to Cd additions, as well as to additions of BaP and Cu, varied significantly among different stations (Tables 1–8; Figs. 1–7). The sensitivity of

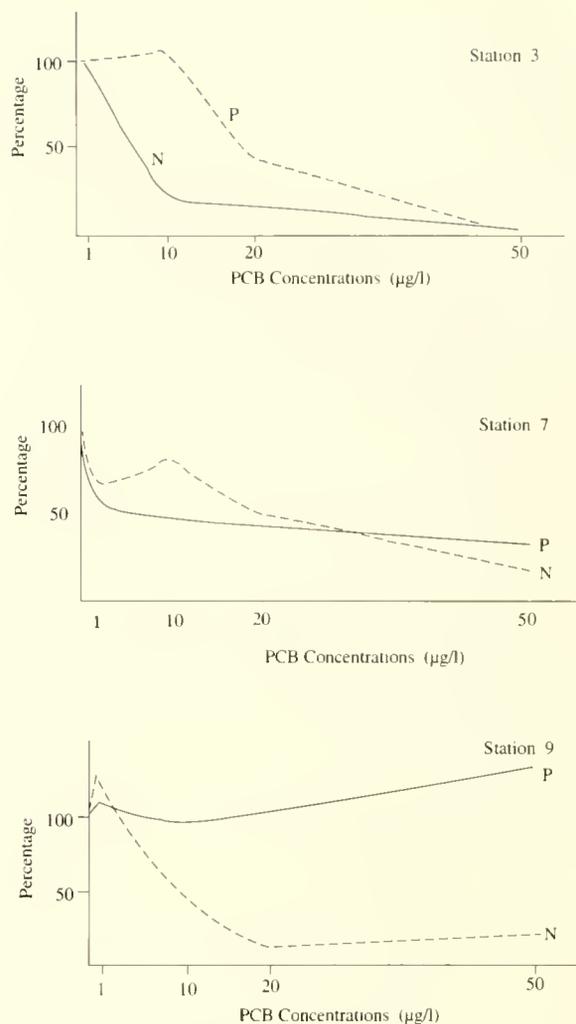


Fig. 4. Distribution of benthic biomass (gm^2) at stations in the Gulf of Anadyr and neighboring waters.

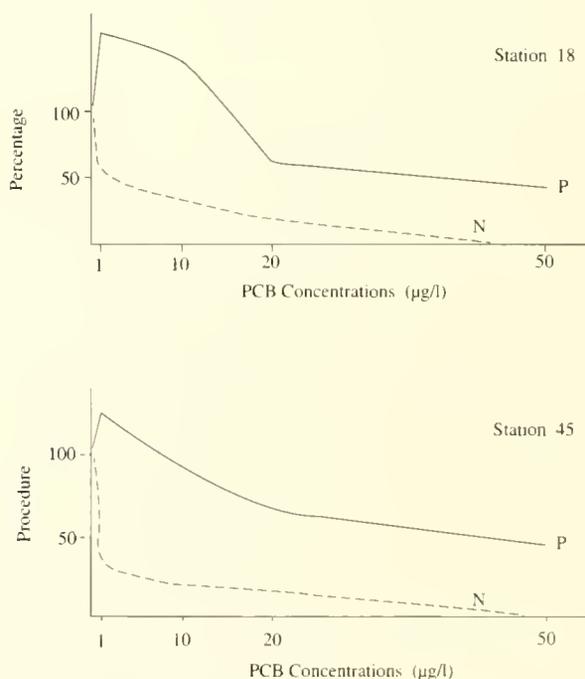


Fig. 5. Negative effects of PCB concentrations on primary production (P) and total number of infusoria (N) on Stations 18 and 45.

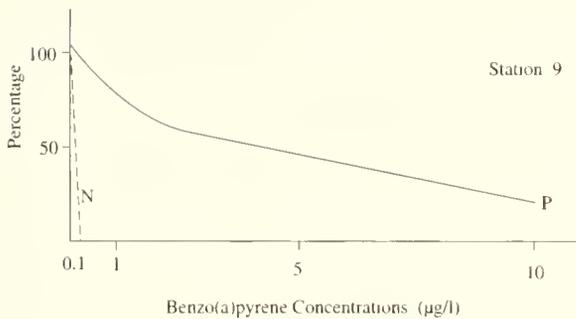
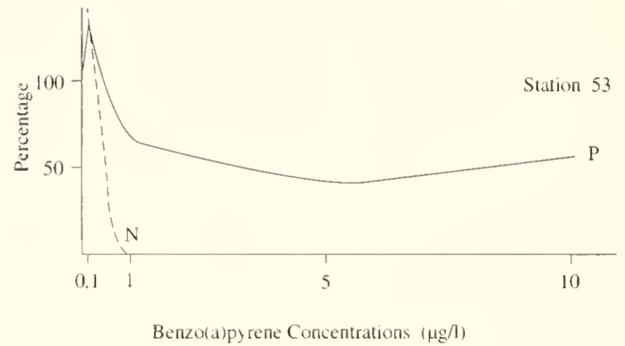
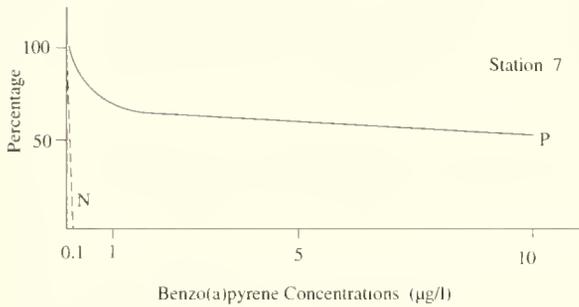
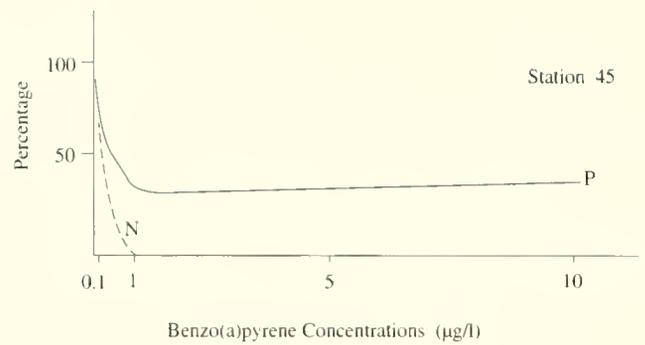
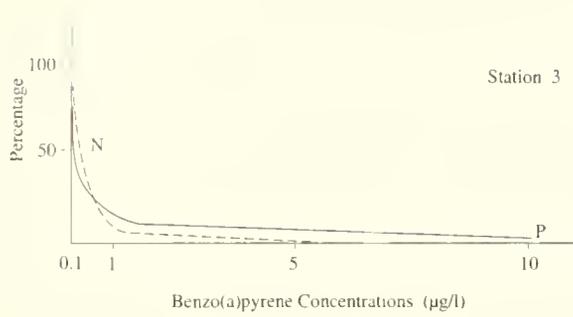


Fig. 6. Negative effects of BaP concentrations on primary production (P) and total number of infusoria (N) on Stations 3, 7, and 9.

Fig. 7. Negative effects of BaP concentrations on primary production (P) and total number of infusoria (N) on Stations 45 and 53.

phytoplankton and microzooplankton to toxicants varied over a range of about one order of magnitude for all values (Table 7).

Concerning the PCB's additions, it should be noted that the highest toxicity on the phytoplankton community was found on Stations 3 and 7, and for microzooplankton on Stations 18 and 41 (Figs. 4,5). The average critical concentrations of PCB's for phyto- and microzooplankton in the Bering Sea ecosystem were 30 µg/l and 11 µg/l, respectively (Table 7). The strongest PCB's toxic effects on bacterial production were found at Stations 3 and 4, and critical concentrations to the bacterioplankton community were about 50 µg/l (Table 3). It was very surprising that on Station 35, additions of Cu, Cd, and BaP had a very strong negative effect, but toxic amounts of PCB's additions showed that values of bacterial production were stimulated (Tables 3 and 4). The PCB's critical concentrations for the whole plankton community calculated for Station 3 were about 5 µg/l (Table 5). The critical concentrations data obtained in the Chukchi Sea ecosystem showed that values of critical concentration of BaP (target

primary production and microzooplankton) were significantly less than in the Bering Sea ecosystem (Tables 7,8). At the same time, the effects of heavy metals and PCB's on primary production in the Bering Sea were slightly stronger than in the Chukchi Sea ecosystem (Tables 7,8).

The critical concentration of BaP and PCB's on infusoria of the Chukchi Sea was three and two times lower than the Bering Sea, while the effects of Cu and Cd were slightly higher (Tables 7,8).

The above mentioned differences in the sensitivity of plankton communities can be ascribed to the difference in adaptation of these communities to the pollutants and also to their species composition. It should be noted that the temperature of the water in the Chukchi Sea during our studies was about 5°C lower than that in the Bering Sea. For this reason, the comparative resistance of the plankton communities of the Chukchi Sea to the toxic contaminants would be even less than was determined in the course of these ecotoxicological experiments (Odum, 1975; Izrael & Tsyban, 1989).

Discussion

The values of critical concentrations of the pollutants obtained in our experiments of 1984 and 1988 show that the resistance of the plankton community of the Bering Sea for the summer period were similar for Cu and Cd (Liftshits & Korsak, 1988; Izrael & Tsyban, 1989). In addition, Station 35 near St. Lawrence Island, which had the highest levels of primary production, was the most sensitive to all toxic contaminant additions, both in 1984 and 1988. Further study is needed to

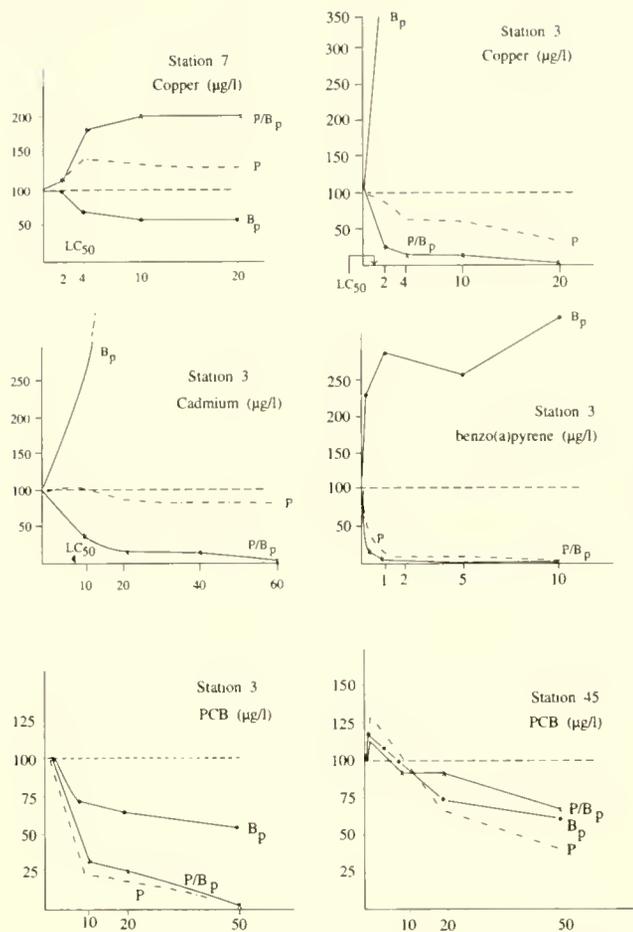


Fig. 8. Variations of some functional characteristics (p, BP, P/Bp) in ecotoxicological experiments.

ascertain the cause of the relatively low resistance to plankton organisms in this part of the Bering Sea to these toxic contaminants.

Comparing the data obtained in the Bering and Chukchi Seas in 1988 and similar experiments performed in the Baltic Sea in 1987, it should be noted that the ranges of critical concentrations of the investigated pollutants were very similar (Tables 7,8) (Liftshits & Korsak, 1988; Korsak & Timoshenkova, 1990). It is evident that the resistance of the plankton community of the Baltic Sea to BaP and PCB's was lower than in the Bering Sea (Korsak & Timoshenkova, 1990; Liftshits & Korsak, 1988). On the other hand, the resistance of plankton of the Bering and Chukchi Seas to Cu and Cd was much lower than that in the Baltic Sea (Liftshits & Korsak, 1988; Korsak & Timoshenkova, 1990). These differences are probably very significant because the temperature of the Bering/Chukchi Sea water was 10°C lower than during the research in the Baltic Sea.

As a result of these investigations, it should be noted that from the number of pollutants under consideration, the most dangerous pollutants to the plankton communities of the Bering, Baltic, and Chukchi Seas are BaP and Cu, because the maximum concentrations of these pollutants in the water are nearly the same values as the critical concentrations. The other pollutants investigated appear less hazardous to the plankton communities.

TABLE 1

The toxic effects of PCB's and BaP to primary production in ecotoxicological experiments (relative values of primary production represented in %).

Pollutant µg PCBs/l	Station Number					Pollutant µg BaP/l	Station Number				
	3	7	8	18	45		3	7	9	45	53
0	100	100	100	100	100	0	100	100	100	100	100
0.1	100	62	112	160	130	0.1	43	89	102	72	126
1.0	20	15	97	140	93	1.0	12	140	78	38	67
5.0	17	43	102	64	67	5.0	7	62	48	38	46
10.0	2.0	33	--	44	45	10.0	5	57	--	44	65

TABLE 2

The toxic effects of Cu and Cd on primary production in ecotoxicological experiments (relative values of primary production in %).

Pollutants µg Cu/l	Station Number						Pollutants µg Cd/l	Station Number		
	3	7	9	89	110	113		3	7	9
0	100	100	100	100	100	100	0	100	100	100
2	87	112	135	82	86	109	10	104	120	125
4	60	136	114	85	83	92	20	88	115	118
10	61	127	156	71	74	81	40	84	128	96
20	31	122	84	48	64	31	60	82	108	90

TABLE 3

The toxic effects of BaP and PCBs on bacterioplankton in ecotoxicological experiments (relative values of bacterial production in %).

	Pollutant µg/l	Station Number					
		3	4	5	35	45	50
BP	0	100	100	100	100	100	100
	0.1	230	--	154	76	88	55
	1.0	280	152	120	50	95	100
	5.0	250	360	114	13	100	96
	10.0	360	370	94	18	95	52
PCB	0	100	100	100	100	100	100
	0.1	100	109	140	160	116	78
	1.0	71	84	160	180	100	67
	5.0	66	71	136	155	73	64
	10.0	55	75	120	130	67	42

TABLE 4

The toxic effects of Cu and Cd on bacterioplankton in ecotoxicological experiments (relative values of bacterial production in %).

Pollutant µg/l	Station Number							
	3	4	7	35	45	50	72	96
Cu	0	100	100	100	100	100	100	100
	2	440	220	102	144	234	103	200
	4	590	1030	77	33	257	108	238
	10	545	665	65	20	257	160	252
	20	1260	360	64	7	300	170	440
Cd	0	100	100	100	100	100	100	100
	10	250	270	59	75	430	93	
	20	560	1030	63	18	250	200	
	40	573	1140	66	8	120	87	
	60	1200	1130	48	0.9	110	77	

TABLE 5

Variations of primary (P), bacterial production (B_p) and P/B_p coefficient in ecotoxicological experiments.

Pollutant	Station 3			Station 45			Pollutant	Station 3			Station 45		
	P	B _p	P/B _p	P	B _p	P/B _p		P	B _p	P/B _p	P	B _p	P/B _p
BaP µg/l							PCB µg/l						
0	78	34	2.3	36	84	0.43	0	78	34	2.3	36	84	0.43
0.1	34	78	0.44	26	74	0.35	0.1	78	34	2.3	47	98	0.48
1.0	9.4	95	0.10	11	80	0.14	1.0	16	24	0.65	33	84	0.39
5.0	5.5	86	0.06	14	85	0.16	5.0	13	22	0.60	24	61	0.39
10.0	3.9	121	0.03	16	80	0.20	10.0	1.6	19	0.08	16	56	0.29

TABLE 6

Variations of Primary (P) and bacterial production (B_p) and P/B_p coefficient in ecotoxicological experiments.

Pollutant	Station 3			Station 7			Pollutant	Station 3			Station 7		
	P	B _p	P/B _p	P	B _p	P/B _p		P	B _p	P/B _p	P	B _p	P/B _p
Cu µg/l							Cd µg/l						
0	78	25	3.1	15	145	0.10	0	78	25	3.1	15	145	0.10
2	68	108	0.62	17	148	0.11	10	81	62	1.3	18	86	0.21
4	46	147	0.31	20	112	0.18	20	69	138	0.50	17	92	0.19
10	48	135	0.36	19	94	0.20	40	66	142	0.47	19	95	0.20
20	24	313	0.08	18.3	92	0.20	60	64	300	0.22	16	70	0.23

Values of primary (P) and bacterial production (B_p) in mg C/m³/day.

TABLE 7

The values of "critical" concentrations of some pollutants in the Bering Sea ecosystem.

Pollutant	Critical concentrations* µg/l			
	Primary Production	Infusoria	Bacterio-plankton	Plankton (P/B _p)
BaP	<u>0.1-10.0</u> 3.6	<u>0.05-7</u> 1.0	10.0	0.05
PCBs	<u>6-50</u> 30	<u>1-20</u> 11	50.0	5
Cu	<u>2-20</u> 10	<u>2-15</u> 6	3 - 20	1 - 3
Cd	<u>25-60</u> 40	<u>5-60</u> 28	15 - 60	8

* Above the fraction bar - the range of variation for the critical concentrations of pollutants; below the fraction bar - the average values.

TABLE 8

The values of critical concentrations of some pollutants in the Chukchi Sea ecosystem.

Pollutant	Critical concentrations* µg/l			
	Primary Production	Infusoria	Bacterio-plankton	Plankton (P/B _p)
BaP	<u>0.5-1.0</u> 0.75	<u>0.15-0.5</u> 0.32	10	0.05
PCBs	<u>30-40</u> 35	<u>1-10</u> 5	35	50
Cu	<u>15-10</u> 12	<u>6-10</u> 8	-	-
Cd	<u>40-60</u> 50	<u>10-60</u> 30	60	-

* Above the fraction bar - the range of variation for the critical concentrations of pollutants; below the fraction bar - the average values.

9.1.2 Effects of Hexachlorocyclohexane on Nitrogen Cycling in Natural Plankton Communities

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Introduction

Man-made substances find their way into the ocean by both direct run off from land and by atmospheric transport. In the case of atmospheric transport, pollutants can be spread to areas far from their point of origin (Flegal & Patterson, 1983); therefore, the question arises as to what effects this input will have on the plankton of the open ocean. The gamma isomer of hexachlorocyclohexane (γ -HCH) has been used widely as the pesticide lindane. This report describes the results of on-board experiments designed to investigate the effects of hexachlorocyclohexane (HCH) on natural plankton communities in the Bering Sea.

A variety of pollutants produce measurable toxic effects on marine plankton. These pollutants include a wide variety of herbicides, insecticides, fungicides, and organochlorines such as DDT (Butler, 1977). Most relevant to this work, the pesticide γ -HCH exhibited toxic effects on marine algae in laboratory studies (Ukeles, 1962; Daste & Neuville, 1974; Moore & Dorward, 1974; Neuville *et al.*, 1974). Additionally, HCH can be transported by the atmosphere to the open ocean. High latitude seas appear to be particularly susceptible to such inputs because HCH is more soluble at the low temperatures commonly found there (Hinckley *et al.*, Subchapter 8.1.1, this volume).

However, it is difficult to extrapolate most laboratory studies into accurate predictions as to the specific effect of pollutants on marine plankton. In the ocean, pollutant concentrations are much lower than those used in most laboratory experiments. Also, laboratory experiments cannot duplicate the community diversity of most ocean plankton systems. Our goal in the present work is to provide a better basis on which to assess the effects of HCH on marine biota by examining the effects of HCH on natural communities at concentrations approaching the actual pollutant levels measured in the ocean.

Methods

Results of two separate experiments carried out during the cruise of the R/V *Akademik Korolev* to the Bering Sea in August and September 1988 are presented here. The basic

protocol for both experiments was similar. Near-surface (5 m) water was collected using clean techniques that included the use of a go-flow™ bottle on a kevlar™ wire. The samples were then transferred to acid-cleaned 5-l polyethylene containers and incubated on-deck in incubators cooled with surface seawater.

The source water for the two experiments was chosen to provide contrasting high latitude plankton communities. The first experiment was started 21 August 1988 with surface water collected at 65°5.2'N and 170°42.7'W (Station 96) that had a total water depth of 42 m. This experiment will hereafter be called the shelf experiment. The second experiment was started 26 August 1988 with surface water collected at 54°25.3'N and 176°43.7'W (Station 108) that had a total water depth of 3,835 m; this will be referred to as the "oceanic experiment." Selected ambient characteristics of each sampling site are shown in Table 1.

Table 1

Characteristics of the water collected for the two HCH experiments.

	Shelf Experiment (Station 96)	Oceanic Experiment (Station 108)
Collection date	8/21/88	8/26/88
Latitude	65°5.2'N	54°25.3'N
Longitude	170°42.7'W	176°43.7'W
Water depth (m)	42	3835
Temperature (°C)	2.33	9.17
Salinity (‰)	32.73	33.12
Oxygen saturation (%)	98.1	104.0
PO ₄ (μM)	2.83	2.71
Si(OH) ₄ (μM)	36.20	34.17
NO ₃ + NO ₂ (N+N; μM)	21.11	20.70
NH ₄ (μM)	0.58	1.92
Chlorophyll <i>a</i> (μg l ⁻¹)	6.3	0.72
Bacteria (10 ⁸ cells/l)	2.4	3.0
Ciliates (#/l)	10,000	

In each experiment, the water was subdivided into three 7.5-l containers: a control that was not modified in any way; an experimental container to which the HCH in an acetone solvent was added; and a solvent control that was treated only with the same amount of acetone that was used as the carrier for the HCH. In the oceanic experiment, the HCH treatment was replicated. At 0, 24, and 48 h after the experiments were started, samples were withdrawn for each of the following measurements:

1. The concentration of HCH was routinely measured in each container by withdrawing 10 ml samples. In the oceanic experiment, the amount of HCH that adhered to the container walls was also measured by washing down the container walls with solvent at the end of the experiment. The specific amounts of HCH and HCH already present in the ambient water, as well as that added to the experimental containers, is shown in Fig. 1.

