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Outer Continental Shelf Environmental Assessment Program

Final Reports of Principal Investigators

VOLUME 57 SEPTEMBER 1988

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YUKON DELTA PROCESSES: PHYSICAL OCEANOGRAPHY

by

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 670

August 1987

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Mr. Stephen Pace, EG&G's Field Logistics Manager for the investigation, was responsible for all field activities and coordination with NOAA logistics personnel in Anchorage. Mr. Mike Meyer and Mr. George Lapiene of NOAA in Anchorage provided EG&G with extensive support for logistics, the 25-foot vessel, and continual assistance from the NOAA helicopter and crew stationed in Emmonak. Mr. Charles Willauer, Mr. John Ryther, Jr., and Dr. McDowell participated with Mr. Pace on many of the field trips. Additional field assistance was obtained from Mr. Mark Avakian.

Data processing and preparation of the final report were performed at EG&G's Waltham, Massachusetts, office. Dr. Sergio Signorini, Ms. Judith Ring, Ms. Elizabeth Miller, and Mr. Bruce Andrews participated in the data processing. The final report was prepared by Dr. McDowell, Dr. Signorini, Mr. Pace, and Mr. John Borchardt. Editorial assistance was provided by Mrs. Sandra MacDonald and Ms. Ring.

EXECUTIVE SUMMARY

EG&G Washington Analytical Services Center, Inc. (EG&G), conducted a multidisciplinary environmental measurement program of the Yukon River Delta during the summers of 1985 and 1986 for NOAA/NOS in Anchorage, Alaska. The study area covered the lower Yukon downstream of Pitkas Point (St. Marys), the entire Delta region, and the nearshore areas around the Delta. A total of five 2-week field trips were made for purposes of in-situ field measurements and servicing of current/water-level moorings and meteorological stations, which were installed to provide time series records of various physical parameters. Emmonak was used as a staging site because of its location near the center of the Delta. NOAA provided a 25-foot boat for the field work, and additional support for transport of fuel and equipment was obtained from a NOAA helicopter and crew stationed in Emmonak.

The primary objective of the investigation was to study the major physical processes of the Yukon Delta region, including river bathymetry, discharge, sedimentology, nearshore currents, tides, water properties, storm surge, and meteorology. Extensive analyses of each measurement type have yielded interesting, quantitative descriptions of each physical process from this vast, natural environment. These results also represent a valuable data source for later studies of pollutant transport in the fragile ecosystem of the Delta.

The bathymetric survey of the lower Yukon revealed a complex system of erosional channels extending from Pitkas Point to the Delta shoreline. Maximum depths across river transects ranged from 27 to 97 feet, the deepest channels being situated where the river was constricted or adjacent to the bank at large meanders. The major channels are expected to persist for many years, whereas the bars, shoals, and "cut banks" are continually being altered by erosion and deposition.

Velocity profiling surveys and moored current measurements revealed strong currents and extensive vertical and horizontal shear throughout the lower Yukon and within the three major Delta distributaries. The maximum observed current speed of 180 cm/sec was measured in Kwikluak Pass during October 1985. River discharge estimates derived from the velocity profiling surveys demonstrated the climatological trend of peak discharge shortly after ice-breakup in early June, followed by a gradual decrease through the summer and early fall. Discharge measurements ranged from 9,000 to 14,000 m^3/sec for the four summer profiling surveys.

The strong summer discharge of the Yukon effectively dominates the flow and water properties in the nearshore areas surrounding the Delta. Observations indicate that saline water from the Bering Sea did not penetrate into the mouths of the major Delta distributaries during the summers of 1985 and 1986. Ocean tides do affect the water level and current speeds within the distributary mouths, but the tides are not able to reverse the flow during the summer periods of strong discharge. Measurements were not made during the period of weak river discharge (fall through spring), but hydraulic calculations indicate that salt water may penetrate a distance on the order of 10 km upstream within the major distributaries, via the process of a stratified salt-wedge intrusion.

The major fraction of the Yukon discharge flows through Kwikluak Pass and into the Bering Sea via South Mouth. During summer and early fall when discharge is strong, the flow through South, Middle, and North Mouths is proportioned as 66%, 26% and 8%, respectively. This indicates that nearshore regions to the west of the Delta receive the greatest contribution of fresh, sediment-laden Yukon waters, whereas the area to the north of the Delta receives much less fresh water.

Current measurements along the Delta front (at two sites located 15 nm west of the Delta) revealed diurnal and semi-diurnal, oscillatory tidal currents of 40 to 80 cm/sec amplitude, and a northeastward, shore-parallel drift of roughly 12 cm/sec. This low-frequency, alongshore current is apparently related to the southwesterly winds which prevail during the summer months.

During summer, suspended sediment concentrations within the lower Yukon exhibited large temporal fluctuations. Concentrations varied from roughly 160 to 475 mg/l, with no apparent relationship to discharge estimates; however, at any given time, suspended concentrations were relatively constant throughout the Delta region. During summer, turbid, freshwater plumes emanate from the mouths of the three major distributaries, and often reach distances of 10 to 15 nm from the Delta shoreline. Along-shore advection, tidal processes, and turbulent mixing cause the individual distributary plumes to spread over the Delta platform, with the result that the turbid waters sometimes encompass the entire Delta. Patches of relatively clear water have been observed between the distributary mouths by other field investigators and from satellite imagery, but these features were not an objective of the present study.

We suspect that sediments within the surface plume and in the pronounced near-bottom turbidity layer are advected northward of the Delta and into Norton Sound and the eastern Bering Sea. This hypothesis is consistent with northward progradation of the Delta and the northward migration of salmon smolt, which are expected to remain within the Yukon plume as long as possible.

1. INTRODUCTION

1.1 PROGRAM OVERVIEW

EG&G Washington Analytical Services Center, Inc., Oceanographic Services (EG&G), under contract to the NOAA National Ocean Service, conducted a multidisciplinary field investigation of the Yukon River Delta in northwest Alaska during the summer and early fall of both 1985 and 1986. This program, identified as the Yukon Delta Processes: Physical Oceanography (NOAA Research Unit 670), was administered by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office of NOAA/NOS in Anchorage, Alaska, with contractual support from the NOAA Western Administrative Support Center in Seattle, Washington.

The study area extended downstream from Pitkas Point, over the entire Delta and surrounding nearshore regions (Figure 1-1). Pitkas Point is located approximately 100 km upstream from the mouth of the river, at the confluence of the Yukon and Andreafsky Rivers. The entire study area encompasses roughly 5,000 sq km of the Yukon Basin, and a distance of 200 km along the main course of the Yukon River and its three major distributaries. In addition, a limited program of hydrographic stations and moorings was conducted to a distance of 30 km offshore of the western Delta.

The field measurement program consisted of five 2-week field trips during the summers of 1985 and 1986. NOAA's specification for a summer measurement program was based upon two factors: first, during spring, ice breakup prevents safe travel and instrument deployment in the river. Since breakup generally occurs in late May or early June, equipment deployment could not be scheduled until mid-June. The second factor limiting the length of the field measurements was primarily logistical and related to weather conditions. In October, air temperatures on