2. The concentration of nutrients, including nitrate and nitrite (N+N), ammonium (NH₄), phosphate (PO₄), and silicate (Si(OH)₄), were measured on an autoanalyzer using conventional autoanalyzer techniques on 50-ml samples (Whitledge *et al.*, 1981).

3. The concentration of chlorophyll *a* was measured by the extracted fluorescence method on 50-ml samples (Parsons *et al.*, 1984).

4. The rates of ammonium uptake were measured by the ¹⁵N tracer method on 1 l samples (Sambrotto *et al.*, 1986).

5. Bacterial counts were obtained from staining and direct microscopy, and bacterial activity was measured by the ³H thymidine technique on 150-ml samples (Fuhrman & Azam, 1982).

6. Microzooplankton abundance was estimated from ciliate counts. These were done immediately on board by microscopic counting of unstained 100-ml samples.

7. Additional volume was withdrawn from the experimental containers for other measurements that are not discussed here. The combined volume requirements of all samples were accommodated within the experimental design and the limitations imposed by the 7.5-l containers.

Results

The amount of HCH added to the experimental containers at the beginning of each experiment was composed of equal parts of the α and γ isomers (Fig. 1a). In all experimental containers, the concentration of HCH decreased over the 48-h period. The net loss of total HCH in the shelf and oceanic replicate #1 were similar, although the net loss in oceanic replicate #2 was almost 50% greater (Fig. 1c). In the oceanic replicates, the net loss of α -HCH was slightly greater than that for γ -HCH.

Functionally, the remaining measurements fall into one of three groups. Group 1 measurements are those that reflect only the biomass of the organisms in the containers and include chl *a*, bacterial counts, and ciliate counts. Group 2 measurements

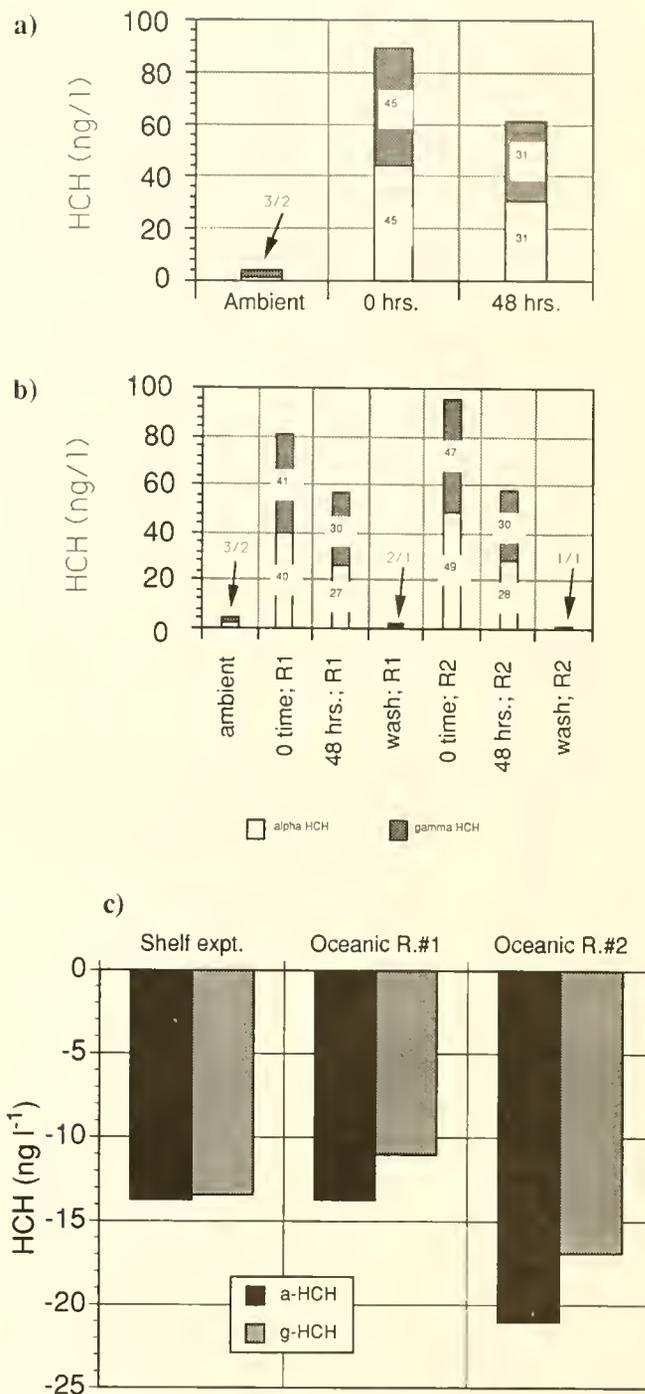


Fig. 1. The concentrations of α and γ isomers of HCH in the experimental (HCH) containers at the beginning and end of the shelf (Fig. 1a) and oceanic (Fig. 1b) experiments. Also shown are the total HCH concentrations in the ambient water when it was first collected and the concentrations recovered from the walls of the containers at the end of the oceanic experiment. Each value is the result of two analyses. Fig. 1c summarizes the net changes in each isomer in the experimental containers over the 48 h periods.

are those that reflect both biomass and specific activity and include bacterial activity and net changes in ambient nutrients. Group 3 measurements reflect only the specific uptake rates of

the plankton and include the NH_4 uptake rates as well as the bacterial activity on a per-cell basis. To further organize the experimental results, the data are presented as the net changes observed during the 48 h of the experiments (i.e., the measurement at the time of observation minus the initial [0 time] measurement).

Chlorophyll *a* levels increased dramatically in all of the containers in the shelf experiment (Fig. 2). The increase was less in the incubations exposed to acetone (the acetone control and the HCH containers). The observed increases in chl *a* levels in the oceanic experiment were much less than those on the shelf. Unfortunately, the untreated control in the oceanic experiment ran out of sample volume before the final chl *a* sample could be taken.

The 48-h increase in bacterial numbers was the same for both the acetone control and HCH experimentals in both shelf and oceanic experiments (Fig. 3). However, the changes in bacterial numbers relative to the untreated control were very

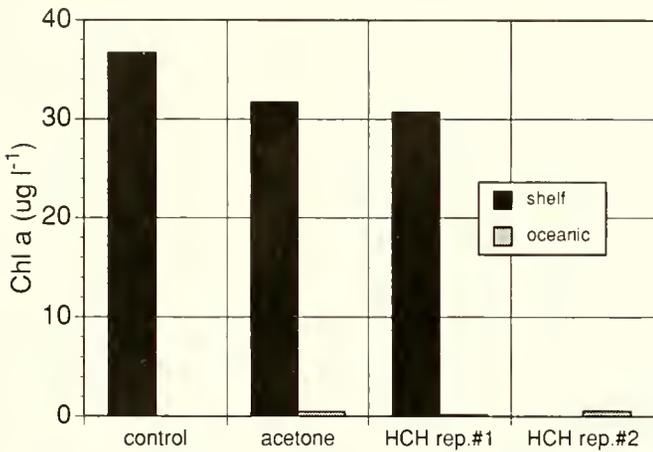


Fig. 2. Net 48 h changes in chl *a* concentration in the untreated control, acetone control and HCH experimental containers. Initial values for each experiment are given in Table 1.

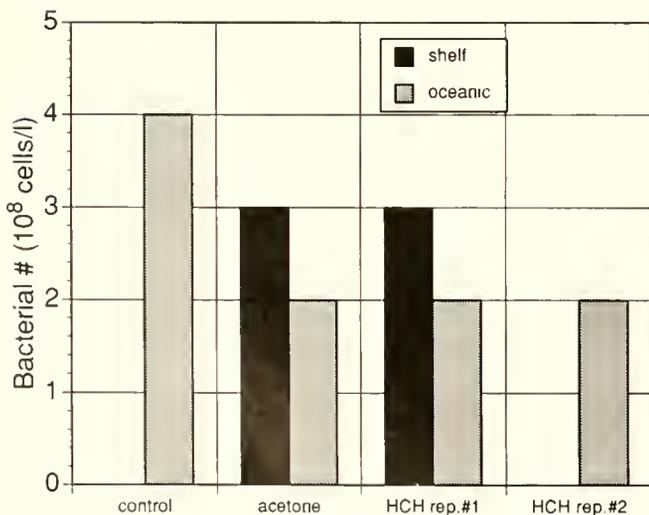


Fig. 3. Net 48 h change in bacterial numbers in the untreated control, acetone control and HCH experimental containers. (Note that untreated shelf control did not change). Initial values for each experiment are given in Table 1.

different between the shelf and oceanic areas. In the shelf experiment, bacterial numbers in the acetone and HCH containers increased more than the untreated control (which did not change). In the oceanic experiment, the opposite change occurred.

There also was a difference between the shelf and oceanic response on the basis of bacterial activity (thymidine incorporation; Fig. 4). There was little difference between the treatments and controls in the shelf experiment. However, in the oceanic experiment, acetone markedly depressed activity. The presence of HCH appeared to make up for this inhibition in that bacterial activity in the HCH experimentals were similar to the untreated control.

Changes in ciliate abundance are only available for the shelf experiment (Fig. 5). Ciliate numbers decreased in all containers. However, the decrease in the acetone control was less than either the untreated control or the HCH experimental.

The 48-h changes in the concentration of dissolved inorganic nutrients fall into one of three distinct categories:

1. The effect of treatments on net 48-h changes are similar in both shelf and oceanic experiments and the effects of HCH cannot be distinguished from acetone alone. In this category

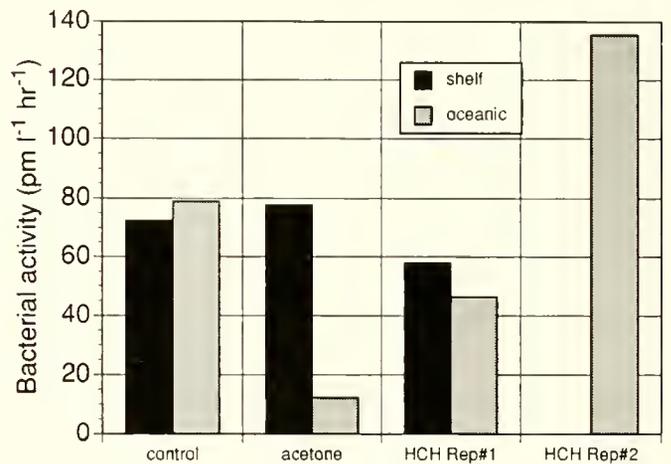


Fig. 4. Net 48 h change in bacterial activity (thymidine incorporation) in the untreated control, acetone control and HCH experimental containers. Initial values for each experiment are given in Table 1.

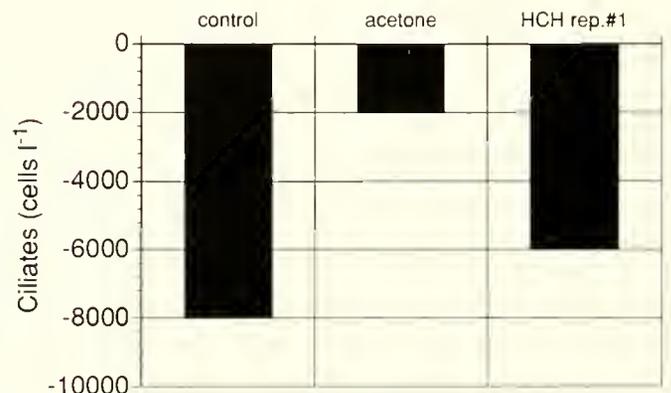


Fig. 5. Net 48 h change in ciliate concentration in the untreated control, acetone control and HCH experimental container for the shelf experiment.

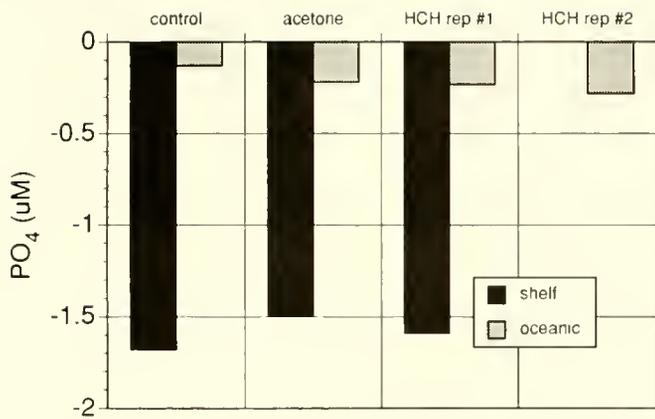


Fig. 6. Net 48 h change in phosphate concentration in the untreated control, acetone control and HCH experimental containers. Initial values for each experiment are given in Table 1.

are the observed changes in phosphate (Fig. 6). However, in the oceanic experiment, the net consumption of phosphate was greater in the HCH treated experimentals than in the presence of acetone alone.

2. The effect of treatments on net 48-h changes are opposite in shelf and oceanic experiments and the effects of HCH cannot be distinguished from acetone alone. In this category are the changes in N + N (Fig. 7) and silicate (Fig. 8). Acetone slowed the net consumption of ambient N + N in the shelf experiment (Fig. 7) but resulted in a net increase in N + N in the oceanic experiment (Fig. 7). Likewise, the presence of acetone slowed the consumption of silicate in the shelf experiment (Fig. 8) and produced a net increase in silicate in the oceanic experiment (Fig. 8).

3. The effect of treatments on net 48-h changes are similar in both shelf and oceanic experiments, and in both locations the effects of HCH are distinct from acetone alone. The observed net changes in ambient ammonium are in this category (Fig. 9). In both the untreated and acetone-treated containers in both shelf and oceanic experiments, the ammonium concentrations

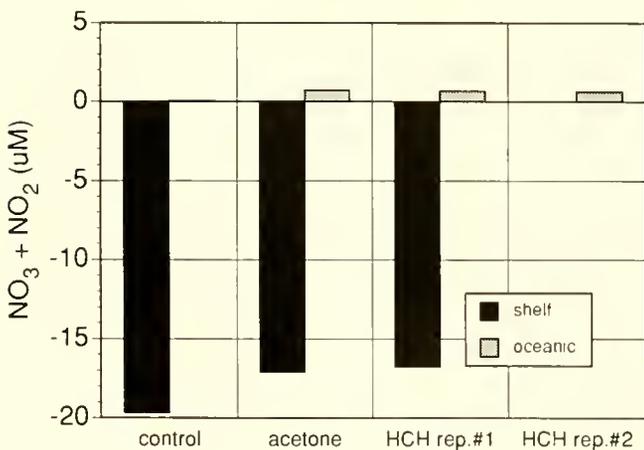


Fig. 7. Net 48 h change in N+N concentration in the untreated control, acetone control and HCH experimental containers. Initial values for each experiment are given in Table 1.

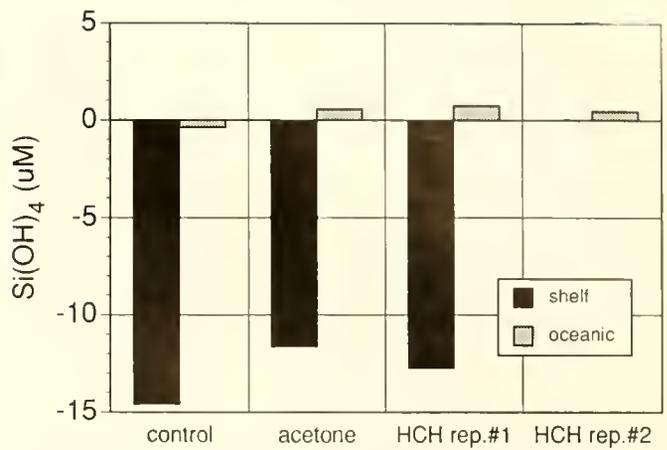


Fig. 8. Net 48 h change in silicate concentration in the untreated control, acetone control and HCH experimental containers. Initial values for each experiment are given in Table 1.

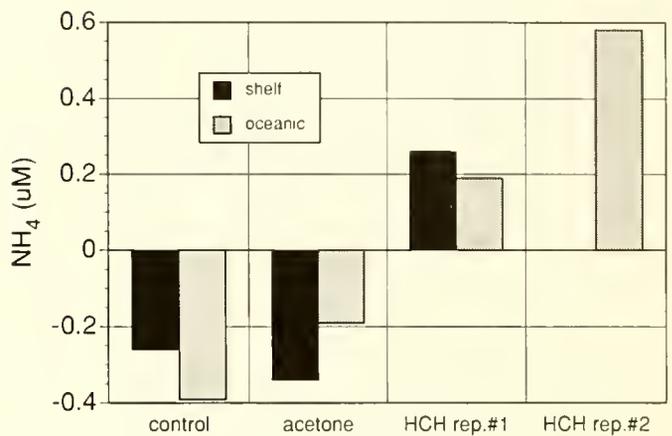


Fig. 9. Net 48 h change in ammonium concentration in the untreated control, acetone control and HCH experimental containers. Initial values for each experiment are given in Table 1.

decreased. However, in all containers treated with HCH, the ammonium concentrations increased during the 48-h experiment.

Like the changes in ammonium levels, the specific rates of ammonium uptake were higher in the HCH-treated containers at the end of both experiments (Fig. 10). In the shelf experiment, ammonium uptake rates increased in the acetone and HCH containers at 48 h. In the oceanic experiment, the ammonium uptake rates in the HCH-treated containers were markedly higher than either the untreated or acetone-treated containers at 48 h.

Discussion

The most significant findings from our experiments were the effects of HCH on plankton nitrogen cycling (Figs. 9,10). The results clearly indicate that the added HCH produced a measurable effect beyond that of the acetone carrier alone. The ambient ammonium pool is extremely dynamic and reflects the net result of uptake and regeneration processes. The fact that both the specific rates of ammonium uptake and the ambient

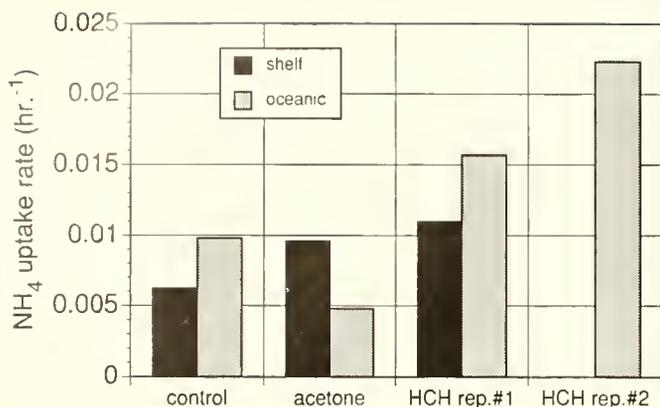


Fig. 10. Net 48 h change in ammonium specific uptake rates in the untreated control, acetone control and HCH experimental container for the shelf experiment. For the untreated control, acetone control and HCH experimental containers of the oceanic experiment, the measured values (and not the changes) are shown because the initial measurements for this experiment are not available.

ammonium levels increased in the experimental containers suggests that HCH acted to increase net ammonium fluxes in both shelf and oceanic areas.

The proportion of new to total nitrogen production (new plus regenerated) in the plankton can be related to the flux of carbon from surface waters (Eppley & Peterson, 1979). Therefore, any change in this ratio would affect the biogeochemical cycling of carbon as well as nitrogen. This is a subject of broad importance because the biological flux of carbon from surface waters is a major sink for atmospheric CO₂ and may be an important sink for rising levels of this greenhouse gas. The changes observed in our experiments suggest that atmospheric input of pollutants like HCH can decrease the amount of carbon exported from surface waters by increasing the amount that is regenerated *in situ*.

We feel that these results provide a basis for preliminary quantitative extrapolation for several reasons. This is one of the few studies to examine the effects of pollutants on natural populations of open ocean plankton. The amount of HCH added to the experimental containers (80–90 ng/l) was approximately 10 times the highest level of HCH yet measured in ocean water (Hinckley *et al.*, Subchapter 8.1.1, this volume). However, it is not unreasonable that localized, higher concentrations of HCH exist in the ocean. Also, although it is difficult to assess the effect of chronic (long-term) exposure of marine plankton systems to pesticides, we suspect that the changes in nitrogen cycling also would have been observed at lower HCH concentrations in longer experiments.

In addition to the potential increased regeneration induced by exposure to HCH, the literature on pollutant effects on plankton indicates that there are significant differences among the sensitivities of plankton populations to pollutants. Although little information on the specific effects of HCH is available, a number of studies with other pollutants have shown that marine algal community changes are a much more sensitive indicator of toxic effect than specific measurements done on unialgal cultures. For example, in a number of studies, diatom populations were particularly sensitive among the organisms studied (Maloney & Palmer, 1956; Menzel *et al.*, 1970; Mosser *et al.*, 1972; Fisher *et al.*, 1974). This suggests that the

combined effects of pollutants on carbon flux are greater than this preliminary HCH experiment suggests because diatoms are typically associated with high levels of new production and their sensitivity to pollutants would further reduce carbon flux.