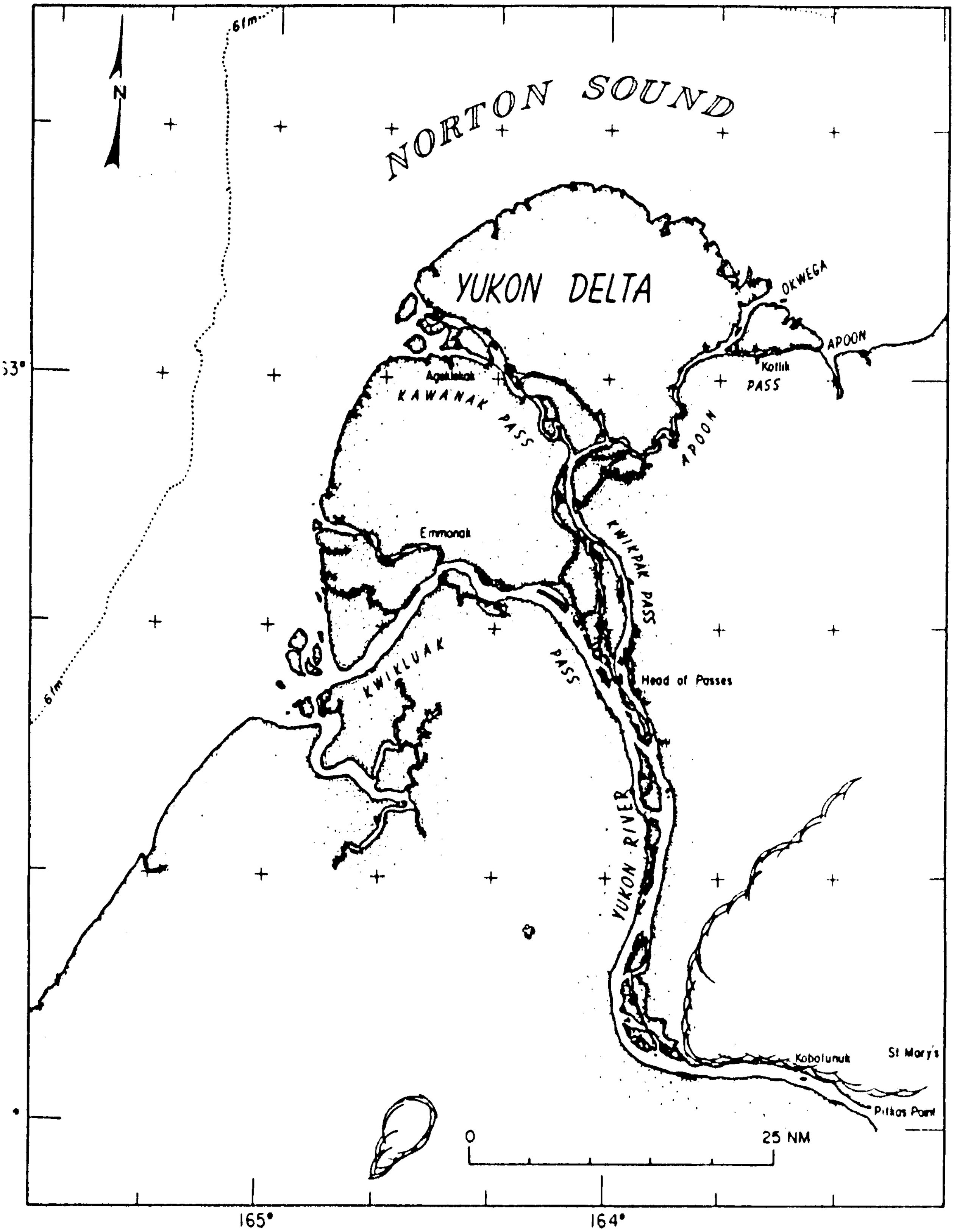


Figure 1-1. The study area of the Yukon Delta Physical Oceanography Program, which extends downstream from Pitkas Point, over the entire Delta region, and into the nearshore areas surrounding the Delta.

However, of the several markers found, many had evidently been disturbed since their original establishment. Without expensive equipment and more field time allocated for this aspect of the project, local vertical controls could not be effectively established for the bathymetric data.

After the cruise, the strip chart records and navigation logs were returned to EG&G's Waltham office for digitization and quality control. The first step in processing the bathymetric data was to plot all Loran-C transect end positions on the existing USGS topographic maps (scales 1:633,360 and 1:250,000). This was done for quality control of the navigation data, but it also confirmed field observations that many of the islands and shoals had changed locations and characteristics since the 1952 topographic survey.

Analysis of the Loran-C data also revealed a significant, yet constant, offset in the latitude and longitude positions that were computed from the lines of positions (LOPs) by the Loran-C receiver. This offset of approximately 0.68 nm due west was practically constant over the entire Delta, as verified by comparison with a few prominent landmarks and positions obtained from the inertial navigation system in the NOAA helicopter during subsequent field trips. Aside from this offset, which was easily corrected, the Loran-C proved to be the most reliable method of navigation on the Delta.

All bathymetric records were manually digitized to 1-foot resolution at 30-second annotations, or more often when the bottom relief was changing slope rapidly. On constant, gradual slopes, the 30-second distance between annotations represented approximately 350 feet (107 m) over the bottom. Where the topography was rough, depths were digitized as often as 50 feet (15 m) in the horizontal direction. All bathymetric transects are included in Appendix A of this report, and a discussion of their major features is provided in subsection 3.1.

success was due to the excellent logistical support from NOAA's OCSEAP office, as well as from the NOAA helicopter pilots who provided transport of personnel and equipment to various sites around the Delta.

Field operations were based in Emmonak, with shipment of equipment from Anchorage via St. Marys. Field activities were described in trip reports submitted to NOAA following each of the five field trips.

Basic results from the 1985 field measurements were presented in a Mid-Program Progress Report submitted to NOAA in March 1986. This Final Report presents the field observations and analysis results from both years of the program. A 9-track data tape containing all current, tide, meteorological, and hydrographic data collected by EG&G was presented to NOAA at the completion of the program.

1.2 PROGRAM OBJECTIVES

The NOAA OCSEAP Office, established under agreement between NOAA and the Department of Interior's Minerals Management Service, has the responsibility of obtaining the scientific data and information needed to predict environmental disturbances that may be caused by oil and gas development offshore Alaska. Concern for the Yukon Delta is high because the Yukon supports a major salmon fishery, while the Delta lowlands represent a nesting area for numerous species of migratory waterfowl. There is particular concern that pollutants and oil spills originating at development sites or along offshore transportation routes may be transported upriver and seriously damage the fragile marine environment. There are a number of physical processes which could cause or facilitate such transport: the gently sloping topography; occurrences of storm surge; suspected salinity intrusion; onshore wind stress and sea breeze; and the heavy load of suspended sediment.