The results of the experiments can be interpreted in terms of the known biological differences between the shelf and oceanic regimes. The shelf and oceanic waters of the subarctic North Pacific differ markedly in the amount and character of phytoplankton productivity (Sambrotto & Lorenzen, 1986). In shelf areas of the eastern Bering Sea, intense, diatom-dominated blooms occur in the spring and summer months (Sambrotto *et al.*, 1986). However, in oceanic areas, the phytoplankton crop remains low throughout the year, despite an abundance of surface layer nutrients, most likely due to intense grazing pressure by both macro- and microzooplankton (Frost, 1990). Thus the shelf and oceanic experiments provide insight into the reactions of two distinct plankton systems to airborne HCH.

A complete analysis of the causality of the effects observed in the nitrogen system is not possible given the limited measurements made and the known complexity of plankton systems. However, observations on specific components of the community over the course of the experiments offer some insight as to the biological changes accompanying the changes in nitrogen cycling. Unfortunately, ciliate abundance data are available only for the shelf experiment and do not reflect any distinct effect of HCH. Volume restrictions at the end of the experiments contributed to the scatter in other measurements relating to biomass as well. For example, the chl *a* change for the replicates in the oceanic experiment varied widely and obscured the detection of any possible difference between the experimental and acetone control.

However, changes in the bacterial community are apparent, particularly if the data are examined on a per-cell basis (Hanson *et al.*, 1988; Fig. 11). On this basis, HCH suppressed cell-specific activity on the shelf, while oceanic cell-specific activities increased. These differences closely parallel the observed changes in phosphate, which were also opposite in

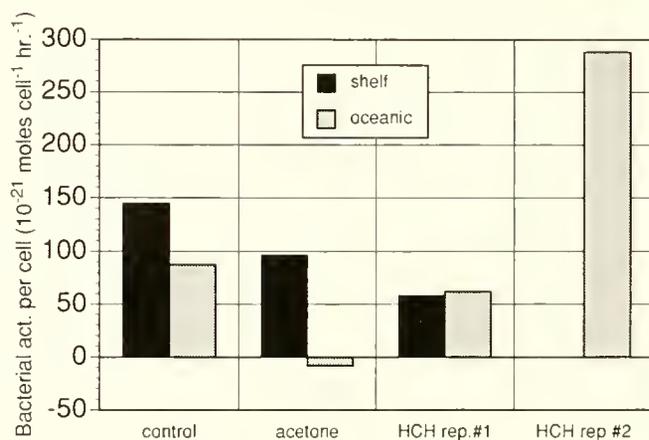


Fig. 11. Net 48 h change in specific activity of thymidine incorporation per bacterial cell (based on the data in Figs. 3 and 4) in the untreated control, acetone control and HCH experimental container for the shelf experiments.

shelf and oceanic experiments (Fig. 6). These observations suggest that there is a causal link between the phosphate pool and bacterial activity. However, it is not known whether this effect is brought about directly by the bacteria or perhaps by reduced bacterial grazing by microflagellates.

Also, the fact that the response of the shelf community was opposite to that of the oceanic communities in terms of both bacterial activity per cell and net phosphate change may be an effect of the known biological differences between the communities. The oceanic community has a greater diversity of bacterial populations as well as a more highly developed microbial loop than shelf waters (Azam *et al.*, 1983). Thus oceanic waters harbor bacterial populations that can metabolize HCH and its metabolites, and in an active microbial loop, these populations would quickly exert dominance. In shelf waters, the rise in bacterial numbers in the treated containers (Fig. 3) may simply reflect diminished grazing pressure because the cell-specific activity for bacteria decreased here (Fig. 11).

Wheeler and Kirchman (1986) suggested that bacterial uptake is an important sink for seawater ammonium. In the oceanic experiment the changes in cell-specific activity for bacteria and ammonium uptake rates are similar and, therefore, enhanced bacterial activity is one possible explanation for the elevated ammonium uptake rates. However, in the shelf experiment, cell-specific activity decreased in the same containers that ammonium uptake rates increased and, therefore, a similar cause and effect is less plausible here.

The results of the HCH analysis on the wall washings (Fig. 1) indicate that little HCH was lost to wall adhesion and that the HCH decreases observed over the experiments were due to chemical or biochemical breakdown. Therefore, the greater per-cell bacterial activity in the oceanic area may also be responsible for the slightly greater disappearance of HCH from the oceanic containers (around 35%) than from the shelf container (around 31%), particularly in the case of oceanic replicate #2, that exhibited the greatest net loss of HCH (Fig. 1); bacterial activity (Fig. 4); ammonium change (Fig. 9); ammonium uptake rate (Fig. 10); and bacterial activity per cell (Fig. 11). However, certain freshwater phytoplankton also have been shown to metabolize HCH (Sodergran, 1971; Singh, 1973) and hydrophobic pollutants are accumulated to varying degrees by marine phytoplankton (Rice & Sikka, 1973). Thus, neither the organisms nor the mechanisms responsible for the observed decrease in HCH can be identified in our experiments.

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Subchapter 9.2:

Toxicity of Sediments to Test Organisms

9.2.1 Acute Toxicity Testing of Sediments

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Introduction

The Bering and Chukchi Seas are rich with living and energy resources valuable to both the USA and USSR. A balance between exploiting the petroleum reserves and conserving the unique structure and functions of the marine food webs must be attained if the Bering and Chukchi Seas are to remain productive ecosystems. As a response to this development, a program must be formulated that will serve to monitor and protect the important ecosystems of these seas (Hood & Calder, 1981; Izrael & Tsyban, 1986; Hale, 1987; Becker, 1988).

A consensus has emerged that a comprehensive monitoring program must integrate chemical survey information, single-species toxicity testing, and field survey data into an ecosystem-level evaluation of contaminants impact. Each of these approaches, taken separately, does not provide the information needed to protect living resources (Levin *et al.*, 1984; Long & Chapman, 1985; Izrael & Tsyban, 1986; Connell, 1987).

While chemical surveys are important in determining the benchmark levels (Rice *et al.*, Subchapter 8.1.3, this volume; Krynitsky *et al.*, Subchapter 8.3.2, this volume) and the biogeochemical pathways of toxicants in the environment (Flegel & Patterson, 1983), little information about the contaminant's biochemical, physiological, and ecological effects can be obtained (Cairns & Pratt, 1987).

Similarly, the utility of measuring individual species' response to environmental contamination has its limitations. Possible responses that can be measured include determining rates of biotransformation (Griffiths *et al.*, 1982), bioaccumulation and food-chain transfers (Foster *et al.*, 1987), and single-species toxicity tests (Chapman & Long, 1983). Extrapolation from these single-species assessments of exposure to a determination of ecosystem-level adverse impacts cannot be properly deduced.

Field survey data are often extremely complex and natural variability may mask perturbations caused by exposure to contaminants (Levin *et al.*, 1984). More sophisticated field experiments are needed to determine the impact of an invertebrate's exposure to a toxicant on its reproduction, immigration, and recruitment and to assess how these impacts change benthic community structure (Kimball & Levin, 1985).

The Sediment Quality Triad provides one model, from many that are being developed, that could serve as a framework. It encompasses chemical surveys, single-species toxicity testing,

and field ecological assessments into an integrated assessment of the actual ecological impact of contaminants on living resources (Long & Chapman, 1985; Chapman, 1986).

The object of this paper is to examine two single-species toxicity tests that might be useful candidate tests as rapid screening procedures in a comprehensive monitoring program. One test uses the brine shrimp, *Artemia salina* (an anostracan crustacean), and examines mortality of instar II and III nauplii as the end-point (See Fig. 1) (Persoone & Wells, 1987). The other uses the marine dinoflagellate *Pyrocystis lunula* and measures the suppression of bioluminescence as an end-point (See Fig. 2) (Stiffey, 1990). These two tests are applied to determine the acute toxicity of sediment samples (collected during the Third Joint US-USSR Bering & Chukchi Seas Expedition, 26 July–2 September 1988) to these organisms.

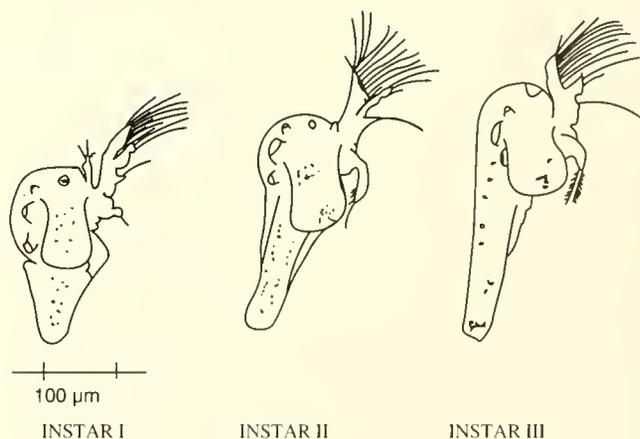


Fig. 1. Morphology of nauplii of *Artemia*.

Materials and Methods

Preparation of Sediments

Sediment samples were collected as described by Rice *et al.* (Subchapter 8.1.3, this volume) and Krynitsky *et al.* (Subchapter 8.3.2, this volume). The sediment was stored at -4°C until analyzed in the laboratory. The suspended particulate phase of the sediment sample was used to determine whether these samples were acutely toxic to the test organisms. Samples were thawed to room temperature and mixed in a blender until thoroughly homogenized (usually about 15 min), and filtered (1 micron- Whatman) 3.8% seawater was aerated and used for

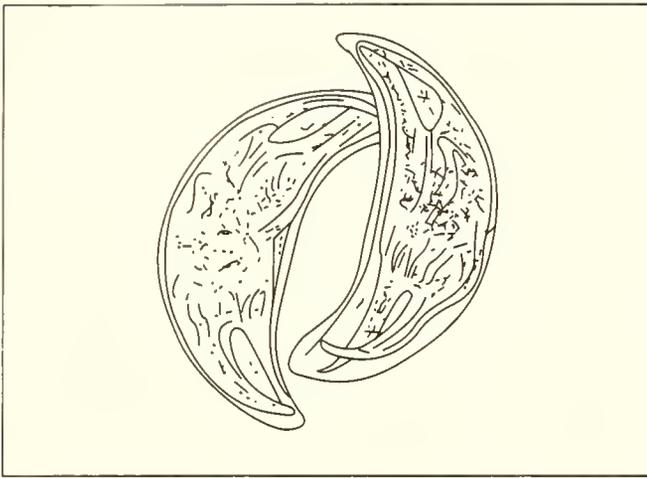


Fig. 2. Drawing of *Pyrocystis lunula* cells; the long axis is approximately 100 microns.

preparing dilution water. A 500-ml sample of the sediment was poured into a 2,000-ml flask and seawater was added to bring the final volume to 1 l. This suspension was stirred for 5 min with a magnetic stirbar and the suspension allowed to settle for 1 h at 25°C. The liquid phase, which is the suspended particulate phase, was then poured into another 2,000-ml flask and stirred for 5 min; then the pH and dissolved oxygen (DO) were recorded. The pH was adjusted to 7.8, and if the DO was below 4.9 parts per million (ppm), the phase was aerated for 5 min. At that point, pH and DO were recorded for 20 min at 5-min intervals. This reaeration continued until DO was stabilized above 4.9 ppm. This test medium was used for toxicity testing (Federal Register, 1985).

Artemia salina Toxicity Test

The *A. salina* toxicity test was modified from several sources (Peltier & Weber, 1985; Vanhaecke & Persoone, 1984; Persoone & Castrisi-Catharios, 1989; Persoone *et al.*, 1989) and ARTOXKIT M (Persoone, State University of Ghent, Belgium). The following is a brief description of the procedure used.

Artemia salina cysts were obtained from Aquarium Products (Glen Burnie, MD), with its cyst origin identified as Columbia. Filtered (1 μ -Whatman) 3.8‰ seawater was used for hatching the *Artemia* cysts and preparing the dilution water (Persoone & Castrisi-Catharios, 1989). Hatching was initiated 48 h before the start of the toxicity test. A 2,000-ml separatory funnel was used as an incubation chamber where 15 to 20 ml of *Artemia* cysts were added and mixed vigorously using an air stream for 24 h at 27°C under continuous illumination. Upon hatching, the nauplii were allowed to settle to the bottom of the separatory vessel and drained into a 250-ml beaker containing fresh dilution water. At the end of the 24-h incubation period, the larvae are at instar I of their life cycle (Fig. 1).

The instar I nauplii were incubated for another 24 h, in continuous light, at 27°C. Their positively phototactic response permits them to be concentrated near the vicinity of a light beam and allows for easier pipetting (Peltier & Weber, 1985). At this point, and for the duration of the exposure to the test

medium, the larvae were at instar II–III stage (Fig. 1). The larvae were not fed during the entire procedure and no mortality was observed due to starvation.

Two multiwell plates each consisting of 24 individual wells (3 ml) were used to test the elutriate produced from the processing of each sediment sample. Two replicates for each sediment sample were produced. In all, forty-four wells (20 experimental and 4 seawater controls) were used and positions within the multiwell plates were randomly assigned. One ml of the test elutriate was added to a well and 10 *Artemia* nauplii were added by micropipetting. The wells were then placed for 24 h in an incubator without light at 27°C. After the incubation period, each well was examined under a dissecting microscope using a $\times 10$ magnification and the live *Artemia* were counted. Mortality was determined if a larva was not observed moving for 10 seconds (Vanhaecke & Persoone, 1984). If any of the sediment elutriate samples showed any signs of mortality, a LC₅₀ was calculated (Peltier & Weber, 1985).

Pyrocystis lunula Toxicity Test

Pyrocystis lunula, a marine dinoflagellate, was maintained in *f/2* medium, its composition given in Table 1 (Guillard & Ryther, 1962). Cultures of *P. lunula* were maintained at 20°C and illuminated with cool white fluorescent lamps shaded to a light intensity of 17 μ -einsteins/cm². The illumination cycle was 12 h light and 12 h dark.

TABLE 1
Composition of *f/2* Medium.

Constituent	Concentration
NaNO ₃	150 mg
NaH ₂ PO ₄ •H ₂ O	10 mg
Fe sequestrene*	10 mg (1.3 mg Fe)
Na ₂ SiO ₃ •9H ₂ O	30-60 mg (3-6 mg Si)
Vitamins:	
Thiamine•HCL	0.2mg
Biotin	0.001 mg
B ₁₂	0.001 mg
Trace Metals:	
CuSO ₄ •5H ₂ O	0.0196 mg (0.005 mg Cu)
ZnSO ₄ •7H ₂ O	0.044 mg (0.01 mg Zn)
CoCL ₂ •6H ₂ O	0.020 mg (0.005 mg Co)
MnCL ₂ •4H ₂ O	0.360 mg (0.1 mg Mn)
Na ₂ MoO ₄ •2H ₂ O	0.0126 mg (0.005 mg Mo)
Seawater [#]	To 1 liter

The medium is modified by the omission of silicate and the addition of TRIS buffer to increase the final pH to 7.6.

* Sodium iron salt of ethylene dinitrilotetraacetic acid (EDTA).

Artificial seawater is prepared from the formula of Lyman and Fleming (1940).

Cells were counted in a Sedgewick-Rafter chamber and their concentration was adjusted to 100 cells/ml for use during the toxicity test.

To be certain that the dinoflagellate culture emits the maximum quantity of light, it is necessary that the culture be stirred vigorously. An acrylic rod was fitted into the chuck of a variable speed electric motor drive set at ~100 rpm. During the test, the rod was inserted approximately two-thirds of the way into the vial containing the test medium and *P. lumula* cells and stirred for 2 min to ensure that the light producing ability of the dinoflagellate was exhausted.

A solid state photometer (Stiffley *et al.*, 1985; Stiffey *et al.*, 1987) measured bioluminescence and a multirange stripchart recorder with a chart speed of 5 cm/min was connected to the photometer that was adjusted so that the recorder registered the cumulative light fluxes as a function of time (Fig. 3).

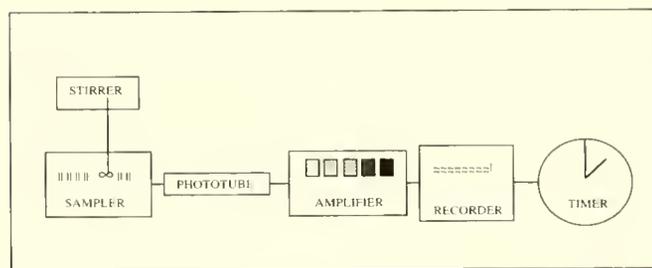


Fig. 3. Equipment used for the measurement of luminescence intensity.

The percentage of bioluminescent quenching was calculated with the following equation:

$$\% \text{ quenching} = \frac{C-E}{C} \times 100$$

where C = displacement of the reorder pen (in mm) during the stirring of the control culture, and E = the displacement of the pen during stirring of the test elutriate (Stiffey, 1990).

Depending on the degree of toxicity of the test medium, bioluminescence may be totally suppressed, or a degree of light diminution relative to seawater controls may be noted. If any decrease in bioluminescence was observed, an LC₅₀ was calculated (Peltier & Weber, 1985).

Results and Discussion

For the stations examined, none of the sediments appear to be acutely toxic to *A. salina* and *P. lumula* (Table 2). This agrees with the levels of contamination reported from this region determined by chemical analysis (Rice *et al.*, Subchapter 8.1.3, this volume; Krynitsky *et al.*, Subchapter 8.3.2, this volume). Since toxicity was not observed, LC₅₀ values were not calculated. This illustrates the rapidity and cost-effectiveness of initial screening for toxicity. In a hierarchical approach to ecotoxicological assessment, a positive indication of toxicity would have triggered a series of assessment procedures where definitive toxicity tests, field experiments, and other investigations could be performed. A negative response allows resources to be redirected to areas of greater concern.

TABLE 2

Stations Where Sediments Were Tested And Results of Toxicity Tests.

Station	<i>Artemia</i>	<i>Pyrocystis</i>
3	-	-
7	-	-
9	-	-
13	-	-
18	-	-
22	-	-
35	-	-
45	-	-
47	-	-
50	-	-
55	-	-
59	-	-
61	-	-
64	-	-
67	-	-
69	-	-
75	-	-
96	-	-
109	-	-
110	-	-

These two toxicity tests showed great potential for use on research vessels and to generate timely information that could be pursued while the vessel is still on-station. During a catastrophe such as an oil spill, a rapid assessment of toxic impact can direct prevention and clean-up procedures, which can maximize the effort in protecting valuable fish and wildlife resources.

The organisms are easy to culture and maintain and require very little in terms of space and equipment. End-points such as mortality or diminution of bioluminescence are easy to measure and provide clearly defined criteria for assessing the quality of the sediment.

Several drawbacks in using these tests do exist and reflect not so much the limitations of these particular tests but the symptomatic problems confronting toxicity testing in general (Kimball & Levin, 1985). While the suspended particular phase testing is a proper approach for use with pelagic organisms such as *Artemia* and *Pyrocystis*, it is not a direct measure of sediment toxicity. It would have been desirable to use a sediment-dwelling organism. While much research is being conducted in the area of sediment toxicity testing, it is not as well developed as water-phase testing (Levin *et al.*, 1984; Long & Chapman, 1985). The lack of cultured benthic species is a major limitation. With a wide spectrum of sediment types found in the marine environment and with each benthic species having its own tolerance for sediment substrate, the definitive marine sediment test that is rapid and cost-effect is still to be developed. A promising approach may be the use of artificially

formulated sediments as substrates for culturing benthic invertebrates in the lab (Watzin & Roscigno, 1990).

An invertebrate common to the Bering and Chukchi Seas that might be suitable is *Ampelisca*. Their importance as food sources for many marine mammals makes species from this genus likely candidates for a sediment toxicity test. Until more region-specific test species are available, organisms such as *Artemia* and *Pyrocystis* will serve as reliable surrogates.

With more developmental work, these two species can be used as part of an integrated ecotoxicological monitoring program that can provide useful information toward establishing baseline conditions for the Bering and Chukchi Seas. The anticipated assaults from oil development can be monitored so that impacts to these ecosystems can be minimized.

Special thanks to W. Walker, M. Watzin, A. Alonzo, and J. Johnston for their help and support.

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Chapter 10:
MARINE BIRDS

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During summer, the Chukchi Sea is supplied with relatively warm water through the Bering Strait which results in ice-free conditions over 50–100% of its area by late summer (Stringer *et al.*, 1980). Three distinct water types that conserve salinity, but not temperature, flow northward through Bering Strait into the Chukchi Sea (Coachman *et al.*, 1975; Aagaard, 1984; NOAA, 1988). Anadyr water on the west is the most saline (>33 ppt), followed by Bering Shelf water in the center, and finally Alaska Coastal water (<31.5 ppt) on the east. Anadyr water mixes extensively with Bering Shelf water and loses its identity soon after entry into the Chukchi Sea (e.g., Grebmeier *et al.*, 1989). During its northward flow, Alaska Coastal water is augmented by additional freshwater inputs from Kotezebue Sound. Siberian Coastal water intrudes from the East Siberian Sea along the Siberian coast and is characterized by salinities <32 ppt (Coachman *et al.*, 1975). The general flow from the strait eventually veers eastward past Pt. Hope, steered in part by bathymetry. Tidal amplitudes are small and do not contribute significantly to water mass movements (NOAA, 1988).

Seabird Censuses

Seabirds were counted aboard the research vessel (R/V) *Akademik Korolev* between 8 and 15 August 1988. Shipboard counts were conducted along transect lines running along the Chukchi Sea Continental Shelf, generally in east–west directions (Frontispiece). Sixty-two 10-min transect counts were conducted in the southern Chukchi Sea portion of the joint expedition. A total of 129.5 km² was censused at an average ship speed of 15 knots (Table 1).

Transects were taken while the ship was in motion and used a 300 × 300 m zone (90° sector) extending forward and abeam of the vessel on the side with the best viewing conditions (Tasker *et al.*, 1984). Ship position (latitude/longitude) was recorded at the beginning and end of each transect count. All birds sitting or flying within the transect were counted, but sitting and flying birds were recorded separately. Counts were conducted between oceanographic stations by a single observer from the ship's flying bridge 12 m above the ocean surface. Binoculars were frequently used to detect birds missed by the unaided eye. Thick-billed (*Uria lomvia*) and common (*U. aalge*) murre, jaegers, and small dark alcids could not always be identified to species. All data were logged on standard USFWS project forms.