The primary focus of the program was to obtain field measurements and conduct scientific analyses which describe the temporal and spatial scales of physical processes that could affect the transport of released pollutants in the vicinity of the Delta, its major distributaries, and adjacent coastal regions. It is anticipated that these results will provide the physical characterization of the Delta that is greatly needed for numerical models of flow in the Yukon and in nearshore regions around the Delta, as well as background information for fisheries habitat studies.

An extensive multidisciplinary measurement program was designed to obtain the following physical measurements:

- bathymetric profile data at closely spaced river transects to determine river cross-sectional area for transport estimates and numerical model generation;
- current data from the Yukon and nearshore areas to determine river flow and offshore transport processes;
- water-level data from upstream in the river, at the mouths of the distributaries, and offshore to monitor river height and determine the effect of tides and storm surge on the Delta;
- velocity profile data from river transects to determine vertical and horizontal shear and river discharge;
- temperature, salinity, and density data from the nearshore areas and distributary mouths to determine whether seawater can enter the distributaries by means of estuarine circulation;
- meteorological data from sites on the Delta for identification of sea-breeze and synoptic-scale meteorological processes; and
- suspended and bottom sediment data from within the river and the nearshore areas to determine large-scale sediment characteristics and affinity for hydrocarbon pollutants.

The measurement results are discussed as separate physical processes in Section 3, and then synthesized in Section 4 for identification of likely pollutant transport processes on the Yukon Delta.

1.3 YUKON DELTA PHYSIOGRAPHY

The physical characteristics of the Yukon Delta have been described in detail by previous investigators: Dupre and Hopkins (1976) describe the geological characteristics of the Yukon-Kuskokwim region with emphasis on morphology and sediment zonation; LGL (1984) presents a general discussion of Delta characteristics based upon an extensive literature review; Jones and Kirchhoff (1976) offer an interesting view of living resources on the Delta; and Envirosphere (1986) presents recent observations which identify local fisheries and preferred habitats around the Delta. Since these references provide a broad characterization of the Delta region, only a brief description of the Delta and the lower Yukon is provided here in order to describe the length scales and environmental conditions of the study area.

The Yukon River is one of the major rivers in North America. Its Delta flood plane extends over an area of western Alaska that is the equivalent size of the state of New Hampshire. The extent of this Delta was traversed by the EG&G field crew by helicopter and boat. The perspective of the Delta provided by the helicopter is that of a broad, gently sloping flood plane, beginning at the foot of the Andreafsky Hills at the town of St. Marys and continuing northwest, with no topographic relief, to the Bering Sea. From the vantage point of 5,000 feet, the landscape appears to be dominated by the broad, main channel of the river, and many side sloughs and oxbow lakes. Midway between St. Marys and the coastal village of Emmonak, the river widens and branches into distributaries. Here, the flood plane broadens and the number of sloughs and interlocking side channels increases dramatically. At the coast, the distributaries broaden and fan out through the numerous channels cutting through the mud flats and shallows of the Delta platform. Dupre (1980) describes this platform as having gentle slopes (1:1000 or less) and connecting the emergent edge of the Delta with the adjacent submerged portion, the Delta front. The turbid river water extends over the entire platform and continues seaward over the Delta front in plumes that reach out into the Bering Sea.

An appreciation of the enormity of the lower area of the Delta is realized from the perspective of a boat. The many interlocking sloughs and side channels reveal a typical riparian environment dominated by alder and willow, and intermixed with expanses of grassland and tundra vegetation. All along the main channel, distributaries, and sloughs, the process of erosion is evident. Strong flow at large river meanders causes steep 'cut banks' and erosion which contribute considerable tree and bush vegetation to the debris carried downriver. Also evident are the bars and shoals which occur in the middle and to the sides of the major channels and sloughs. These subsurface features are rarely evident from a helicopter because of the opaque, sediment-laden river water. The presence of bars, shoals, and channels was discovered by the boat crew during the bathymetric surveys and the frequent transit between sampling stations.

In the nearshore area of the Delta, several other bathymetric features were also noticed by the field crew when using the echo sounder to navigate. Boat navigation over the submerged portion of the Delta was often complicated by the narrow, shallow, winding channels present over the Delta platform. During times of low water large portions of the platform become exposed mud flats, and passage was extremely difficult. The Delta platform extends approximately 12 to 15 miles offshore to a point where the bottom begins to slope gently seaward. This sloped transition zone constitutes the Delta front. Farther offshore is the prodelta, which extends up to 60 miles seaward to the edge of the deltaic sediments (Dupre, 1980).