In addition to the transect counts, 18 station counts were obtained while the ship was stopped for oceanographic sampling. Station counts recorded all birds seen within 600 m of the ship during a 15-min period.

Ecological research on the R/V *Akademik Korolev* was undertaken in five ecosystems in the Bering and Chukchi Seas (Bering Sea Shelf, Bering Sea Slope, Gulf of Anadyr, Chirikov basin, and southern Chukchi Sea). The oceanographic data used in this analysis are from the southern Chukchi Sea, the only region from which we had sufficient seabird transects and station counts. Along the transect lines, the vessel was stopped to deploy instruments for measuring physical and biological attributes of the water at 32 stations (Stations 44–75, Frontispiece). A CTD hydrocast unit recorded depth, pressure, water temperature, conductivity, salinity, and density (σ_t). Vertical cross-section profiles along transect lines were obtained from programs developed at the Institute of Marine Science, University of Alaska, Fairbanks, and Woods Hole Oceanographic Institution.

Analysis

Relationships of seabirds to water masses were examined by first categorizing all 10- and 15-min counts by the water type in which they occurred. Ship position, sea surface temperature, and salinity were used to place each transect within the proper water mass. Seabird abundances were expressed both as the number km⁻² and hour counted. Numbers of birds per 10-min transect were used as sample units in multiple comparisons (Kruskal-Wallis rank sums analysis) across all water mass types. When there were significant overall differences, individual comparisons between water mass types were made using Mann-Whitney *U*-tests. If values of *U* were outside limits of regular probability tables due to large sample size, the approximate normal deviate *Z* was used as the test statistic (Snedecor & Cochran, 1980). *Z* values were corrected for tied groups.

Results

Water Mass Distributions

Three distinct water masses were recorded within the southern Chukchi Sea during August 1988 (Figs. 2–6). We follow previous convention in designating these water mass types (e.g., Coachman *et al.*, 1975; Coachman, 1987).

TABLE 1

Allocations of census effort by water mass type:
SCW=Siberian Coastal water; BSAW=mixed Bering
Shelf-Anadyr water; ACW=Alaska Coastal water.

	10-min transect counts				15-min Station Counts			
	Number of counts	Total time (min)	Average speed (knots)	Range	Total area censused	\bar{x} area/ transect	Number of counts	Total time (min)
SCW	23	230	15.0	13-16	48.07	2.09	7	105
BSAW	24	240	15.0	15-16	50.16	2.09	8	120
ACW	15	150	15.0	15	31.35	2.09	3	45

The water masses were oriented south to north across the Chukchi Shelf and were not exclusively related to bathymetry. Water from Bering Strait progressed northward through the central Chukchi Sea and constituted a tongue of relatively high surface salinity, with less saline water both on the west and east sides (Fig. 2).



Fig. 2. Surface horizontal distributions of salinity (in parts per thousand; ppt) along the southern Chukchi Sea Continental Shelf. Alaska Coastal water (<31.5 ppt) lies to the east of mixed Bering Shelf-Anadyr water (>31.5 ppt) which was situated immediately north of Bering Strait. Siberian Coastal water (<31.5 ppt) lies west of Bering Shelf-Anadyr water between Kolyuchin Bay and Cape Dezhnev on the north coast of the Chukchi Peninsula.

Alaska Coastal water (ACW) occurred in the eastern part of the southern Chukchi continental shelf (Fig. 2). This water mass is characterized by salinities <31.5 ppt, relatively high surface temperatures (>6°C; Figs. 3,4), and a north-south orientation along the coast of western Alaska. The transition between this and the next water mass was weaker than between the other two water masses (cf. Coachman *et al.*, 1975).

Mixed Bering Shelf-Anadyr water (BSAW; Grebmeier *et al.*, 1989) was confined to the area immediately north of Bering Strait between the two other water masses and is characterized by salinities in excess of 31.8 ppt (Fig. 2), low surface temperatures of -1 to +2°C, and a vertically mixed water column (Figs. 3-6). The contribution of Bering Shelf and Anadyr Waters to the southern Chukchi Shelf is especially evident in Fig. 3, which illustrates a tongue of colder surface water extending northward from Bering Strait into the Chukchi Sea. Also, because isolines of temperature and salinity (Figs. 4,5) were oriented more vertically along the southern (e.g., Stations 72-75) than along the northern, more stratified sections, the separate identity and lack of lateral exchange of water masses flowing north through the strait is apparent.

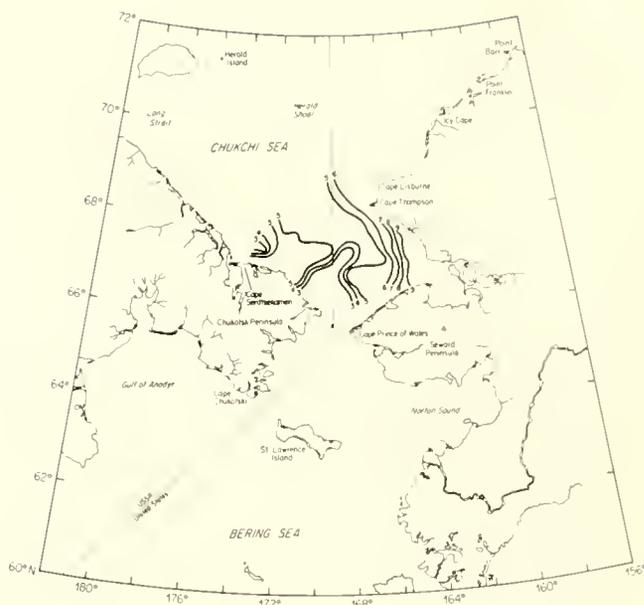


Fig. 3. Surface horizontal distributions of temperature (in °C) along the southern Chukchi Sea Continental Shelf.

To the east of BSAW and north of the Chukchi Peninsula, Siberian Coastal water (SCW) occurred. This water mass was characterized by very low surface salinities (24-31.5 ppt), medium surface (3-5°C) and low bottom temperatures (-1 to 1°C), and a highly stratified water column (Fig. 6). The bottom salinity in SCW (Fig. 5, top) is also higher than that of water from Bering Strait (Fig. 5, bottom). Siberian Coastal water is thought to intrude eastward from the East Siberian Sea along the Siberian coast (Coachman *et al.*, 1975). The tongue of SCW during the 8-15 August 1988 cruise of the *Akademik Korolev* (Fig. 2) extended further east than during the 24 July-1 August 1972 cruise of the *R/V Oshoro Maru* (Fig. 72, Coachman *et al.*, 1975). The transition between SCW and BSAW was marked by very steep gradients of temperature and salinity compared to the BSAW-ACW transition.

Species Accounts

Northern Fulmar (*Fulmarus glacialis*). Fulmar abundance was highest (>2 birds km⁻²) in SCW (Tables 2,3), but this procellariiform also occurred in BSAW and ACW in lesser numbers. Colonies west of Provideniya on the Chukchi Peninsula (D. Siegel-Causey & J. Piatt, personal communication) and at St. Matthew Island in the central northern Bering Sea (Sowls *et al.*, 1978) would be the nearest origins for fulmars in the Chukchi Sea. Both of these colonies are south of Bering Strait (Fig. 1).

Short-tailed Shearwater (*Puffinus tenuirostris*). Short-tailed shearwaters were >50 and >500 times more abundant in SCW than BSAW and ACW, respectively (Table 2). This austral species breeds in New Zealand, southern and eastern Australia, Tasmania, and adjacent islands, migrating to the Bering and Chukchi Seas during the Northern Hemisphere summer (Hunt *et al.*, 1981). High concentrations have been recorded at Aleutian Island passes (e.g., Unimak) during May-June and September-October and northeast of St. Lawrence Island during August-September (NOAA, 1988).

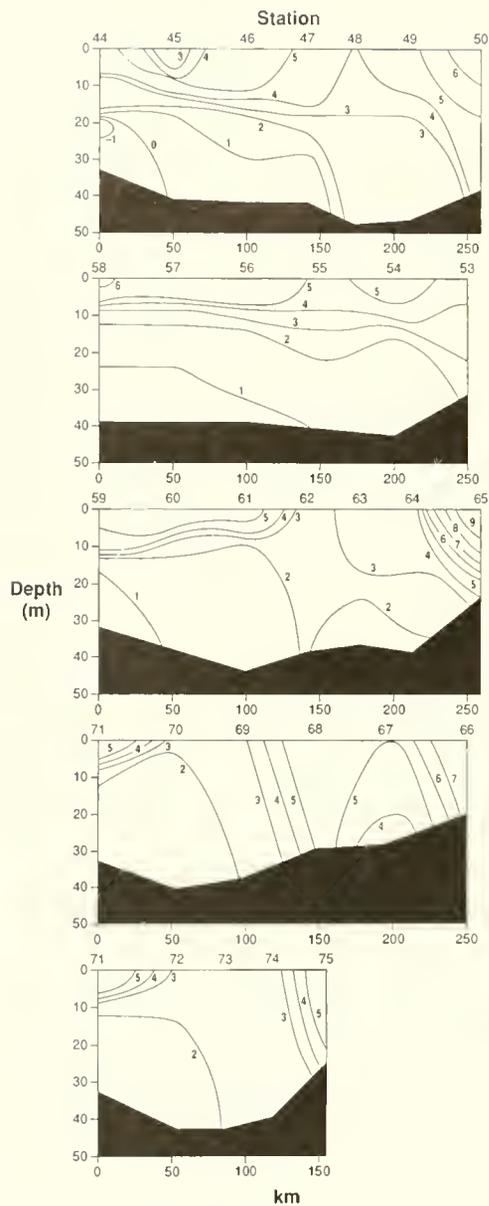


Fig. 4 Vertical cross-section profiles of temperature (in °C) along five west to east transect lines along the southern Chukchi Sea Continental Shelf. Panels are arranged from north (top) to south (bottom) (cf. Frontispiece).

Red Phalarope (*Phalaropus fulicaria*). Phalaropes were absent from ACW but were recorded in both BSAW and SCW where they were equally abundant (Table 2). Many of the phalaropes tended to occur either near the boundary between water masses or at locations with steep horizontal gradients in salinity—for example, Stations 60, 70, and 72–73 (cf. Frontispiece, Fig. 2). Little is known about phalarope distributions and autumn staging areas in the western Chukchi Sea. Small flocks of 10–20 individuals were also observed feeding in association with gray whales (*Eschrichtius robustus*).

Pomarine Jaeger (*Stercorarius pomarinus*). Based on 10-min transect counts, Pomarine jaegers were most abundant in SCW (Table 2), possibly because this water mass also had large numbers of short-tailed shearwaters that jaegers could

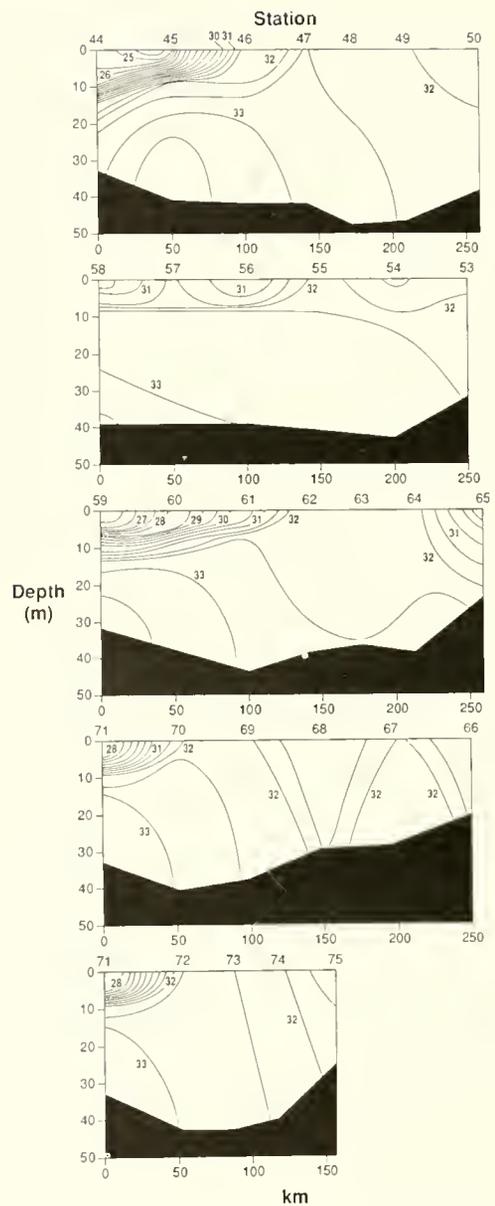


Fig. 5 Vertical cross-section profiles of salinity (in ppt) along five west to east transect lines along the southern Chukchi Sea Continental Shelf. Panels are arranged from north (top) to south (bottom) (cf. Frontispiece). Isohalines are illustrated in 0.5 ppt.

exploit (kleptoparasitize) for food. Jaeger abundances derived from the 15-min station counts (Table 3) were equal across the three water masses.

Long-tailed Jaeger (*Stercorarius longicaudus*). Three individuals of this jaeger species occurred in SCW near Station 61 (Frontispiece).

Herring Gull (*Larus argentatus*). Herring Gulls were most abundant in SCW (Tables 2, 3). Although apparently not nesting locally on the Soviet side of the southern Chukchi Shelf (e.g., NOAA, 1988), herring gulls breed on the Chukchi Peninsula (AOU, 1983) and at Koozata Lagoon on St. Lawrence Island in the northern Bering Sea (Fay & Cade, 1959; Sowls *et al.*, 1978). The race that occurs in the southern Chukchi and northern Bering Seas is the darker-mantled Siberian form, *L. a. vegae* (Grant, 1986).

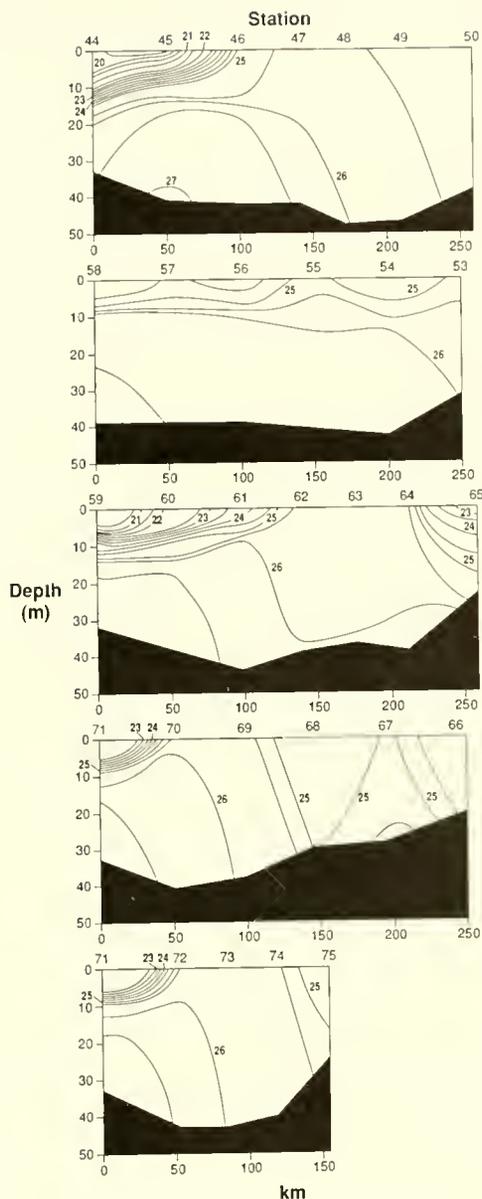


Fig. 6. Vertical cross-section profiles of density (in σ_t units) along five west to east transect lines along the southern Chukchi Sea Continental Shelf. Panels are arranged from north (top) to south (bottom) (cf. Frontispiece). Isopycnals are illustrated in 0.5 units of σ_t .

Glaucous Gull (*Larus hyperboreus*). This gull was about equally abundant in SCW and BSAW as recorded by 10-min transects (Table 2). Based on 15-min station counts (Table 3), it was most abundant in SCW and approximately equally common in BSAW and ACW. The more homogeneous distribution of this species across the three water mass types compared to the herring gull may be due to colony distribution and adjacency. Glaucous gulls nest in small colonies (<100 individuals) from Kolyuchin Bay eastward to capes Serdtse Kamen and Dezhnev on the northern coast of the Chukchi Peninsula, and on the coast of western Alaska from Cape Lisburne south to Kotzebue Sound (NOAA, 1988). Larger colonies (>100 individuals) exist near Cape Thompson and at the Diomede Islands (Sowls *et al.*, 1978; NOAA, 1988).

Black-legged Kittiwake (*Rissa tridactyla*). Kittiwakes were more than twice as common in SCW than in BSAW and

ACW (Tables 2, 3). Small colonies (<10,000 individuals) are found around the coastline of the entire southern Chukchi Sea, whereas large colonies (>10,000 individuals) are restricted to Cape Lisburne, Cape Thompson, and the Diomedes (Sowls *et al.*, 1978; NOAA, 1988).

Sabine's Gull (*Xema sabini*). Small numbers of Sabine's gulls were observed only in SCW and BSAW (Tables 2,3).

Arctic Tern (*Sterna paradisaea*). Ten arctic terns were recorded in SCW near Station 45 (Table 2; Frontispiece). This location is not far from a small breeding colony on Kolyuchin Island (NOAA, 1988) near the western edge of the study area.

Common Murre (*Uria aalge*) and Thick-billed Murre (*Uria lomvia*). Abundances of murre showed a trend of increasing abundance from west to east when unidentified individuals and both species were combined (Table 2). Thus, ACW had the highest murre densities: 3.5 birds km^{-2} versus 2.6 and 1.3 birds km^{-2} in BSAW and SCW, respectively. The at-sea abundances parallel the distribution of colonies from which murre probably originate. Only small colonies (<100,000 individuals) are located on the Soviet (western) side of the Chukchi Sea, whereas two large colonies (100,000–1,000,000 individuals) are situated at the eastern end of the study area in Alaska at Cape Lisburne and Cape Thompson (Fig. 1; NOAA, 1988; Sowls *et al.*, 1978). Within each water mass type, there was generally a decrease in murre abundance with increasing distance from land and colony of probable origin. Largest numbers were counted near Stations 49, 50, and 51 (<120 km from the Cape Lisburne colony) and near Stations 60 and 61 (<100 km from colonies at and east of Cape Serdtse Kamen; Fig. 1).

Kittlitz's Murrelet (*Brachyramphus brevirostris*). Four of these murrelets were seen together on 15 August in BSAW near Station 74 (Frontispiece). Although very uncommon in the Chukchi Sea, this alcid breeds north to Pt. Hope, Alaska, and is casual in northeastern Siberia (AOU, 1983).

Parakeet Auklet (*Cyclorhynchus psittacula*). Three parakeet auklets were counted between Stations 73 and 74 in BSAW (Frontispiece). This location is <65 km from the closest of several colonies at Cape Dezhnev on the western side of Bering Strait (NOAA, 1988).

Least Auklet (*Aethia pusilla*). Least auklets were far more abundant in BSAW than SCW and ACW (Table 2). Except for a few individuals near Stations 50, 55, 58, and 61 (Frontispiece), greatest numbers were in the southern portion of the Chukchi Sea between Stations 72 and 75. This latter location is 85–95 km from the closest colony on Little Diomed Island, where the breeding population of least auklets numbers just under 1,000,000 birds (Sowls *et al.*, 1978).

Crested Auklet (*Aethia cristatella*). Crested auklets occurred only near Station 73 in BSAW (Table 2; Frontispiece). A breeding colony of 140,000 birds is located 85 km south at Little Diomed Island (Sowls *et al.*, 1978).

Tufted Puffin (*Fratercula cirrhata*). Tufted puffins were unrecorded in SCW and on the western side of the southern Chukchi Sea (Tables 2, 3). Single birds only were observed near Stations 49, 50, and 72–75. As few as 100 individuals of this puffin species breed north of Bering Strait, mostly near Capes Lisburne and Thompson in northwestern Alaska (Sowls *et al.*, 1978).

TABLE 2

Seabird abundance (density and number per hour) recorded during 10-minute transects in the southern Chukchi Sea by water type.