1.4 YUKON DELTA CLIMATOLOGY

Meteorological data, consisting of wind speed and direction, air temperature, and barometric pressure from the Yukon Delta, were collected by EG&G during the summers of 1985 and 1986. These measurements and data from government-operated weather stations at Emmonak, St. Marys, Unalakleet, and Cape Romanzof are presented in Section 3, along with a discussion of the dominant meteorological processes in the vicinity of the Delta. Since these data represent only the summer season during 2 consecutive years, a brief summary of climatological conditions encountered on the Delta is presented here for comparison with the recent observations. These data have been extracted primarily from two sources: The Climatic Atlas of the Bering Sea Region (Brower et al., 1977) and The Alaska Marine Ice Atlas (La Belle et al., 1983). These atlases include data from approximately 1948 through 1974, depending upon the reporting station.

The Yukon Delta, located on the 63rd parallel, receives extended daylight during the summer months. The duration of daylight reaches a maximum of 20.5 hours on the summer solstice (21 June) and decreases to 11.5 hours on 1 October. This was beneficial for the field operations during the Yukon Delta Program because navigation within the river distributaries and sloughs is extremely difficult during darkness. Winter operations on the Delta would be hampered by the limited daylight hours, which reach a minimum of 4.7 hours on the winter solstice (21 December).

Mean monthly air temperatures on the Delta range from a high of 10°C in July and August to a low of -14°C during the winter months. Monthly mean temperatures for the Delta (computed as an average of observations at Unalakleet and Cape Romanzof) and the extreme minimum and maximum observed values for each month are presented in Table 1-1. For the period June through September, extreme temperatures can range from -1 to +18°C (map set numbers in Brower et al., 1977). These extremes are underestimated, because a maximum temperature of 27.8°C was observed at St. Marys during mid-July 1985 (during the first Yukon field trip). Air temperatures will be discussed further in subsection 3.6.

Barometric pressure in the Yukon Delta region is primarily governed by the large-scale pressure field that dominates the Bering Sea and Gulf of Alaska. During the period from September through April, low-pressure centers can be found over the Aleutians, in Bristol Bay, or in the Gulf of Alaska. As indicated in Table 1-1, monthly mean pressures on the Delta range from 1,004 to 1,014 mb during the period from September through April. During the summer, the large-scale pressure system relaxes, but mean monthly pressures on the Delta remain between 1,009 and 1,013 mb. These means do not, of course, represent the extremes experienced during the passage of extra-tropical storms.

In correspondence with the pressure field, the large-scale wind field is also governed by the low-pressure system that normally lies near the Aleutians. Mean monthly wind statistics from Unalakleet and Cape Romanzof (Table 1-2) illustrate very steady conditions except during the summer months. At Unalakleet, easterly winds prevail from September through May and scalar mean speeds range from 8.5 to 13.8 knots. At Cape Romanzof, prevailing winds are from the northeast during the period September through June, and scalar mean winds are slightly greater than at Unalakleet (8.4 to 14.8 knots). During the summer at both sites, winds reverse direction and weaken slightly. Wind directions on the Delta closely resemble those at Cape Romanzof (southerly during summer) due to the similar orientation of the coastline and proximity to the Bering Sea.

Table 1-1. Monthly mean meteorological statistics for the Yukon Delta region determined by averaging statistics for Unalakleet and Cape Romanzof, as given by Brower et al. (1977). Values are given for mean monthly air temperature, minimum and maximum extreme air temperature, and barometric pressure. Data from Unalakleet cover the period 1948 through 1974, while data from Cape Romanzof extend from 1953 through 1968.

		Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Air Temp (°C)	Mean	-13	-14	-12	-6	+2	+7	+10	+10	+7	+1	-5	-14
	Min	-31	-33	-31	-22	-11	-1	+3	+5	+1	-10	-18	-28
	Max	+2	+2	+2	+5	+11	+14	+18	+16	+14	+8	+3	+1
Pressure (mb)		1011.5	1009.6	1013.7	1012.5	1011.6	1012.5	1012.3	1009.0	1007.8	1004.0	1005.0	1008.6

Table 1-2. Mean monthly wind statistics from Unalakleet and Cape Romanzof from Brower et al. (1977). Values are given for scalar mean wind speed, prevailing wind direction ($\pm 22^{o}$), and the percent frequency of occurrence that the wind lies within the prevailing wind direction.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Unalakleet												
Scalar Mean Speed (kt)	13.8	13.1	11.8	9.8	8.5	8.3	8.7	9.2	9.9	11.0	13.2	12.5
Prev. Dir.	E	E	E	E	E	SW	W	E	E	E	E	E
% Frequency	54	48	43	30	24	22	20	24	34	42	55	53
Cape Romanzof												
Scalar Mean Speed (kt)	14.5	14.8	12.8	13.3	10.3	8.4	8.0	9.2	10.7	11.4	13.7	14.5
Prev. Dir.	NE	NE	NE	NE	NE	NE	SW	S	NE	NE	NE	NE
% Frequency	27	33	28	25	27	23	21	22	28	30	29	33

The Yukon Delta coastal region is also influenced by a thermally driven mesoscale circulation (sea breeze) during the summer months. A detailed description of the Yukon Delta sea breeze system is given in subsection 3.6.

Extreme wind speeds occur episodically on the Yukon Delta during the passage of Bering Sea extra-tropical storms. These storms are more frequent during mid- to late fall; during this time period, storms may occur as frequently as three to five times per month. Storm winds may cause severe coastal flooding of the Delta, as discussed in subsection 3.6.

The Delta region is normally subjected to 20 inches of rain and 40 to 50 inches of snowfall on an annual basis. Climatologically, precipitation is observed roughly 35% of the days during the year, with a maximum occurrence of 60% in August and a minimum of 25% during winter months. Similarly, cloud cover exhibits a maximum in August (75% probability on a given day) and a minimum probability of 40% during February and March when air temperatures are extremely low. Snowfall, during the 9-month period from fall through spring, occurs with a daily probability of roughly 15%.

Sea ice surrounds the Delta region during winter months, as illustrated in maps of the climatological ice-edge location, which are presented in The Alaska Marine Ice Atlas (La Belle et al., 1983). In mid-October, no ice is observed around the Delta, but by mid-November, there is a 40% probability that sea ice is present at the Delta front. Between mid-December and mid-April, ice is always present, but ice concentrations may range from 70 to 100%. The shorefast ice in the Yukon Delta region extends much farther offshore than in any other coastal region of the Sound (Muench and Ahlnas, 1976; Ahlnas and Wendler, 1979) due to the shallow topography of the Delta platform.

In general, the ice cover offshore of the Delta (beyond the shorefast ice) persists until April or May and consists primarily of loose pack ice with thicknesses ranging from 0.7 to 1.2 meters (Thor and Nelson, 1981). Ice breakup in May is illustrated in the ice atlas by ice concentrations of 50 to 60% during this period. By mid-June or early July, the Delta region is normally ice free. The available ice atlases do not provide information on ice cover in the lower Yukon, but discussions with local inhabitants suggest that the cycle of river ice is nearly the same as that of sea ice around the Delta shoreline.

With the extensive ice cover in the Bering Sea during three seasons of the year, sea-surface temperature measurements are sparse. The climatological data of Brower et al. (1977), which cover the period from May through October, indicate that mean sea-surface temperatures in the vicinity of the Yukon Delta range from a minimum of 0.5^{O}C in May to a maximum of 11^{O}C in July. Mimimum temperatures in summer are roughly 5^{O}C, whereas those during ice cover can approach -1.8^{O}C. Maximum observed sea-surface temperatures of 16^{O}C have been observed in July, but without corresponding salinity data, one cannot be sure that these extremes were not a result of relatively warm river outflow, rather than warm ocean water.

The only intensive hydrographic survey in the vicinity of the Yukon Delta was conducted in Norton Sound during the period 1976 through 1978 (Muench et al., 1981). Summer (1976 and 1977) hydrographic profiles were conducted from a vessel, and winter profiles (1978) were made through the ice from a helicopter. Although all stations were made at least 40 km from the Delta, these measurements are useful for identification of oceanic water properties and the lateral persistence of Yukon River water. The summer measurements revealed a broad layer of warm, low-salinity water that was associated with the Yukon River. The spatial and temporal variability of hydrographic properties within this surface layer was high; during three summer surveys, surface properties over the Sound ranged from 6 to 16^{O}C and 16 to 31 ppt.

Near-bottom water properties exhibited somewhat less variability because they were isolated from river effluent by a strong pycnocline; bottom properties ranged from 1 to 9^{o}C and 26 to 34 ppt during summer throughout the Sound.

During winter when the Sound is ice covered, the region is nearly isothermal and near the freezing point (-1.6^{o}C in 1978). Winter salinities also exhibit much less vertical and horizontal variability than during summer months: salinities ranged from 30.0 to 31.6 ppt over the entire survey during February 1978.

Although these observations from Norton Sound do not represent an extensive census of hydrographic properties around the entire Yukon Delta or for all seasons, they do illustrate seasonal variations in vertical structure, property variability, and Yukon River influence. Further discussion of water properties is given in subsection 3.5.