	Siberian Coastal water		Bering-Anadyr water		Alaska Coastal water	
	Number/km	Number/hr	Number/km	Number/hr	Number/km	Number/hr
Northern fulmar (<i>Fulmarus glacialis</i>)	2.1	26.9	0.1	1.5	0.2	2.0
Short-tailed shearwater (<i>Puffinus tenuirostris</i>)	53.3	668.9	1.0	13.0	<0.1	0.8
Red phalarope (<i>Phalaropus fulicaria</i>)	0.1	1.3	0.4	5.3	0.0	0.0
phalarope sp. (<i>Phalaropus</i> sp.)	0.2	2.9	0.0	0.0	0.0	0.0
Pomarine jaeger (<i>Stercorarius pomarinus</i>)	0.5	6.5	0.1	1.8	<0.1	0.8
Long-tailed jaeger (<i>Stercorarius longicaudus</i>)	<0.1	0.8	0.0	0.0	0.0	0.0
jaeger sp. (<i>Stercorarius</i> sp.)	<0.1	1.0	0.0	0.0	0.0	0.0
Herring gull (<i>Larus argentatus</i>)	0.2	3.1	0.0	0.0	0.0	0.0
Glaucous gull (<i>Larus hyperboreus</i>)	<0.1	0.5	<0.1	0.3	0.0	0.0
Black-legged kittiwake (<i>Rissa tridactyla</i>)	1.4	18.0	0.4	5.0	0.2	2.4
Sabine's gull (<i>Xema sabini</i>)	<0.1	0.8	<0.1	0.8	0.0	0.0
Arctic tern (<i>Sterna paradisaea</i>)	0.2	2.6	0.0	0.0	0.0	0.0
Common murre (<i>Uria aalge</i>)	0.3	3.7	1.3	16.5	0.3	4.0
Thick-billed murre (<i>Uria lomvia</i>)	0.1	1.6	0.0	0.0	0.0	0.0
murre sp. (<i>Uria</i> sp.)	0.9	11.5	1.0	12.8	3.2	40.0
Kittlitz's murrelet (<i>Brachyramphus brevirostris</i>)	0.0	0.0	<0.1	1.0	0.0	0.0
Parakeet auklet (<i>Cyclorhynchus psittacula</i>)	0.0	0.0	<0.1	0.8	0.0	0.0
Least auklet (<i>Aethia pusilla</i>)	0.1	1.6	6.8	85.8	0.1	1.2
Crested auklet (<i>Aethia cristatella</i>)	0.0	0.0	1.1	13.3	0.0	0.0
auklet sp. (<i>Aethia</i> sp.)	1.1	13.3	2.6	32.8	0.4	5.2
Tufted puffin (<i>Fratercula cirrhata</i>)	0.0	0.0	0.1	1.5	<0.1	0.4
Horned puffin (<i>Fratercula corniculata</i>)	<0.1	0.3	0.2	2.5	0.0	0.0
TOTAL	60.7	765.3	15.2	194.7	4.5	56.8

Horned Puffin (*Fratercula corniculata*). Horned puffins were most abundant in BSAW (Tables 2, 3) and were unrecorded in ACW. This puffin was observed near Stations 58, 59, 69, 70, and 72–75. All of these locations lie within 90 km of small colonies (<1,000 individuals) in the southwestern portion of the study area at Cape Serdtse Kamen, Cape Dezhnev, and Little Diomed Island (Sowls *et al.*, 1978; NOAA, 1988). No horned puffins were recorded west of the Cape Lisburne and Cape Thompson colonies at distances greater than 45–60 km, even though one large (1,000–10,000 individuals) and several small colonies are close to the Station 49–53 transect line (Frontispiece).

Seabird Abundances Across water Mass Types

Differences in total seabird abundances among the three water masses as detected by both 10-min transects ($H = 7.848$, $P = 0.0198$) and 15-min station counts were significant ($H = 7.247$, $P = 0.0267$; Table 4). Seabirds were significantly more abundant in SCW than ACW (Mann-Whitney U , $Z = -2.542$, $P = 0.011$) and more abundant in BSAW than ACW (Mann-Whitney U , $Z = -2.156$, $P = 0.0311$) as detected by 10-min transects.

Differences in seabird abundances between SCW and BSAW were not significant (Mann-Whitney U , $Z = -1.139$, $P = 0.2545$).

Analyses of the 15-min station counts indicated that seabirds were more abundant in SCW than BSAW (Mann-Whitney U , $Z = -1.967$, $P = 0.0491$) and in SCW than ACW (Mann-Whitney U , $Z = -2.393$, $P = 0.0167$). Differences in abundances between BSAW and ACW were not significant (Mann-Whitney U , $Z = -1.025$, $P = 0.3052$). Because over 87% of the seabirds in SCW were short-tailed shearwaters, this species was largely responsible for influencing the differences in seabird abundances observed among water mass types.

Discussion

Seabird species recorded in the southern Chukchi Sea tended to fall into one of four groups: rare/local vagrants, terrestrial postbreeders, locally-breeding marine species, and long-distance migrants. The status of each species strongly influenced their use of (or detected affinities for) the three Chukchi Sea water masses. At least four species nest inland on

TABLE 3

Seabird abundance (number per hour) recorded during
15-minute station counts in the southern Chukchi Sea by water type.

	Siberian Coastal water	Bering-Anadyr water	Alaska Coastal water
Northern fulmar (<i>Fulmarus glacialis</i>)	14.9	4.0	0.0
Short-tailed shearwater (<i>Puffinus tenuirostris</i>)	546.3	5.0	2.7
Red phalarope (<i>Phalaropus fulicaria</i>)	6.3	0.0	0.0
phalarope sp. (<i>Phalaropus</i> sp.)	0.0	0.0	0.0
Pomarine jaeger (<i>Stercorarius pomarinus</i>)	0.6	0.5	1.3
Long-tailed jaeger (<i>Stercorarius longicaudus</i>)	0.0	0.0	0.0
jaeger sp. (<i>Stercorarius</i> sp.)	0.0	0.0	0.0
Herring gull (<i>Larus argentatus</i>)	50.3	0.5	0.0
Glaucous gull (<i>Larus hyperboreus</i>)	6.9	1.5	1.3
Black-legged kittiwake (<i>Rissa tridactyla</i>)	12.6	4.5	1.3
Sabine's gull (<i>Xema sabini</i>)	0.0	0.0	0.0
Arctic tern (<i>Sterna paradisaea</i>)	0.0	0.0	0.0
Common murre (<i>Uria aalge</i>)	1.7	7.5	0.0
Thick-billed murre (<i>Uria lomvia</i>)	0.0	0.5	0.0
murre sp. (<i>Uria</i> sp.)	6.3	7.0	5.3
Kittlitz's murrelet (<i>Brachyramphus brevirostris</i>)	0.0	0.0	0.0
Parakeet auklet (<i>Cyclorhynchus psittacula</i>)	0.0	0.0	0.0
Least auklet (<i>Aethia pusilla</i>)	0.0	21.5	0.0
Crested auklet (<i>Aethia cristatella</i>)	0.0	0.0	0.0
auklet sp. (<i>Aethia</i> sp.)	0.0	9.5	0.0
Tufted puffin (<i>Fratercula cirrhata</i>)	0.0	0.5	0.0
Horned puffin (<i>Fratercula corniculata</i>)	2.3	4.5	0.0
TOTAL	648.2	67.0	11.9

TABLE 4

Kruskal-Wallis rank sum results for
abundances of all seabirds among water
mass types.

Water mass	Number of cases	Σ rank	Mean rank
10-min transects			
SCW	23	863	37.522
BSAW	24	777	32.375
ACW	15	313	20.867
15-min station counts			
SCW	7	94	13.429
BSAW	8	64	8.000
ACW	3	13	4.333

Arctic tundra and use offshore marine areas primarily in fall after breeding is terminated (i.e., red phalarope, Pomarine and long-tailed jaegers, Sabine's gull). Arctic tern and Kittlitz's murrelet are rare anywhere in the Chukchi Sea, and too few were recorded in this survey to certainly detect water mass affinities. Gulls and all alcids were generally most abundant in areas near colonies and large population sources, although the three gulls (herring and glaucous, black-legged kittiwake) occurred in SCW in greater abundances than the geographic distribution of their Chukchi Sea breeding populations would suggest.

Long-distance migrants (northern fulmar, short-tailed shearwaters) gave the strongest and least ambiguous evidence for preferred use of a specific water mass. Neither species breeds locally, and both must pass north through Bering Strait to reach the Chukchi Sea during late summer (NOAA, 1988). Because each water mass is equidistant from the origins of the birds, their affinity for SCW is best explained by favorable foraging conditions within this water mass. Fulmars and shearwaters may have been attracted to SCW because of higher productivity, because the strong horizontal transition between SCW and BSAW (Fig. 2) concentrated prey, or because the highly stratified water column (Figs. 4–6) offered a more stable foraging environment. Although BSAW is known to be up to

six times more productive (Sambrotto *et al.*, 1984) and have different (more oceanic) plankton composition (Springer *et al.*, 1989) than ACW, the productivity and food webs of SCW are largely unknown.

The southern Chukchi Sea Shelf is somewhat unique in having uniformly shallow bathymetry and water masses aligned across rather than along the shelf. Both northern fulmars and short-tailed shearwaters exhibited greater along- as opposed to across-shelf variability in abundance, and this variability corresponded well to the locations of water masses (Table 2). Other studies have related an opposite trend—that is, greater across-shelf variability in seabird abundance—to across-shelf gradients in bathymetry or water flow (e.g., Schneider *et al.*, 1988). These studies, however, did not control for the cross-correlation of water mass orientation and bathymetry. Shallow areas of continental shelves frequently have distinct mixing regimes because freshwater inputs, tidal, and atmospheric forcing create and maintain different water masses than further offshore in deeper areas of the shelf, where density forcing, or geostrophic currents, may play greater roles (e.g., Atkinson *et al.*, 1983). Relationships of seabirds to oceanographic features can be determined with greater confidence if areas lacking large numbers of intercorrelated environmental gradients are employed to test such hypotheses. Detection of seabird affinities for water masses in high-latitude seas is often complicated by the geographic adjacency of colonies (Wahl *et al.*, 1989) and the foraging distances that limit birds commuting between colonies and offshore foraging sites (cf. Schneider & Hunt, 1984). In this context, nonbreeding

species such as the short-tailed shearwater may provide better clues for determining factors that influence marine distributions of seabirds in such environments.

The Third Joint US–USSR Bering & Chukchi Seas Expedition was organized at the 11th meeting of the US–USSR Joint Committee on Environmental Protection in Moscow (February 1988), the Soviet–American Conference on the Ecology of the Bering Sea, and the plan of the joint bilateral activity 02.07-2101 entitled “Comprehensive Analysis of Marine Ecosystems and Ecological Programs of the World Ocean.” We appreciate the assistance of US Fish and Wildlife Service personnel: Harold J. O’Connor, Patuxent Wildlife Research Center, Steven G. Kohl, Office of International Affairs, Sharon Janis and William Mattice of the Division of Realty, Regional Office, Anchorage. Mr. Anthony Amos and Dr. Terry Whittedge of the University of Texas Marine Science Institute provided technical support and CTD data. Dr. Lawrence K. Coachman volunteered much information on the oceanography of the Bering and Chukchi Seas during the data gathering phase of the project. The Soviet delegation was headed by Professor Alla V. Tsyban, Goskomgidromet and USSR Academy of Sciences. Weather data were compiled faithfully and accurately by Irena Mataeva. Volodya Kalytyak assisted in data gathering and provided much appreciated comradeship. Thanks are also extended to the captain and crew of the R/V *Akademik Korolev* for providing a safe and friendly platform for observing birds and mammals in the Bering and Chukchi Seas. Manuscript preparation was supported by The John D. and Catherine T. MacArthur Foundation, The J. N. Pew, Jr. Charitable Trust and the Marine Policy Center program in marine biodiversity and ocean conservation at Woods Hole Oceanographic Institution. This is WHOI Contribution No. 7324.

10.2 Associations Between Seabirds and Water Masses in the Northern Bering Sea

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Introduction

Seabirds are an important part of the high-latitude ecosystems of the Bering Sea by virtue of the very large size of their populations and the spatial and temporal concentration of their numbers, particularly during the breeding season. Recent estimates have shown that birds may consume a much greater part of secondary production in the Bering Sea than previously believed (Walsh & McRoy, 1986; McRoy *et al.*, unpublished report). Birds can also significantly contribute to recycling carbon to an ecosystem (Portnoy, 1990).

Over the past 30 years, it has become widely accepted that seabirds have species-specific affinities for particular pelagic habitats, and that these affinities are based on the factors in a given habitat which, when compared with others (e.g., stratified versus well-mixed waters, [Hunt *et al.*, 1990]), enhance the foraging success of birds feeding there (Uspenski, 1958; Brown, 1980; Hunt *et al.*, 1981). However, the mechanisms by which birds find suitable pelagic habitats and how the characteristics of the habitat promote foraging success are poorly understood (Hunt *et al.*, 1990). In addition, little is yet known about the scales at which birds use their marine environments (Hunt & Schneider, 1987).

Previous studies have suggested a causal link between seabird reproductive success and changes in fisheries (Furness & Cooper, 1982; Springer & Byrd, 1988). Because seabirds are closely tied to the Bering Sea ecosystem and are its most visible component, results of studies monitoring their foraging and breeding ecology can be used as an index to the "health" of the ecosystem. For this reason alone, seabirds are an important resource to both the USA and the USSR. In addition, native cultures in both countries use birds and their eggs for food. The extensive mobility of seabirds gives further motivation for cooperative study and management of this resource.

Relatively little research has considered the effect of large-scale habitat patterns in this region on the distribution of seabirds, particularly across existing political boundaries. Hunt *et al.* (1981) described distributions of birds in the southeast Bering Sea, and acknowledged the potential importance of oceanographic conditions and the related availability of prey for determining these observed distributions. Wahl *et al.* (1989) identified differences in seabird community assemblages among broadly defined habitats in the southern Bering Sea. Day *et al.* (in prep.) considered seabird distributions with respect to water masses in the Bering Sea east of the USA–USSR Convention Line in September 1985. Andrew and Haney (Subchapter 10.1, this volume) describe these patterns across the Chukchi Sea. Much remains to be learned, quantitatively, about how macroscale variations in habitat affect foraging seabirds across the Bering Sea Shelf.

To this end, this report describes patterns of bird distribution with respect to water types observed at depths of 20 m or less during July and August 1988 from the Soviet research vessel (R/V) *Akademik Korolev*. The term "water type" is used here to denote a parcel of water characterized by a unique combination of physical and biological properties (i.e., ranges of salinity values and zooplankton communities).

Each water type is given the same name as the formally-recognized water mass (Coachman & Shigaev, Subchapter 2.1, this volume) with the most similar properties (e.g., ASW type has similar properties to the water mass known as Anadyr Stream water). The following hypotheses were tested using these data (not stated as null hypotheses):

1. Birds are unevenly distributed among water types, and these distributions are related to physical features of each water type that may affect availability of prey (zooplankton versus fish) and effectiveness of foraging methods employed.

2. Auklet distribution is related to the position of potentially prey-rich waters (i.e., parallels patterns of secondary production), even if these waters occur at depth.

This study is based on a relatively small number of observations (96 "transect" sampling units). Given the temporal and spatial limitations of these data, this report may best serve as a preliminary "sketch" with which to develop further studies.

I am presently working with seabird data collected during 1987–1990 in conjunction with National Science Foundation project ISHTAR (Inner Shelf Transfer and Recycling) to address these questions in greater detail.

Water Types

Three principal water types (differing in salinity by as much as 1 ppt; see Methods section below) define the macroscale ecology of the northern Bering Sea. These are: Anadyr Stream water (ASW) the most western of the three; Bering Shelf water (BSW), centrally located; and Alaska Coastal water (ACW) in the east. Periodically, a fourth hydrographic entity, here called Chukchi Coastal water (CCW), is observed as a shallow surface layer near the western shore. The seabird data considered here were primarily collected from ASW and BSW types and also from areas overlain by CCW. For the purposes of this paper, CCW will be referred to as a "water type," even though it does not have the spatial or temporal magnitude of the other two. Where CCW occurs, it affects the habitat within which seabirds are foraging (e.g., through stratification, stabilization, etc.) and these areas may be considered a different habitat from areas where ASW or BSW is found at the surface.

These water types exhibit distinct differences that affect biological patterns across the shelf. Anadyr Stream water, transported from the North Pacific Ocean at depth and upwelled onto the Bering Sea shelf, is the most nutrient-rich of the three. Intermediate nutrient concentrations are typically measured in BSW, which originates in the Bering Sea (Coachman & Shigaev, Subchapter 2.1, this volume). The lowest nutrient concentrations among waters of the Bering Sea Shelf are found in ACW. Chukotski Coastal water is also nutrient-poor in comparison with ASW or BSW.

The properties of each of these water types are reflected in distinct changes in the east–west distributions of flora and fauna. Types of primary producers and their biomass vary among the water types (Robie *et al.*, Subchapter 5.1.2, this volume). Zooplankton communities are distinctively different among water types (Springer *et al.*, 1989), and communities of higher-order consumers such as fishes and mammals also exhibit longitudinal variation that may be related to water type effects (Nasu, 1974; Wyllie Echeverria & McRoy, Subchapter 5.3.1, this volume).

Coachman and Shigaev (Subchapter 2.1, this volume) provide further detail of the origins and physical properties of the northern Bering Sea water masses. In addition, they describe a separate water mass in this region, Gulf of Anadyr water, that is apparently the same "cold core" previously detected by other oceanographers (e.g., Zenkevitch, 1963). This water mass apparently remains near the bottom in the central Gulf of Anadyr and so was not included in this bird-oriented study.

Methods

Spatial distributions of seabird densities and zooplankton biomass were compared with each other and with the relative locations of the three water types surveyed. Positions of oceanographic stations and seabird transect counts are shown in Figs. 1 and 2.

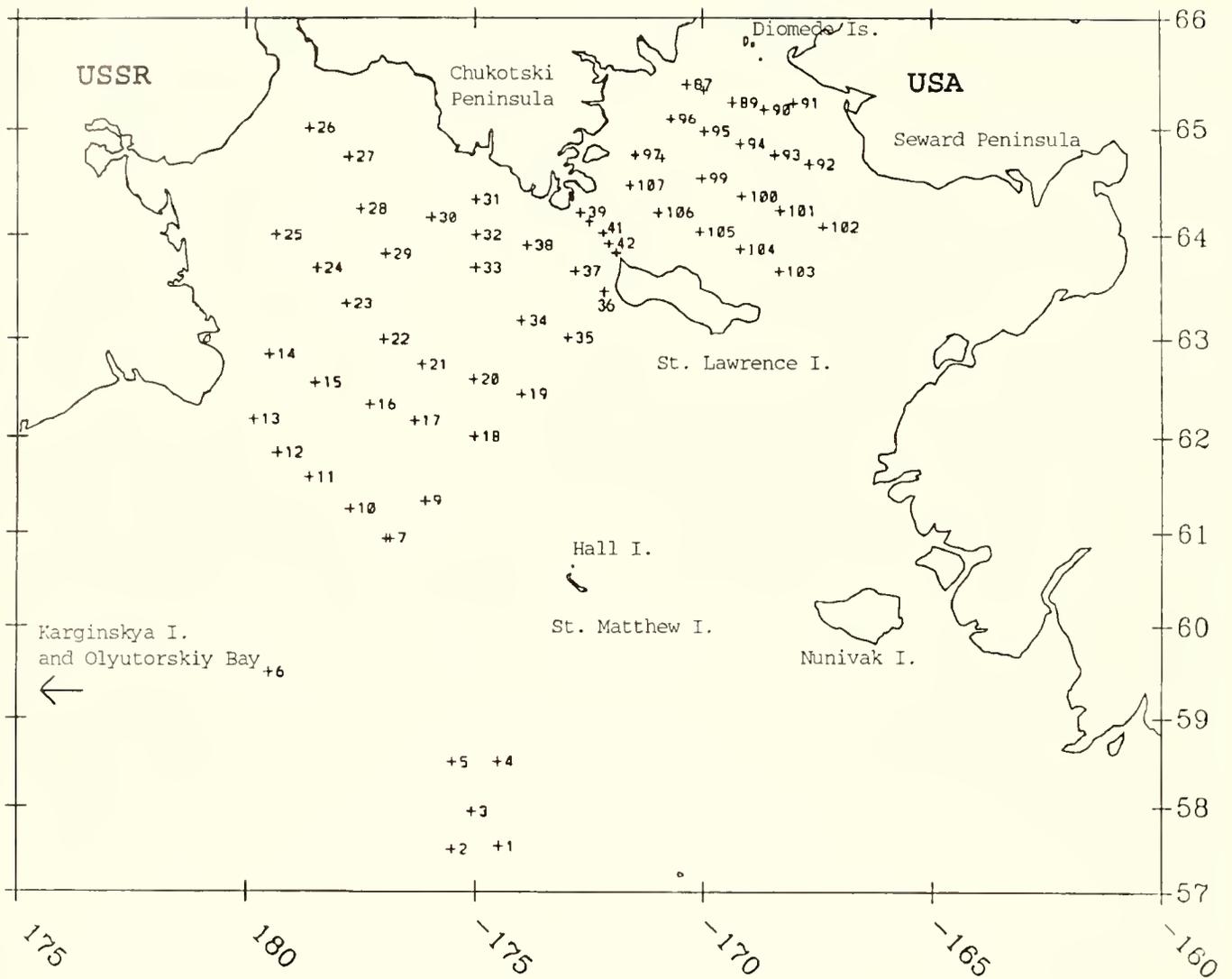


Fig. 1. Oceanographic stations/locations of zooplankton collections south of Bering Strait occupied by the Soviet research vessel *Akademik Korolev*.

Seabird Transect Locations

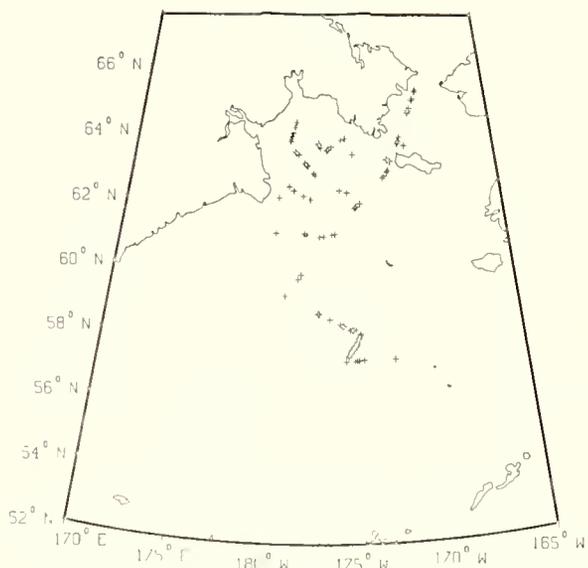


Fig. 2. Seabird transects surveyed south of Bering Strait during July-August 1988 from the Soviet research vessel *Akademik Korolev*. Crosses (+) mark the beginning of each 10 min transect.