Wave observations during the open-water season in the Bering Sea and Norton Sound indicate that waves are generally small in the vicinity of the Yukon Delta. The percent frequency of occurrence of wave heights less than 1.5 m are: 95% in May, 65% in August and September, and 45% in October. High winds accompany the extra-tropical storms in fall and winter, but ice cover often precludes extreme wave conditions. Map set 16 of Brower et al. (1977) indicates that from December through April, mean ice concentrations to the west of the Delta exceed five-eighths concentration, and the percent frequency of occurrence of wave heights less than 1.5 m exceeds 90%. Throughout the open-water season, the probability of waves greater than 3.5 m is less than 5%.

Climatological aspects of the Yukon River, such as river temperature, water level, flow characteristics, river ice, and storm surge on the Delta, are addressed in the discussion of results presented in Section 3.

2. FIELD MEASUREMENTS

2.1 LOGISTICS AND FIELD OPERATIONS

Detailed planning and logistical coordination were required to successfully execute the field program on the Yukon Delta. The EG&G facility in Anchorage served as the base for staging the field trips, and Mr. Stephen Pace was responsible for all planning and logistical coordination with NOAA operations personnel located in Anchorage. While in the field, the base of operations was located in the coastal village of Emmonak, proximally located to the three major distributaries on the Delta. At the field base, daily coordination was maintained with the NOAA field representative for scheduling boat and helicopter use.

The transportation of personnel and equipment between the Anchorage staging facility and the Emmonak field base was accomplished via St. Marys, Alaska. All project equipment and personnel were transported between Anchorage and St. Marys via commercial air carrier; the transportation link between St. Marys and Emmonak was supplied by a NOAA Bell-205 helicopter and a commercially operated Cessna Caravan aircraft.

Field measurements were conducted within the Delta and along the nearshore Delta platform using a 25-foot NOAA supply vessel, with support from the NOAA helicopter. U.S. Coast Guard-qualified EG&G personnel operated the vessel on a daily basis out of Emmonak, except when great distances and lengthy observation periods dictated living on the vessel. During these extended periods of operation, scheduled radio contact with the NOAA helicopter provided a safety net in the event immediate assistance was required. The helicopter functioned as the critical link in the net, supplying the EG&G field team with spare parts and extra fuel for the vessel, transferring scientific equipment and personnel to remote sites not accessible by boat, and evacuating personnel in case of a medical emergency. The support provided by the helicopter crew proved to be very useful during all of the field trips, especially during the second year of the program, when a member of the field party incurred an injury and had to be transported to a nearby medical clinic.

As the primary observation platform in this program, the 25-foot vessel was equipped to quickly transport bulky loads over large distances under a variety of conditions ranging from the swift currents, everpresent bars, and opaque waters characteristic of the distributaries and of the upper Delta, to the wind-chopped, shallow areas of the nearshore Delta platform. The vessel was nominally equipped with such navigation and communications gear as an echo sounder, a Loran-C receiver, and a VHF radio. As a Coast Guard-approved vessel, it was also equipped with the appropriate safety gear and a Zodiac raft. Additionally, EG&G outfitted the vessel with heavy ground tackle, stout rigging, and survival and camping equipment. This logistical approach resulted in maximizing the data recovery during the limited periods of boat availability.

Performing beyond contractual obligations, on the third field trip EG&G's field personnel conducted a diving operation to locate and recover an Aanderaa tide gauge that had been deployed by another NOAA contractor. This instrument was covered with debris and had to be dislodged before it could be raised to the surface. Without diver assistance, this instrument would have been lost.

For each of the field trips, a contingent of two or three experienced EG&G scientists and/or field engineers was chosen in order to provide the most successful and cost-effective measurement program. The selection of team members for each trip was based upon the nature of the work scheduled. For instance, the personnel for the first trip were highly skilled in mooring deployments and bathymetric surveys, while those needed for the second trip were expert at instrument checkouts and CTD profiles. Additionally, most of the team members held U.S. Coast Guard licenses, and all were highly experienced in working at remote locations and under adverse conditions.

2.2 SCHEDULE OF SAMPLING ACTIVITIES

As proposed, five field measurement trips were conducted on the Yukon Delta: three during the summer and early fall of 1985 (27 July through 3 October), and two during the summer of 1986 (16 June through 23 August).

Each of the five field trips was scheduled around an 8- to 12-day period when the NOAA boat was available for EG&G use. The schedule was established by NOAA to prevent conflicts of boat usage between EG&G and another contractor who was simultaneously conducting a fisheries study of the Yukon Delta (NOAA Research Unit 660).