Birds were surveyed in a 300-m-wide area extending forward and abeam, to the side of the ship that afforded the better visibility (Tasker *et al.*, 1984). Only observations made when the ship was under way have been included in this report (Table 1). Thirty-six "station counts" were also conducted while the ship was occupying an oceanographic station. These have been excluded from this analysis because seabirds are known to be attracted to a ship when it is not moving and this may bias the observations. At the beginning of each 10-min count period, the date of transect, time, ship's position, speed, ocean depth, and sea surface temperature were recorded. The species, number, and general behavior (sitting or flying) of birds seen during the count period were recorded subsequently. At the end of the prescribed 10-min period, the 300-m survey area was "collapsed" forward, the ship's position noted, and a new transect was begun immediately. Counts were not conducted during periods of fog or low light. All observations were made by J. Andrew during this cruise.

To assess how trophic status and foraging tactics relate to seabirds' use of pelagic habitats, all birds were classified as either planktivores or piscivores, based on principal prey

TABLE 1

Allocation of census effort by water type.

Water Type	Number of Transects	Total time (min)	\bar{x} Speed	Range	Area (km ²)	\bar{x} Area/transect
ASW	42	420	15.0	-----	58.38	1.39
BSW	47	470	15.0	-----	65.33	1.39
CRW	9	70	15.0	-----	9.73	1.39

consumed, as reported in the literature (Bedard, 1969; Sowls *et al.*, 1978; Hunt *et al.*, 1981; Springer & Roseneau, 1985). Additionally, birds were classified by the principal foraging method each species employs—that is, surface feeders, shallow divers (<5 m) and deep divers (>5 m) (Ashmole, 1971; Sowls *et al.*, 1978; Brown, 1989). Only observations of sitting birds were used for comparison with habitat parameters to provide the most conservative estimate of birds actually using a water type habitat. Both sets of reclassified bird data were examined along with the other biological and physical data to determine the degree of pattern concurrence and differences in average abundance among water types.

Hydrographic data were collected with a Sea-Bird(R) CTD at all stations (Coachman & Shigaev, Subchapter 2.1, this volume). Seawater density is arguably the most useful physical property for differentiating between water types and masses. Density is primarily a function of salinity in this and other high-latitude baroclinic flow systems (Royer, 1981). Further, the communities that inhabit these water types differ, reflecting the different sources of these waters, and this information can also be used in a definitive manner (Springer *et al.*, 1989). Therefore, salinity values and, secondarily, zooplankton distributions were used collectively to delineate differences among water types. Anadyr Stream water was defined as waters having salinities >32.5, BSW salinities were ≤ 32.5 and >31.0, and CCW salinity values were ≤ 31.0 . These definitions approximate those described for water masses by Coachman and Shigaev (Subchapter 2.1, this volume) for this cruise of the R/V *Akademik Korolev* and also take into account water type positions as defined by a more biological parameter, zooplankton communities (see Wyllie Echeverria & McRoy, Subchapter 5.3.1, this volume).

The diving depth capabilities of planktivorous seabirds in this region, primarily auklets (*Aethia* spp.), are largely unknown. However, water depths throughout the northern Bering Sea Shelf region do not exceed 50 m, and the most conservative prediction of diving capabilities based upon currently available information (Piatt & Nettleship, 1985) puts most of the water column within reach of even the smallest of these birds. Auklets depend heavily on large deep-water copepods advected onto the Bering Sea Shelf via ASW (Springer & Roseneau, 1985), and so they may be able to exploit prey stocks carried in the ASW at depth. For this reason the position of each bird transect was determined with respect to water type distribution at the surface, and distribution of auklets in particular was also

compared with water type distributions at each of 5, 10, 15, and 20 m depths.

Zooplankton were collected by vertical tow of a 1-m-diameter ring net at all oceanographic stations (Fig. 1). These tows were made from the ocean bottom through the full water column, so the data reported here give an integrated view of zooplankton distribution and abundance, but it is not possible to derive depth of occurrence for any given zooplankton. Evidence from previous oceanographic cruises suggests that the majority of zooplankton concentrate near the pycnocline, which is generally located in the upper 15–20 m in the north Bering Sea in summer (Coachman, 1986; Hunt *et al.*, 1990; ISHTAR group, unpubl. data). Zooplankton samples were preserved at sea in 5% formalin in seawater. In the lab, these samples were sorted by the lowest taxonomic level possible, usually to species (Springer *et al.*, 1989). To compare the distribution and abundance of zooplankton with that of seabirds, only zooplankton species reported to be most important in the diets of planktivorous seabirds are considered here. These are calanoid copepods, including *Calanus marshallae*, *Neocalanus plumchrus*, *N. cristatus*, and the euphausiid genus *Thyssanoessa* (Bedard, 1969; Piatt *et al.*, 1988; Hunt & Harrison, 1990). Because it is unknown which particular zooplankton species birds may have been feeding on during this cruise, if any, these four species will be considered collectively and their quantities summed as an estimate, or index, of available prey.

Statistical comparisons were made between categorically classified seabird data and water type position at the surface. Except for the case of auklets as discussed above, more species-specific comparisons generally were not often possible because of the high variability associated with at-sea observations. Significant differences in seabird abundances among water types were detected using a series of Kruskal-Wallis nonparametric tests ($p < 0.05$) (Zar, 1984).

Results

Densities of all seabird species combined were not significantly different among water types ($p > 0.05$, Table 2). However, average densities of surface-feeding birds were significantly more abundant in ASW than BSW or CCW (Fig. 3). Densities of this group of birds were not highest in BSW but significantly different between BSW and CCW. Abundances of shallow-feeding birds, predominantly short-tailed shearwaters and black-legged kittiwakes, were not

TABLE 2

Seabird densities (sitting birds/10 min transect and birds/km²) in each water type in the northwest Bering Sea during July and August 1988.

Seabird Species	Anadyr Stream water		Bering Shelf water		Coastal Runoff water	
	\bar{x}	\bar{x}	\bar{x}	\bar{x}	\bar{x}	\bar{x}
	birds/ transect	birds/ km ²	birds/ transect	birds/ km ²	birds/ transect	birds/ km ²
Northern Fulmar	49.6	35.7	2.2	1.6	0.4	0.3
Short-tailed Shearwater	0.3	0.2	0.2	0.1	1.5	1.1
Fork-tailed Storm-Petrel	11.2	8.1	0.4	0.3	0.0	0.0
Herring Gull	<0.1	<0.1	0.0	0.0	0.0	0.0
Glaucous Gull	0.0	0.0	<0.1	<0.1	0.0	0.0
Black-legged Kittwake	0.5	0.4	0.0	0.0	1.7	1.3
Common Murre	0.0	0.0	1.4	1.0	25.0	18.0
Thick-billed Murre	0.1	0.1	0.0	0.0	0.0	0.0
murre sp.	0.4	0.3	1.4	1.0	12.7	9.2
Parakeet Auklet	<0.1	<0.1	<0.1	<0.1	0.0	0.0
Least Auklet	4.6	3.3	5.7	4.1	0.3	0.2
Crested Auklet	1.2	0.8	0.5	0.4	0.0	0.0
auklet sp.	0.3	0.2	0.3	0.2	0.0	0.0
Tufted Puffin	0.0	0.0	0.1	0.1	0.1	0.1
Horned Puffin	0.0	0.0	<0.1	<0.1	0.0	0.0
total murre	0.5	0.4	2.8	2.0	37.7	27.2
total auklets	6.1	4.3	6.5	4.7	0.3	0.2
TOTAL	68.2	49.1	12.2	8.8	41.7	30.2

significantly different among the three water types. The trend was for shallow-feeders to be more abundant in CCW than in BSW or ASW (Fig. 3). Deep-feeding bird abundances were significantly higher in CCW than in either ASW or BSW. Bird densities in ASW and BSW were not apparently different, however (Fig. 3). Densities of murre, particularly common murre (*Uria aalge*), made up the majority of the deep divers in CCW. Planktivore distributions were significantly different among water types. These were much more abundant in ASW than BSW or CCW, and differences between BSW and CCW could not be detected (Fig. 3). Piscivorous seabirds, predominantly murre and black-legged-kittiwakes (*Rissa tridactyla*), were also significantly different in abundance among water types. Birds with this prey preference were more abundant in CCW than either ASW or BSW. The latter two water types did not have different bird densities (Fig. 4).

Zooplankton (number of zooplankters/km²), or potential prey of planktivores, was more abundant in ASW and BSW than CCW. Between ASW and BSW, zooplankton densities were not significantly different, although abundance in ASW exceeded that of BSW (Fig. 4).

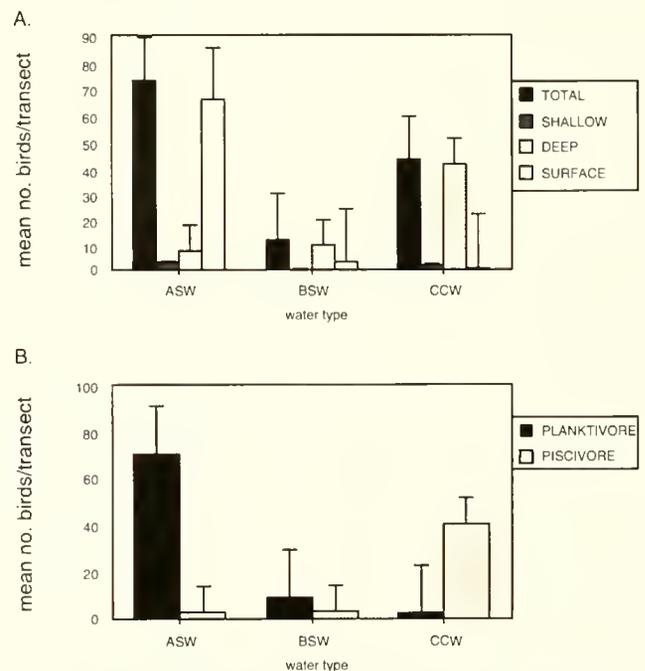


Fig. 3. Mean densities (plus/minus one standard error) of seabirds grouped by foraging method (A) and prey preference (B), in three water types in the northwest Bering Sea. ASW = Anadyr Stream water, BSW = Bering Shelf water, CCW = Chukchi Coastal water.

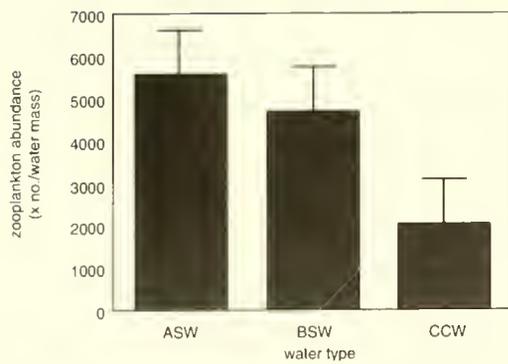


Fig. 4. Average zooplankton abundance (mean number/water type plus/minus one standard error) in each of three water types in the northwest Bering Sea. Abbreviations are as indicated in Fig. 3.

Auklet distributions (i.e., all auklet species considered collectively) did not differ significantly between ASW and BSW when the distributions of those water types were considered at the surface, and at 5, 10, and 15-m depths, respectively (see Fig. 5). Mean abundances of auklets in both these water types were significantly greater than the mean abundance of auklets in CCW, however. This pattern changed at the 20-m depth; auklets were significantly more abundant in ASW than BSW (Table 3). Chukchi Coastal water was not observed anywhere in the cruise track at the 20-m depth.

Discussion

Implicit in all studies of this type are the assumptions that physical features of the pelagic habitat in which birds forage may enhance prey availability and that birds can exploit these features in some way to promote foraging efficiency. In this study, seabirds are unevenly distributed among the water types detected at the surface in the northwest Bering Sea. At these

large spatial scales, it appears that seabirds are foraging selectively in water types in which their preferred prey type may be most abundant. Planktivorous birds preferred ASW, which contains the greatest abundance of large oceanic zooplankters. Piscivores, in turn, preferred CCW, which may have the greatest abundances of fish of the three water types. This last conclusion is limited by a lack of information about prey-sized fish distribution in this area at this time, but what data are available suggest that oceanographic conditions in ACW (low salinities, shallow depths, high stability) provide better habitat for small/juvenile fish than BSW or ASW. In that CCW also has these properties, it may also be assumed to be good prey fish habitat.

How the different water types affect foraging success via specific foraging strategies requires further investigation. Where ASW is observed at the surface, it may be upwelling zooplankters that would otherwise be unavailable to surface-foragers. Birds employing this strategy are known to congregate at mesoscale features such as convergent fronts that concentrate prey (Brown, 1980). Further, they are among the most mobile and far-ranging foragers of the seabirds included here, and are thereby least limited to a single broad domain.

Deep-feeding birds might be expected to be found in water types in which vertical structure concentrates prey and thereby reduces energetic costs of diving (Hunt *et al.*, 1990). Deep-feeding birds in this study were found in highly-stratified areas where a lens of CCW overlay BSW or ASW. Because deep-feeding birds are exploiting a foraging niche unavailable to surface- or shallow-feeders, their distributions might be related to distributions of preferred subsurface waters. Planktonic prey abundance and distribution can be better assessed than those of fishes with the sampling methods used here, so the relationships between planktivorous, deep-feeding auklets and zooplankton was used to explore this idea. However, when

TABLE 3

Auklet abundance (\bar{x} /km²) in each water type in the northwest Bering Sea in July and August 1988. Water mass positions are estimated at five depths: 0, 5, 10, 15 and 20 m.

depth (m) ¹	Anadyr Stream water		Bering Shelf water		Coastal Runoff water	
	\bar{x}	SE	\bar{x}	SE	\bar{x}	SE
0	6.3	2.1	4.4	2.8	0.7	0.7
5	6.3	2.1	4.4	2.8	0.7	0.7
10	6.3	2.1	4.4	2.8	0.7	0.7
15	5.1	1.6	5.0	3.5	1.0	1.0
20*	8.2	3.4	1.3	0.5	--	--

¹ Water type positions did not differ appreciably at depths above 15 m.

* $p < 0.05$, determined by Kruskal-Wallis test.

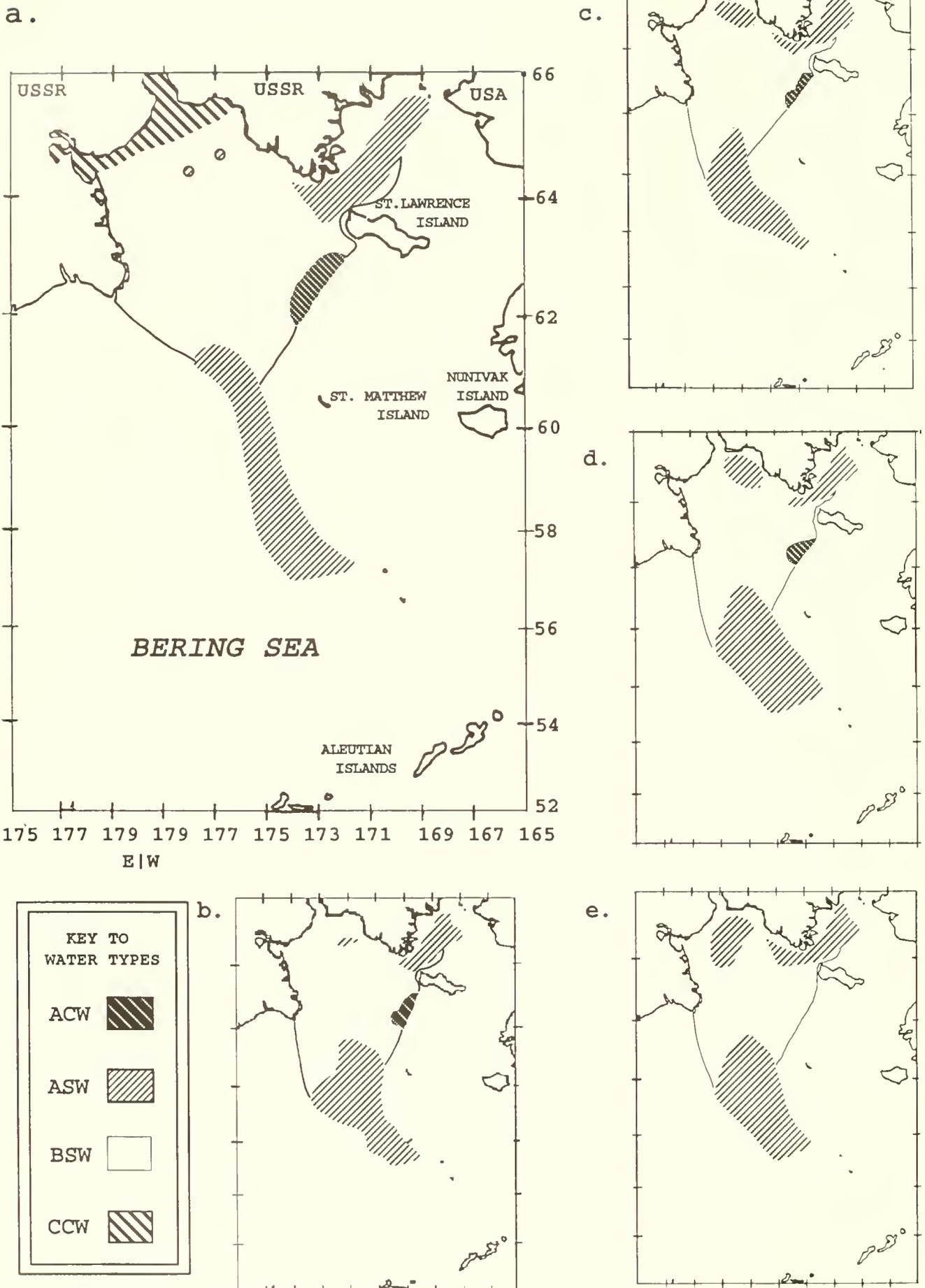


Fig. 5. Distribution of water types at various depths (surface/0 m (a), 5 (b), 10 (c), 15 (d), and 20 (e) m) in the northwest Bering Sea. Abbreviations are as indicated for Fig. 3.

planktivorous deep-feeding birds, the auklets, were considered separately with respect to water type positions at the surface, the pattern was quite different.

Auklets (i.e., least [*Aethia pusilla*] and crested auklet [*A. cristatella*] abundances combined) were found in the greatest numbers where ASW occurred at depths of at least 20 m. At 15 m or shallower, auklets did not show apparent preference for either ASW or BSW, the same result reported by Day *et al.* (in prep.). Results of dietary analyses suggest that diet composition of auklets does not change much from year to year, in terms of the prey species consumed (Bedard, 1969; Springer & Roseneau, 1985; Piatt *et al.*, 1988; Hunt *et al.*, 1990). Zooplankton species are not evenly distributed among water types, so auklets might be expected to select water types that contained their preferred prey. Again, it is assumed that auklets have access to each of the water-type habitats considered here. Despite their energetically-costly mode of flight, auklets have been observed feeding in large aggregations at least 111 km from the nearest colony (Schauer, personal observation). Most auklets breeding in the area of this cruise would be able to reach each of these water types within this distance. Based on the results of the zooplankton distribution analysis in this study (see also Springer *et al.*, 1989), auklets should occur in greatest abundance in ASW. When water type distribution is examined at 20 m below the surface, auklets are clearly concentrated in ASW areas. This may be related to concentration of prey at strong property gradients between water types (e.g., halocline, pycnocline). Examination of these data using only surface salinity values obscures this pattern, and no preference between ASW and BSW can be determined.

Taken as a whole, these results suggest that prey preference dictates foraging habitat selection by seabirds at macroscales. Foraging method is probably more important in explaining mesoscale variations in seabird distribution.

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APPENDIX I

Species Accounts

This section summarizes the relative densities of seabirds among water masses at the species level. When possible, information has been provided here regarding locations of nearest known breeding colonies, abundance of North Bering Sea breeding populations, and pertinent foraging habits for each species described. In addition, how each species was reclassified for the analysis of trophic group(s)/water type relationships is noted here. Nineteen seabird species were

observed in the study area. Some seabird species were observed in such low numbers that statistical analysis of their habitat preferences was not possible. For this reason, these species are not included in the detailed species-specific densities given in Table 2, but their presence in the cruise track area is noted in this section.

Average densities of all seabird species combined were highest in ASW (49.1 birds/km²) (Table 2). Areas influenced by CCW had the next highest total densities (30.2 birds/km²), followed by BSW (8.8 birds/km²). All of the locations of colonies of breeding seabirds referred to below are shown in Fig. 1.

Northern Fulmar (*Fulmaris glacialis*). This surface-feeding seabird was found in average densities in ASW, 22 times higher than densities detected in BSW (Table 2). The closest breeding colony of this species is at St. Matthew Island, from which fulmars may fly several hundred kilometers to feed (Sowls *et al.*, 1978). However, this species is known to forage nocturnally, so birds observed by day in the northern Bering Sea could be nonbreeders rather than breeding birds foraging at great distances from their colonies.

Short-tailed Shearwater (*Puffinus tenuirostris*). This species does not breed in the Bering Sea but spends the boreal summer here. This shallow-diving planktivorous species was at least five times more abundant in CCW than in BSW or ASW. Observations were made by J. Andrew during this cruise.

Fork-tailed Storm-Petrel (*Oceanodroma furcata*). These surface-feeding planktivores nest mostly in the Aleutian Islands (Sowls *et al.*, 1978). They are commonly found at sea, north to the latitude of the Pribilof Islands, although there are no reports of nesting there. This species was 28 times more abundant in ASW than in BSW and was absent from CCW.

Steller's Eider (*Polysticta stelleri*). Six flying individuals were observed in only one of the transects surveyed, over BSW. Little can be said, therefore, about pelagic habitat preferences of this species. They are noted here because of current interest in the pelagic distribution (largely unknown) of this species.

Red Phalarope (*Phalaropus fulicaria*). This species was seen flying in very low densities (<0.1 birds/km²) in ASW and BSW. No conclusions can be reached about significant habitat preferences for this species. Results from other studies indicate that mesoscale oceanographic features may be most important in explaining distribution of phalaropes at sea (Brown, 1980).

Pomarine Jaeger (*Stercorarius pomarinus*), Parasitic Jaeger (*S. parasiticus*), and Long-tailed Jaeger (*S. longicaudus*). The distribution of these species might be expected to mirror that of fulmars or kittiwakes (*Rissa* spp.), which they often parasitize. Observations of jaegers are too limited in this study, however, to draw conclusions about their habitat preferences. Flying jaegers were observed in low numbers in all three water types.

Herring Gull (*Larus argentatus*) and Glaucous Gull (*L. hyperboreus*). Abundances of these two species were too low for determination of habitat preferences (both <0.1 birds/km²). Only small populations of herring gulls nest in Alaska, with five of the six documented North Bering Sea breeding sites located on St. Lawrence Island. Most of

these are probably the Siberian race *L. argentatus vegae* (Sowls *et al.*, 1978). Trukhin and Kosygin (1987) recorded numbers of these birds on the order of hundreds to thousands between February and August 1963–65 and 1983–84 in the Gulf of Anadyr. Although they were considering a wide variety of factors influencing distribution (e.g., sea ice, breeding, and nonbreeding periods combined), it may be that this species was not adequately sampled during the study described here or that abundances or distributions of this species within this area are changing through time.

Glaucous gulls are relatively more numerous and are not found south of 59°N (Sowls *et al.*, 1978). Breeding birds occur on St. Matthew and Hall Islands, St. Lawrence Island, and much of the northwest coast of Alaska, including Norton Sound. Pelagic densities reported here are similar to those found previously for the study area (Trukhin & Kosygin, 1987).

Blacklegged Kittiwake (*Rissa tridactyla*). In Alaska, an abundance of black-legged kittiwakes breed throughout the northern Bering Sea. These breeding populations are estimated to be over 1.3×10^6 birds (Sowls *et al.*, 1978).

This kittiwake has been classified as a shallow-diving piscivore for this analysis, although they are known to eat crustacean prey as well, in small amounts. This species was found in the greatest density in CCW, at three times the density observed in ASW. In BSW, kittiwakes were not observed on the water or taking prey.

Common Murre (*Uria aalge*) and Thick-billed Murre (*U. lomvia*). Murres are classified here as deep-diving piscivores, although a small fraction of the thick-billed murre's diet may also consist of zooplanktonic crustaceans. Breeding colonies of these birds are widespread throughout islands and coasts of the north Bering Sea: St. Matthew and Hall Islands, Karaginskiya Island, St. Lawrence Island, the Diomed Islands, and coastal cliffs of Alaska and the Chukchi Peninsula all support nesting murres, totalling over 2×10^6 birds (Sowls *et al.*, 1978; Gerasimov, 1986; Vyatkin, 1986; Kondratiev & Kitesky, unpubl. data).

The two murre species are sometimes difficult to distinguish at sea, so that densities were calculated for unspecified "murres" as well as for each species when available. Common murre density in CCW was 17 times their density in BSW. This species was not observed on the water in ASW. Thick-billed murres were less common in the study area; these birds were found only in ASW in low numbers. The density of murres not distinguished to species followed the general pattern of common murres described above, as did densities of total murres (all murre data considered collectively regardless of species).

Pigeon Guillemot (*Cepphus columba*). Only one individual of this species was seen flying over ASW. No conclusions may be made as to its habitat preferences in this study.

Parakeet Auklet (*Cyclorhynchus psittacula*). This species breeds on St. Lawrence Island, King Island, the Diomed Islands, and in small numbers at a few points along the mainland Alaska coast where suitable crevices are available (Sowls *et al.*, 1978). It is estimated that 1×10^3 parakeet auklets nest on the southern portions of the Chukchi Peninsula (Kondratiev & Kitesky, unpubl. data). Nesting is also assumed on Karaginsky Island (Gerasimov, 1986). Parakeet auklets were observed in very low densities in BSW and ASW, and they were not found at all in CCW.

Crested Auklet (*Aethia cristatella*). These deep-diving planktivores nest in large numbers on the St. Matthew and Hall Islands, St. Lawrence Island, King Island, and the Diomed Islands. North Bering Sea populations are estimated at 1×10^6 birds. Crested auklets were absent from CCW, and the density found in ASW was about two times that found in BSW.

Least Auklet (*A. pusilla*). Like the other auklet species, Least Auklets prey on zooplankton, primarily crustaceans, and are capable of relatively deep diving. This species could be the most abundant breeding seabird of the north Bering Sea, with breeding populations totalling about 2.3×10^6 (Sowls *et al.*, 1978). Breeding colonies are located at St. Matthew Island, St. Lawrence Island, King Island, and the Diomed Islands. Densities of least auklets were approximately the same in ASW and BSW, but low in CCW.

Auklet species. Small numbers of auklets observed during this cruise could not be identified to species. Birds in this classification showed the same trends as for the identified auklet species (i.e., absent from CCW and found in similar abundances between ASW and BSW, with the density in ASW only slightly exceeding that of BSW). Previous work indicates that the absence of auklets from coastal waters (i.e., ACW) occurs across the north Bering Sea (Hunt *et al.*, 1981; Day *et al.*, in prep.).

Tufted Puffin (*Fratercula cirrhata*) and Horned Puffin (*Fratercula corniculata*). These two species occurred at very low densities only in BSW, although small breeding colonies, primarily of horned puffins, occur on island and coasts throughout the north Bering Sea. Both species breed in the greatest numbers in the Gulf of Alaska. Other observations (Schauer, unpublished data) east of the Convention Line have shown both species of puffins to be present in significantly higher densities at sea in ACW than in ASW or BSW. Because ACW was not sampled during this study, it is probable that puffins were not present in the cruise track rather than being undersampled. Based upon the low densities reported here, little can be concluded about their habitat preferences in this study area.

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**SUMMARY
&
GENERAL CONCLUSIONS**

Summary

The Third Joint US–USSR Expedition to the Bering and Chukchi Seas was carried out in the summer of 1988. This expedition is the third in a series of expeditions are being carried out under the auspices of the Joint US–USSR BERPAC program. The BERPAC program is a program for long-term ecological research of ecosystems of the Bering and Chukchi Seas and the Pacific Ocean (BERPAC). Its goals include 1. assessment of ecological consequences of contamination; 2. study of the processes determining the assimilative capacity for contaminants in marine ecosystems; 3. study of the elements of the biogeochemical carbon cycle and its role in global climatic processes; and 4. investigations of the physical mechanisms related to climate variations. Central to the BERPAC program is the occupation of fixed sites at regular intervals in order to provide data on long-term trends.

The Bering–Chukchi Sea plays a critical role in global climate processes. This region can be defined as a major impact area. Since it is located at the boundary of so many critical temperature dependent forces, it is logically very susceptible to disruptions in the world's temperature budget. Several of these critical processes are discussed; unfortunately most of them are only partially understood. Better understanding of these processes will be necessary in order to assess the full impact that global warming will have. For example, this region is directly impacted by the major northward cold-water current flow, which arrives from the deep Pacific and which is part of the major global current that has a central role in regulating the world's climate. This oceanic current is largely responsible for the high productivity of the Bering–Chukchi Shelf regions, and thus, the fisheries are intimately linked to this system, not to mention the entire biology of the area. This area is also the boundary region for the annual iceover cycle, which has a major impact on climate, sea level, and other critical processes.

The specific results of the Third Joint US–USSR Bering & Chukchi Seas Expedition are discussed in a series of 45 separate research articles, including observations from many scientific disciplines. The major focus of the program was on biological processes and anthropogenic pollutant interactions, especially chemical pollutants. Studies of the hydrology of the system and several hydrochemical parameters were also monitored in order to better understand material transport processes. Overall, 119 stations were occupied. Sampling included areas in the deeper waters of the Bering Sea, several stations along the western portion of the Bering Shelf, the Chirikov basin, the Bering Strait, and the southern half of the Chukchi Sea. Two specific sites in the Bering Sea, the East and North Polygons (see Frontispiece), were sampled as a continuation of long-term sampling at these locations that was started on the 1977 cruise. Data from these sites were analyzed for trend characteristics.

The northern Bering–Chukchi Sea ecosystem is a series of three centers of high biological production deposition centers arranged in the prevailing northward flow from the northern Bering Sea into the Arctic Ocean. Advection transports the

nutrient supply, which is in sufficient abundance to seldom become limiting. The northward current arises from the shelf edge of the northern Bering Sea and flows first around the Gulf of Anadyr, containing the first production center; it then crosses the Chirikov basin, with the second; and then traverses the southern Chukchi Sea, which contains the third. An overview paper describes 1. the water masses of the system, their spatial arrangement, interannual variability, and formation; 2. the flow field including transports and residence times; and 3. the Chukchi Sea, a center of very high production, but about which little is known. In a second paper, the more than 100 conductivity, temperature, and density depth (CTD) stations occupied during the expedition were used to provide the first complete synoptic picture of the regional water masses. Rates of change indicate the different degrees of effectiveness of vertical and lateral mixing in different parts of the basins.

The biogenic nutrient content of the Bering Sea is closely coupled to the primary production and regeneration processes occurring in its water. The waters at depth in the deep Bering Sea hold large quantities of nutrients compared to other parts of the world's oceans, indicating that the Bering Sea is a sink rather than a source for these nutrients. The Gulf of Anadyr receives deep water from the open Bering Sea. The surface waters in the Gulf of Anadyr are productive, especially near the coastline where upwelling occurs. The resulting phytoplankton probably act as seeds for the bathymetrically upwelled water in Anadyr Strait and provide organic matter to support subsequent regenerative processes. The Chukchi Sea receives the northward flow of nutrients and organic matter from the Bering Strait. In the central portion of the Chukchi, surface concentrations of nitrate are high, greater than 1 $\mu\text{mole/l}$, while subsurface values are as high as 20 $\mu\text{mole/l}$. Along the Siberian coast in the Chukchi, an additional source of high salinity-high nutrient water was encountered. The high nitrate content of this southward flowing coastal water adds to the central Chukchi Sea as it joins the Bering Strait water. The gains and losses of nutrients in the Bering–Chukchi Shelf ecosystem ultimately transit to the deep-ocean Arctic basin.

Studies of the microbiological regime of the Bering Sea showed that the concentration of bacterioplankton during this expedition was, generally, higher than in the BERPAC expeditions of 1981 and 1984. For instance, the total number and biomass of microorganisms for the entire area varied over a wide range (i.e., from 0.12 to 3.3×10^6 cells/ml and 2.7–75 $\mu\text{g C/l}$, respectively). Maximum average values for the total number and biomass of bacteria for the whole of the water column were highest in the northern region of the sea, followed by the Gulf of Anadyr, and lowest in the southern part of the basin. The average values for all these areas together were 0.67×10^6 cells/ml and 15 $\mu\text{g C/l}$. The indices for microbial cenoses were five times higher than they were in 1984. For the Chukchi Sea, the total number of microorganisms varied from 0.31 to 2.0×10^6 cells/ml, and the biomass varied from 6.9 to 44.7 $\mu\text{g C/l}$. The most developed microbial cenoses were

detected in the coastal areas near the Chukchi Peninsula and Alaska. The average values for the total number and biomass of microorganisms for the whole of this sea amounted to 0.92×10^6 cells/ml and $20.7 \mu\text{g C/l}$, making them higher than in the Bering Sea.

The values for bacterial destruction of organic matter in the Bering Sea in 1988 varied over a two order of magnitude range ($4.8\text{--}435.5 \mu\text{g C/l/day}$). Maximum values of bacterial destruction were found in the central and southern areas of the sea ($107.3 \mu\text{g C/l/day}$ at the East Polygon and $71.2 \mu\text{g C/l/day}$ at the South Polygon [see Frontispiece]). The production of bacterial biomass in the Bering Sea varied over the range of $1.5\text{--}136 \mu\text{g C/l/day}$, averaging $17.3 \mu\text{g C/l/day}$ for the entire region. In the Chukchi Sea, bacterial production varied from $6.4\text{--}215 \mu\text{g C/l/day}$, averaging $20.2 \mu\text{g C/l/day}$. The highest values were found in the open waters of the southern Chukchi Sea and in the coastal zone of Chukchi Peninsula, which were 26.8 and $26.2 \mu\text{g C/l/day}$, respectively.

The results of special microbiological observations reflected a significant heterogeneity in the water column. Bacterial production studies using cell division frequency and thymidine incorporation varied over the range of $1\text{--}5 \times 10^6$ cells/h in the Chirikov basin. Comparison of data on bacterial production versus phytoplankton production indicated that phytoplankton accounted for $5\text{--}33\%$ of the total amount of carbon assimilated during primary production.

The generic composition of heterotrophic saprophytic microflora in the Bering Sea was as follows: *Pseudomonas* (26.8%); *Bacillus* (23.4%); *Planococcus* (17.8%); and lesser abundances of *Xanthomonas*, *Alcaligenes*, *Halobacterium*, *Flavobacterium*, *Micrococcus*, *Aerococcus*, and *Arthrobacter*. The genera in the Chukchi Sea were not so diverse: *Pseudomonas* (45%); *Bacillus* (18.2%); *Flavobacterium* (9.1%); and *Staphylococcus* (9.1%). Also species in the following genera were frequently observed: *Xanthomonas*, *Alcaligenes*, *Klebsiella*, *Aeromonas*, *Micrococcus*, *Planococcus*, and *Arthrobacter*. Thus, the taxonomic composition of the microbial cenoses of the Bering Sea proved to be more diverse than the Chukchi Sea.

Laboratory experiments on isolated strains of bacteria from these regions also possessed variable resistance toward antibiotics and heavy metal salts. This reserve indicates the presence of extrachromosomal genetic elements of the plasmid type in their cells. Further experiments on some isolates from the region showed that representatives of different taxonomic groups possessed the ability to synthesize metabolites that had mutagenic and genotoxic (RNA-damaging) potentials. The RNA-damaging effect was strongest in certain pseudomonad species that actively develop in conditions of marine pollution, especially when dense populations (10 to 100×10^6 cells/ml) of these microorganisms are found. The predominance of pseudomonads in impacted regions of the world oceans may be an indicator of secondary pollution of the marine environment. The absolute numbers of anthropogenic indicator microflora in the Bering and Chukchi Seas are not large, but the observed

trend toward an increase in their number and distribution confirms the necessity for increased controls over man-made pollutants and the need to continue to carry out systematic observations aimed at the development of scientifically based protection measures.

The study of the phytoplankton abundance and productivity constituted a major focus of this expedition. In the Chirikov basin, cell counts ranged between 0.5 and 1.7×10^6 cells/l, while in the central Bering Sea, these were $0.1\text{--}2.4 \times 10^6$ cells/l. In the Gulf of Anadyr, the counts were similar to those of the central Bering Sea. There was a general trend for diatoms and peridinians to be numerically dominant in more northern waters, while cyanophytes were most numerous toward the south. Biomass dominance was maintained by the diatoms and peridinians throughout the area. Quantitative measures varied sharply from station to station and with depth. The observed heterogeneity is due to the hydrographic complexity of the region. The standing stock of phytoplankton of the northern Bering Sea is dominated by small nanoflagellates (<10 m). These represent about 63% of the biomass both in terms of integrated carbon and cell numbers.

Chlorophyll distribution measurements support the hypotheses for advective flow of deep nutrient-rich oceanic water moving northward. At the East Polygon, an area on the shelf edge, elevated chlorophyll amounts were measured, indicating that nutrient rich oceanic water was upwelling and cycling into the Gulf of Anadyr. Large chlorophyll concentrations observed in the Gulf of Anadyr and Anadyr Strait merge as the Bering Shelf water flows northward toward the western edge of the Bering Strait. Once into the Chukchi, the flow travels initially in a northwesterly direction. High chlorophyll concentrations were frequently observed throughout the Chukchi basin; however, there was no obvious pattern.

High Performance Liquid Chromatography analysis of pigment samples from throughout the study area allowed fractionation of several pigment types. These pigments served as source markers for inferring distributions of major algal groups in this region. The most abundant accessory pigments detected were chlorophyll *c*, diadinoxanthin, and fucoxanthin, which suggest the dominance of diatoms in the Gulf of Anadyr and the Chukchi Sea. Green algae abundance was indicated by the presence of chlorophyll *b* and peridian pigments in a band extending from north of St. Lawrence Island through the Bering Strait and into the Chukchi Sea. Chrysophytes and prymansiophytes were present in waters overlying the Chirikov basin and the central and southern regions of the Bering Sea (the unique pigments for these groups are $19'$ -hexanoyloxyfucoxanthin and $19'$ -butanoyloxyfucoxanthin).

Optical measurement techniques for monitoring particulates in the water column were employed to intercompare with the more conventional techniques. The findings in most cases were in good agreement and served to validate each other. Angular and integral light scattering were typical of diatomic slurries in the Gulf of Anadyr and divergence zones in the Chukchi Sea. Zonal charts of diatomic slurries identified by

hydrooptical means matched the chlorophyll intensities that were associated with these zones.

Study of epipelagic mesozooplankton of the Bering and Chukchi Seas revealed structural characteristics with considerable dependence on distribution of four groups of species (south Bering Sea oceanic, north Bering Sea oceanic, neritic and Anadyr), as well as two eurybiontic species (*Oithona similis* and *Pseudocalanus minutus*). In deep-water regions of the Bering Sea and on the northern shelf, high biomasses (40 g fresh weight/m² average in the 0–100 m layer) were made up of species from south Bering Sea oceanic groups. In the cold-water masses from the shelf, there was a predominance of species from the north Bering Sea oceanic groups. Neritic groups of species (including *Rotatoria*, *Clodecera*, and small species of copepods, as well as pelagic larvae of benthic organisms) constituted over 70% of the total number in the eastern part of the Chirikov basin, which was out of reach of Anadyr Currents. The mesozooplankton community of the Chukchi Sea basically consists of neritic and eurybiontic species. The persistent presence of species from the south Bering Sea and Anadyr groups among the Chukchi Sea species confirms the obvious influence of Bering Sea fauna on this region.

Study of zooneuston in the Chukchi Sea found copepods to be most abundant throughout. The mosaic distribution of Bering Sea groups in the neuston layer of the Chukchi Sea verified the complex hydrodynamics of near-surface water and their connection with the Bering Sea.

Necrozooplankton were measured throughout the study area. Stratification of dead zooplankton were observed at water mass boundaries most typically characterized by differences in temperature. More typically, the necrozooplankton were found at the same zones where they had died and were not layered. Noteworthy for the Anadyr was the presence of dead zooplankton of both oceanic and neritic types.

Ciliate protozoa were monitored over the study area. Their abundance followed the general abundance of other planktonic species. The Chukchi Sea is characterized by a unique mix including several larger species. The levels of ciliate development in the deep Bering Sea, the East Polygon, and Bering Strait exceeded those for the Chukchi Sea. Elevated ammonia and chlorophyll accompanied high ciliate biomass. Overall, for the Bering Sea, the ciliates constituted 1.5 g of primary and bacterial production per m³/day, yielding 0.5 g/m³/day. For the Chukchi Sea, these figures are 2 g/m³/day and 1 g of production, respectively.

The $\delta^{13}\text{C}$ values for copepods and euphausiids zooplankton showed enrichment in $\delta^{13}\text{C}$ relative to similar taxa collected in 1986 from the Beaufort Sea. Euphausiids were approximately 1.1 parts per thousand (ppt) more enriched in $\delta^{13}\text{C}$ than copepods from the same area. Overall $\delta^{13}\text{C}$ values for zooplankton were about 1 ppt depleted in 1988 relative to the same taxa collected in 1987. The changes in average zooplankton $\delta^{13}\text{C}$ values reflect previous studies in the isotopic composition of bowhead whales (*Balaena mysticetus*), which

feed on the zooplankton in these regions and carry multiyear records of feeding activity in the ^{13}C : ^{12}C ratios in their baleen plates.

Seven families of ichthyoplankton were identified among the zooplankton species sampled. Exact species were identified from the codfish and the flatfish families. Two of these specimens were newly hatched at a location considerably north of reported spawning grounds, *Theragra chalcogramma* (walleye pollock) and *Hippoglossoides elassodon* (flathead sole). These findings suggest the possible occurrence of a new spawning location considerably north of previously reported sites. Larval fish densities were highest where shelf waters overlie Anadyr water and in areas where integrated chlorophyll *a* concentrations were less than 100 mg/m³.

A plankton model was described that was developed from 1981 and 1984 BERPAC results from the North and East Polygons. Bacterioplankton, phytoplankton, and zooplankton (micro- and mesozooplankton) were considered the major contributors to the biological activity in the model. The modeling results indicated that production and destruction of organic matter were occurring at very high rates and seasonal factors have an overriding influence on the ecosystem. Similar modeling is planned with the 1988 data. With the high rates of organic turnover indicated by the model, anthropogenic influences on these rates, even when they are very slight, could have profound effects on the natural processes in this system.

The distributional patterns of primary production reflected similar trends to those observed in the Bering Sea during the summer of 1984. The average areal production was 1.8 g C/m²/d¹ with a high of about 15 g C/m²/d¹. Primary production during the growing season fixed an estimated 0.2×10^9 metric tons of carbon. In addition, the sampled areas of the Chukchi Sea contributed another 8.3×10^6 metric tons for the growing season. The particulate phytoplankton carbon flux through the Bering Strait was estimated to be 3.2×10^6 metric tons per year. The estimated flux of dissolved carbon to the Chukchi Sea–Arctic Ocean amounted to 0.82×10^9 metric tons per year. A significant portion of this carbon likely finds its way to the deeper waters of the Arctic Ocean. Eventually, this carbon may be incorporated into the North Atlantic bottom water. Both of these avenues would act as greenhouse gas sinks.

In studying benthic processes, significant correlations were found between the stable oxygen isotope composition of bottom seawater, salinity, and tunicate cellulose in the study area, enabling determination of $\text{O}^{18}/\text{O}^{16}$ ratios and spatial locations for the major water masses in the region. High sediment oxygen uptake rates and high benthic biomasses were observed in the western shelf regions of the Gulf of Anadyr, Chirikov basin, and southern Chukchi Sea. Low sediment respiration and faunal biomass were observed in the central and slope areas of the Gulf of Anadyr and near the Alaska coastline. There was little difference in benthic faunal composition over the entire study area. Species composition was always characterized by panarctic and boreal–arctic complexes. Average benthic biomass was always high, exceeding

400–500 g/m². The *Macoma calcarea* community type was the most widely distributed in the areas investigated. Two new biocenoses, *Leionucula inflata* in the Chukchi Sea and *Nucula lamellosa radiata* in the Gulf of Anadyr, were found with average biomass values of 647 and 1,413 g/m², respectively. At the outlet from the central Gulf of Anadyr, biocenosis *Macoma calcarea* had been replaced by biocenosis *Nuculana lamellosa radiata*.

Sediment accumulation, measured using ²¹⁰Pb inventories in surface sediments, was low in the sandy regions of the northern Bering Sea, with higher accumulation zones occurring in the silt and clay regions in the central Gulf of Anadyr and southern Chukchi Sea. Hydrodynamics have a major influence on benthic community structure, biomass, and sediment respiration in this arctic region.

Filtered seawater and particulate material was collected and analyzed for their isotopic content of Th²³⁴/U²³⁸. Using a ratio technique for these two isotopes, biosedimentation rates in the Bering Sea were found to be 46.5 ± 5.3 mg/m³/d, suspended organic matter averaged 0.98 ± 0.04 mg/m³/d, and residence times were 29.7 ± 2.7 days. The values for the Gulf of Anadyr were much lower, while those in the Chukchi Sea were much higher. Calculated on an areal basis, the biosedimentation flux values range from 0.67 in the Gulf of Anadyr to 5.9 g/m²/d in the Chukchi Sea. Regional variations can be accounted for by phytoplankton blooms. The high rates of biosedimentation demonstrate the high productivity in this region.

Humic acids comprise the bulk of dissolved organic matter, which resists biochemical breakdown. They also form a large fraction (30–60%) of the total dissolved organic carbon in this system. The concentration of humic substances was related to primary production and served as a measure of primary productivity even after actual plankton blooms had disappeared. The highest values were found in the region near the Bering Strait. This is a result of the transport of water masses from highly productive areas such as the Gulf of Anadyr, as well as *in situ* production. Local maxima of humic acids in other areas were related to freshwater discharges from the Anadyr River and the Yukon River. The organic carbon distribution in sediments indicate that there are several depositional zones in the major basins that were studied. The major total carbon depositions appeared to follow the regions where the major algal blooms occurred. The carbon signatures for these regions were mostly marine rather than terrestrial. Some specific regions of organic matter buildup indicated terrestrial origins, especially near the mouth of the Yukon River. Chemical and isotopic data indicate that terrestrially derived organic matter is transported from the North American continent into the eastern area of the Anadyr–Bering–Chukchi study area, while little Asian-derived terrestrial material is incorporated into the western sediments.

Observation of seabird abundance and distribution were compared to the several distinct water masses that existed over the studied regions. Piscivorous birds predominated by 10 to 20 times in the Alaska coastal area and planktivorous birds were by far more numerous in the Anadyr and Bering Central

Shelf water masses. There also was a distinct water mass affinity for northern fulmars and short-tailed shearwaters to locate in the Siberian Coastal water, and these were the same species that were dominant in the Bering Shelf–Anadyr waters. For the southern Chukchi Sea Shelf, these same bird species exhibited greater along, as opposed to across, shelf variability in abundance. The densities corresponded well to the locations of distinct water masses in similar zonal patterns.

Anthropogenic pollutant impacts on the area were assessed by observing their distributions, degradation processes, and toxic effects. In general, concentrations of chlorinated hydrocarbon pesticides and polychlorinated biphenyls (PCB's) were typical of data reported for other nearby arctic ecosystems. Chlorinated hydrocarbons quantified in the atmosphere included hexachlorocyclohexanes (HCH), hexachlorobenzene, toxaphenes, and chlordane. Polychlorinated biphenyls and DDT's were found at excessively high concentrations, suggesting possible contamination from the ship. Detailed studies of the flux of α - and γ -HCH across the air–sea interface indicated that, in many areas, the predominate flux for the γ isomer was from the air and that there was a net atmospheric loading of this compound into this area. No local sources were apparent.

The concentration of DDT in the seawater was lower than the 1984 BERPAC data, although its level of accumulation in the suspended sediment was still very high, as before. In water, the HCH's are the contaminant group of highest concentration (3.44 ng/l), exceeding the concentration of the other chloroorganic pesticides more than 10-fold. The HCH isomer ratio, α -HCH versus γ -HCH, indicates their presence is probably due to long-distance atmospheric transport.

In biota, PCB's were measured at levels as high as 67.9 ng/g in neuston and 23.9 ng/g in zooplankton. α -HCH concentration ranged from 1 to 10 ng/g; the isomer concentrations were lower. Chlordanes, DDT, and hexachlorobenzene were present at low concentrations in most samples. Toxaphene was measured in biota for the first time in these seas. Residues were highest in fish at 10.8 ng/g. Sediments had low to nondetectable residues of most compounds analyzed.

The HCH's (α , β , and γ isomers) displayed behavior that was different from the other measured organochlorines (OC's). Global behavior of these compounds in the world's oceans indicates that higher levels tend to occur in colder waters of the poles rather than equatorial waters, which are geographically closer to the areas of their major use. It has been postulated that the globe may function as a giant distillation device, driving them into the air near the equator where they eventually distill into the cooler waters at the poles. In support of this theory, it was observed that the water concentrations for the HCH isomers did indeed exhibit a gradient for higher water concentration with increasing latitude; this relationship was strongest for the β -HCH isomer. The HCH's also bioaccumulated to a lesser extent than the other OC's in this system, e.g., bioaccumulation factors for HCH of 5.8×10^5 versus 6.3×10^7 for the sum of DDT residues in fish tissue; this appears to relate to their relatively low lipid solubility.

Aliphatic and aromatic petroleum hydrocarbons were ubiquitous in the sediment from the study area. Generally, hydrocarbon concentrations were low and similar to previous reports. The occurrence of high fluorescence intensity and R ratio values and GC-derived indicators suggests the presence of microseepage at several locations; this implies that underlying petroleum deposits may exist. Low level polyaromatic hydrocarbon (PAH) concentrations (<100 ppb) appear to be related to combustion sources.

Specific studies on benzo(a)pyrene (BaP) distribution were conducted, with the assumption that BaP was a good model compound for the other PAH's in the system. The spatial and vertical distribution of BaP in the water of the Bering Sea was relatively uniform, having an average value of 3.5 ng/l. Similar concentrations were observed in previous collections from these areas in 1981 and 1984. A relatively high BaP content was recorded in the Chirikov basin. Benzo(a)pyrene concentrations in sea ice samples averaged about 15 ng/l; in bottom sediments it was 0.7 to 1.7 µg/kg dry wt. Benzo(a)pyrene concentrations in plankton and neuston, respectively, ranged from 0.2 to 10.0 and 0.6 to 10.0 µg/kg dry wt. The concentration of BaP in benthic organisms ranged from 0.05 to 13.0 µg/kg on a dry weight basis. Mixed PAH's were specifically characterized in several compartments of the system. In the water, bottom sediments, suspended sediment and biota of the Bering and Chukchi Seas, 10 PAH's were identified, of which eight are carcinogenic and three of these, benzo(b)fluoranthene, benzo(k)fluoranthene, and BaP, are highly carcinogenic. In the surface water layer, BaP and pyrene prevailed. The overall concentration in the surface water layers did not exceed 5.1 ng/l, but in the near-bottom layer it reached 24 ng/l. The total concentration of PAH's in the suspended matter reached 11.2 ng/g. The total concentration of PAH's in the plankton varied widely (12 to 677 µg/kg) and for the neuston ranged from 20 to 188 µg/kg on a dry wt. basis.

The first data for heavy metals for this area were recorded on this expedition. Concentrations of copper in the water varied from 0.01 to 0.46 µg/l in the open areas of the Bering Sea with an average value 0.08 µg/l. Shallow-water stations demonstrated a direct relation between copper concentration in water and bottom sediments. The other heavy metal water concentrations were as follows: cadmium ranged from <0.01 to 0.13 µg/l; manganese did not exceed 0.04 µg/l; zinc varied from <0.01 to 3.67 µg/l; and lead varied from <0.01 to 1.03 µg/l. In the sediment, the metals investigated (As, Cd, Co, Cu, Pb, Mn, and Hg), with the exception of mercury, were detected in all of the surficial samples (0–2 cm). The concentrations of cadmium, cobalt, lead, mercury, and arsenic appeared to be higher in the shelf areas. Downward fluxes of planktonic organisms and biogenic debris are likely sources. Arsenic and cadmium were elevated in most of the marine biota. Tendencies for bioaccumulation rather than localized pollution appear to be the cause.

The average concentration of Cs¹³⁷ for the entire area was 2.4 Bq/m³. The vertical distribution of Cs¹³⁷ in the Bering Sea was homogeneous, but for the Chukchi Sea it was characterized

by an elevated concentration in the bottom layers (ranging from 2.5 to 5.5 Bq/m³) and an overall average of 3.1 Bq/m³. The observed homogeneity of the Cs¹³⁷ indicates the lack of local input of this material. The maximum possible contribution of "Chernobyl's" Cs¹³⁷ did not exceed 6%.

Microbial degradation of many of the PCB congeners (19 of 70 that were added) was observed. Of these 19 congeners, the dichlorobiphenyl homologs were degraded the fastest, 95 to 100%, and the trichloro homologs next, 64 to 66%, then the tetra's, 10 to 58% and the penta's at 36 to 44%. The hexachlorobiphenyls (HCB's) were degraded only slightly, 7%. With photochemical degradation of PCB's in seawater, it was found that those congeners of the PCB mixture that did not undergo microbial transformation were often more susceptible to photochemical decomposition. Hexachlorobiphenyls and higher-chlorinated compounds did not undergo any reaction. The photochemical degradation proceeded with direct dechlorination accompanied by isomerization and condensation. The rate of the reaction depends on the molecular configuration, with locations 2,2' or 4,4' favoring photochemical attack. Overall rates of photochemical degradation were slower than the rates for microbial breakdown. Thus microbial breakdown is probably more important to the removal of PCB's than are photochemical processes. It was also determined that the presence of PAH's could inhibit the photochemical degradation processes by 10%.

Microbial degradation experiments with BaP showed that pelagic microflora of this region can transform between 8 and 45 percent/time of the total concentration of BaP. Maximum rates were observed in the Gulf of Anadyr, at the North Polygon, and in the southwest Chukchi Sea. In 21-days of incubation, 84% of the added BaP was destroyed. The photochemical transformation is described by a formal first-order kinetic equation. The rate constant values was 0.69 h. Based on relative rates of reaction for microbial versus photochemical breakdown of BaP, photoxidation shares in importance with microbial processes.

Natural populations of phyto-, microzoo-, and, bacterioplankton were tested for their susceptibility to some representative natural contaminants (BaP, PCB's, Cu, and Cd). Primary productivity, bacterial respiration, and cell growth were monitored. Susceptibility was found to vary with pollutant type, collection location, and with the endpoint being monitored. The range of toxicity from the most toxic to the least were as follows: BaP, Cu, PCB, and Cd. For BaP, the range of LD₅₀ to phytoplankton was 0.1 to 10 µg/l for primary productivity and for microzooplankton, 0.05 to 7 µg/l for cell growth. Bacterioplankton had a higher tolerance for all the chemicals than the phytoplankton or microzooplankton, and in some cases their activity was stimulated by the toxicants. This behavior was believed to be an indirect effect caused by increased organic matter resulting from the death of the other organisms in the mixed cultures. Chukchi communities were found to be more sensitive than the Bering Sea organisms to BaP and PCB but less sensitive to Cu and Cd. Characterization of an area of low resistance near St. Lawrence Island agreed with similar findings in 1984 for this area. Comparing the

critical concentration values in the Bering–Chukchi Sea to those for the Baltic Sea, a highly polluted region, it was found that the Baltic was more susceptible to PCB's and BaP but slightly less susceptible to Cu and Cd. For the Bering and Chukchi Seas, BaP and Cu are the two pollutants whose critical concentration levels approached the natural levels that were found for this region; therefore, these pollutants may be having an impact in this region.

Toxicity of α - and γ -HCH to natural communities of microplankton were tested. At concentrations from 80 to 100 ng/l, distinct effects were observed on the ambient ammonium pool and ^{15}N ammonium uptake rates, both of which increased in the experimental containers.

Bacterial activity per cell increased in the oceanic experiments and decreased in the shelf experiment. These tests indicate that HCH has the capability of altering plankton nitrogen cycling in open ocean systems.

A sediment bioassay technique was employed to examine the toxic potential of sediment collected from several regions throughout the study area. Standard single species test protocols were carried out employing *Artemia salina* (brine shrimp), and a dinoflagellate, *Pyrocystis lonula*. No acute effects were observed. These first time tests provided benchmark values that will be useful to future studies monitoring the status of these waters.

Conclusions

The Third Joint US–USSR Bering & Chukchi Seas Expedition was very productive. It provided new information and improved data sets to enable better understanding of the processes that are occurring in these subpolar–polar regions. Several measures of biological activity confirmed that the summertime productivity here is extremely high, matching some of the highest natural biological activity in the world. As expected, the activity was also quite variable. This variability was caused by several interacting factors. The most dominant factor for this system is the upwelling of nutrient-rich deep current waters that takes place predominantly on the northern Bering Sea Shelf and within and the Chirikov basin. Some representative high values of biological activity that were measured are as follows: 800,000 cells/ml and 18 $\mu\text{g C/l}$ for bacteria for the northern Bering Sea; bacterial destruction rates of 107 $\mu\text{g C/l/d}$ in the Bering Sea; 1,800 $\text{mg C/m}^2/\text{d}$ of carbon fixation in the Chirikov basin; phytoplankton counts between 500 and 1,700 cells/ml in the Chirikov basin; average biomass of 40 g wet weight/ m^2 for microzooplankton in the Chirikov basin; and benthic biomass in excess of 400–500 g/m^2 in productive areas.

As with previous BERPAC expeditions, the intricate balance of numerous processes working together was verified. A modeling effort revealed the obvious importance of seasonality to regulating this biological activity but it also demonstrated the importance of taking a more holistic approach to future studies. Plans for future modeling are being built around carbon cycling. Carbon is also central to the problems involved with global climate; therefore, it is important to understand more fully the role of carbon processes that are taking place in the Bering–Chukchi Seas ecosystem. Initial data were accumulated on the carbon budget of this system. As a likely carbon sink, this area has an important role in minimizing CO_2 increase worldwide, especially since increasing CO_2 may be the single most important factor leading to global warming. The estimated flux of dissolved carbon to the Chukchi Sea–Arctic Ocean amounted to 0.82×10^9 metric tons per year. A significant portion of this carbon likely finds its way to the deeper waters of the Arctic Ocean and eventually may be incorporated into the North Atlantic bottom water. Both of these avenues would act as a sink for greenhouse gas. In addition to its significant impact on the carbon budget, the Bering and Chukchi Seas area also plays a critical role in global climate processes because of the major northward current flow that arrives from the deep Pacific and that is part of the global current that has a central role in regulating the world's climate. This oceanic current is largely responsible for the high productivity of the Bering–Chukchi region and thus, the fisheries and economy of the area are intimately linked to this system. Achieving a better understanding of this current flow and its link to the biology of this system is therefore of extreme importance.

The expedition provided further evidence to show that there is still much about the processes taking place in this ecosystem that is only poorly known. For example, using observations from the Gulf of Anadyr and along the Chukchi Peninsula, it was possible to confirm the hypothesis about the current entering the Gulf of Anadyr with a large quantity of nutrients to produce production–deposition centers in the Gulf of Anadyr and Chirikov basin. Also, improved access to areas in the Chukchi allowed discovery of many new features about this system. For example, evidence was found for a previously unreported southerly flow of nutrient- and salt-rich water flowing southward along the Siberian coast and merging with the northerly flowing Bering Strait water. Also, many zonal current patterns were identified in the Chukchi basin that had major effects on the biology of the system—for instance, bird sightings, optical measurements, and Cs^{137} concentration profiles.

Considering the fact that such an intense period of biological activity is compressed into the relatively short ice-free period in this region, there is a great deal of concern that disruptions, even though relatively slight, may have profound effects on the ecosystem components and functions. Anthropogenic influences were one of the effects that were studied. Monitoring at specific sites provided information for long-term assessments. With benzo(a)pyrene (BaP) and polychlorinated biphenyls (PCB's), the concentration levels have remained relatively stable since the 1981 and 1984 BERPAC cruises; for DDT, the levels have declined. The absolute abundance of bacterioplankton has increased since the summers of 1981 and 1984, and for this expedition the indices for microbial cenoses were five times higher than they were in 1984. Indirect evidence of an anthropogenic impact is indicated by the fact that species that can tolerate and metabolize certain pollutants were isolated from these regions. These species also appeared to have increased in abundance over the 1984 levels. In toxicity tests with mixed populations of pelagic flora, harmful effects were observed with BaP and copper at LD_{50} values as low as 2 ppm. These concentrations are approached by the natural levels measured in this region. Representatives of several taxonomic groups of bacteria from the region were isolated that had the potential to produce products with mutagenic or genotoxic (RNA damaging) effects. Fortunately, for the present, expression of this trait is unlikely, since factors leading to the expression (i.e., extreme anthropogenic pressures or dense bacterial abundance) do not presently exist in the Bering–Chukchi Seas ecosystem, although the fact that the potential is there is certainly cause for concern.

Several organic contaminants were measured for the first time in these areas. Among these were observations of high levels of the hexachlorocyclohexane (HCH) class of compounds, with an average concentration in water of 3.44 ng/l , and toxaphenes. Also, chlordanes were measured in most samples

(e.g., atmosphere, water, biota [plankton, benthos and fish], sediment, and suspended matter). The levels of these organochlorines were typical of those found in other neighboring arctic areas, which indicates that there are no local sources of contamination. One especially interesting observation concerning the levels of HCH's in surface water was a suggestion of an increasing gradient of concentration with increase in latitude. This supports a theory that these compounds are released into the atmosphere from warm seawater near the equator, and they condense in the colder waters at the poles. There was also evidence, from careful studies of the equilibrium partitioning of the α and γ isomers at the air-water interface, that the present levels of the γ isomer (Lindane) was on the increase in the Bering-Chukchi Sea area. Trace metal concentrations were measured for the first time in this area. Levels were typical of pristine areas, and no local sources were indicated. Cadmium, however, may require future study, since biomagnification to moderate levels was noted in some of the biota.

Microbial degradation of selected congeners of PCB was observed using laboratory incubations of isolates from the region. Rates under these conditions were most rapid for the lower chlorinated homologs, i.e., 95 to 100% reduction of the dichlorobiphenyls in 20 days; and less for each succeeding increase in chlorine number, with only 7% reduction of some of the hexachlorobiphenyl homologs. The activities also varied with the structural position of the chlorines. Studies of

photochemical degradation of PCB in *in situ* tests indicated that the rates for photooxidative breakdown were much slower than microbial degradation rates. However, many of the congeners resisting microbial breakdown were degraded in the photochemical tests. In similar tests with BaP, it was found that the rates for BaP degradation by microbial action were comparable to the rates for photochemical decay. These tests demonstrate that even in ecosystems such as the easily damaged and cold waters of the Bering-Chukchi Sea possess the capability to cleanse themselves of man-made pollutants.

Several interesting findings emerged from the benthic studies. There were several sites where evidence for petroleum seepage was observed. This confirms the possibility that there may be underlying petroleum deposits in the area. Based on isotope and carbon data from the bottom, it was noted that there is a gradual east to west gradient and high to low concentration of terrigenous source carbon across the areas of each of the major basins. The evidence suggests that most of the land-based carbon is supplied from the Alaskan coastline to these major basins.

Contour plots of dissolved humics in surface water samples indicated that the maximum levels were often displaced from the areas where actual algal blooms were occurring. This suggests that monitoring for these resistant forms of dissolved organic matter might provide a means to measure the locations and source strengths of previous blooms.

Appendix A

Participants of the Third Joint US-USSR Bering - Chukchi Seas Expedition, Summer 1988.

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Vaytekaya, Y. I.		Scientific Secretary
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Whitledge, T. E. *	Group Leader	Nutrient chemistry
Barinova, S. P.		Microorganism indicators
Gorelkin, M. I.		Nutrient chemistry
Hanson, R. B.		Bacterial production
Kudryatsev, V. M. *		Bacterial production
Mamaev, V. O.		Numbers and biomass of microorganisms
Marchenko, A.		Technician
Robertson, C.		Bacterial production
Veidt, D. *		Nutrient chemistry
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Belyaeva, O. L. *		Polyaromatic hydrocarbons
Hinckley, D. A.		Chlorinated hydrocarbon
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Kolobova, T. P.		Trace metals
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Pershina, I. V.		Dissolved organic matter
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Drakov, S. N.		Vertical profiles
Kumeisha, A. A.		Hydrooptics
Lavender, M.		Conductivity/temperature/depth, currents
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Holmes, G.		Phytoplankton, C/N
Korzhikov, I.		Primary production
Kulikov, A. S.		Mesozooplankton
Levina, O.		Microzooplankton
Mamaeva, N. V.		Microzooplankton
Polishchuk, L. N.		Biogeography of zooneuston
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Wright, T.		Sediment hydrocarbons, phytoplankton pigments

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