Figures 2-1 and 2-2 present a summary of data collection activities for 1985 and 1986, respectively. As evident from these schedules, the various data categories included in the Yukon Delta program are diverse and multi-disciplinary. The data collection methods, instrumentation and sampling equipment, and analytical procedures used in the case of each data category are described in detail in the following subsection. The rationale for sampling locations and numbers of measurements is presented within individual subsections of Section 3.

2.3 EQUIPMENT AND PROCEDURES

2.3.1 Bathymetric Surveys

EG&G conducted an extensive bathymetric survey of the lower Yukon River over the course of two field trips. The major portion of the survey extended from Pitkas Point to Kwikluak Mouth during the first field trip (July 1985) and consisted of

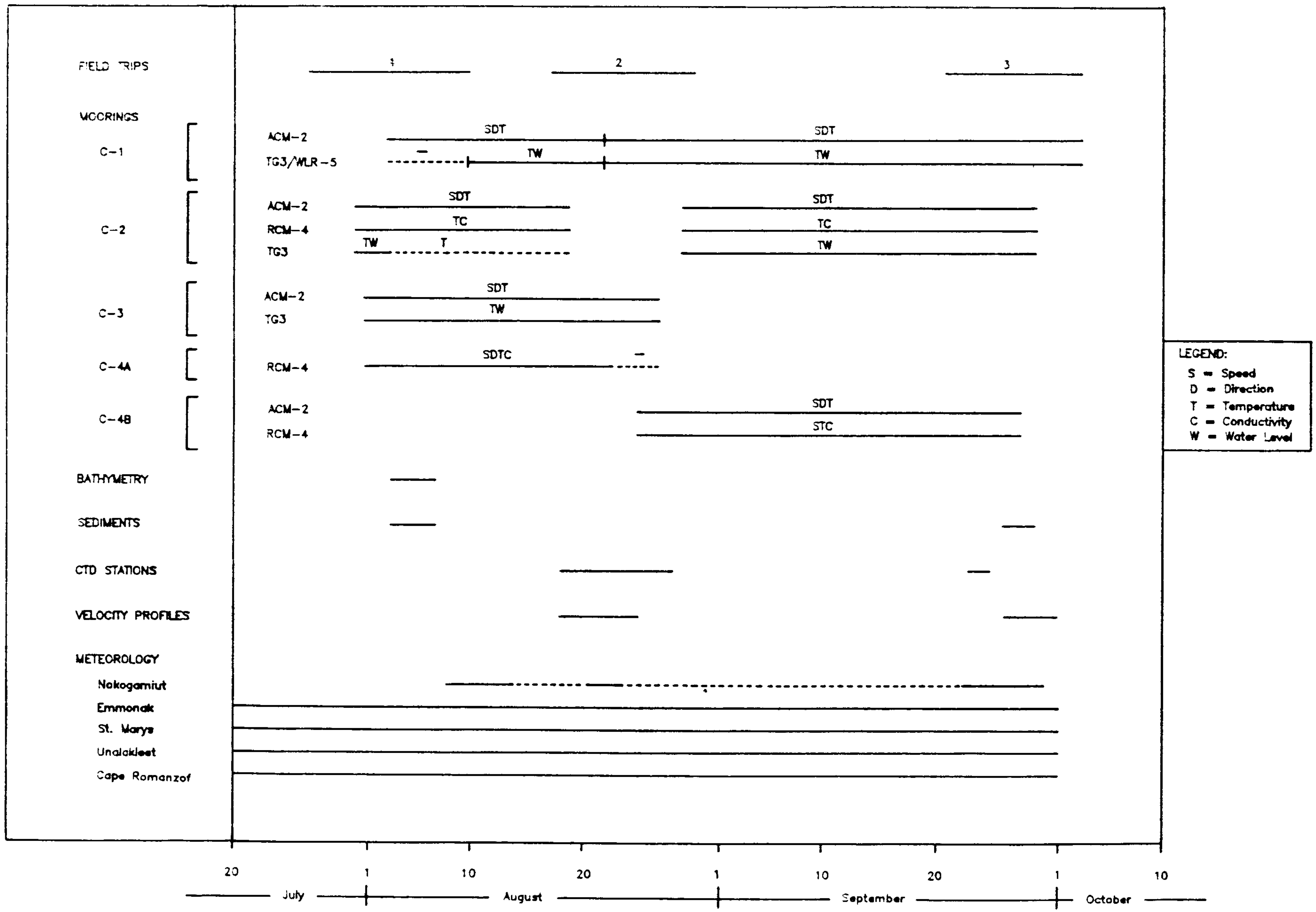


Figure 2-1. Summary of data collection activities on the Yukon Delta during the 1985 measurement program. Dashed lines indicate periods of missing or disqualified data.

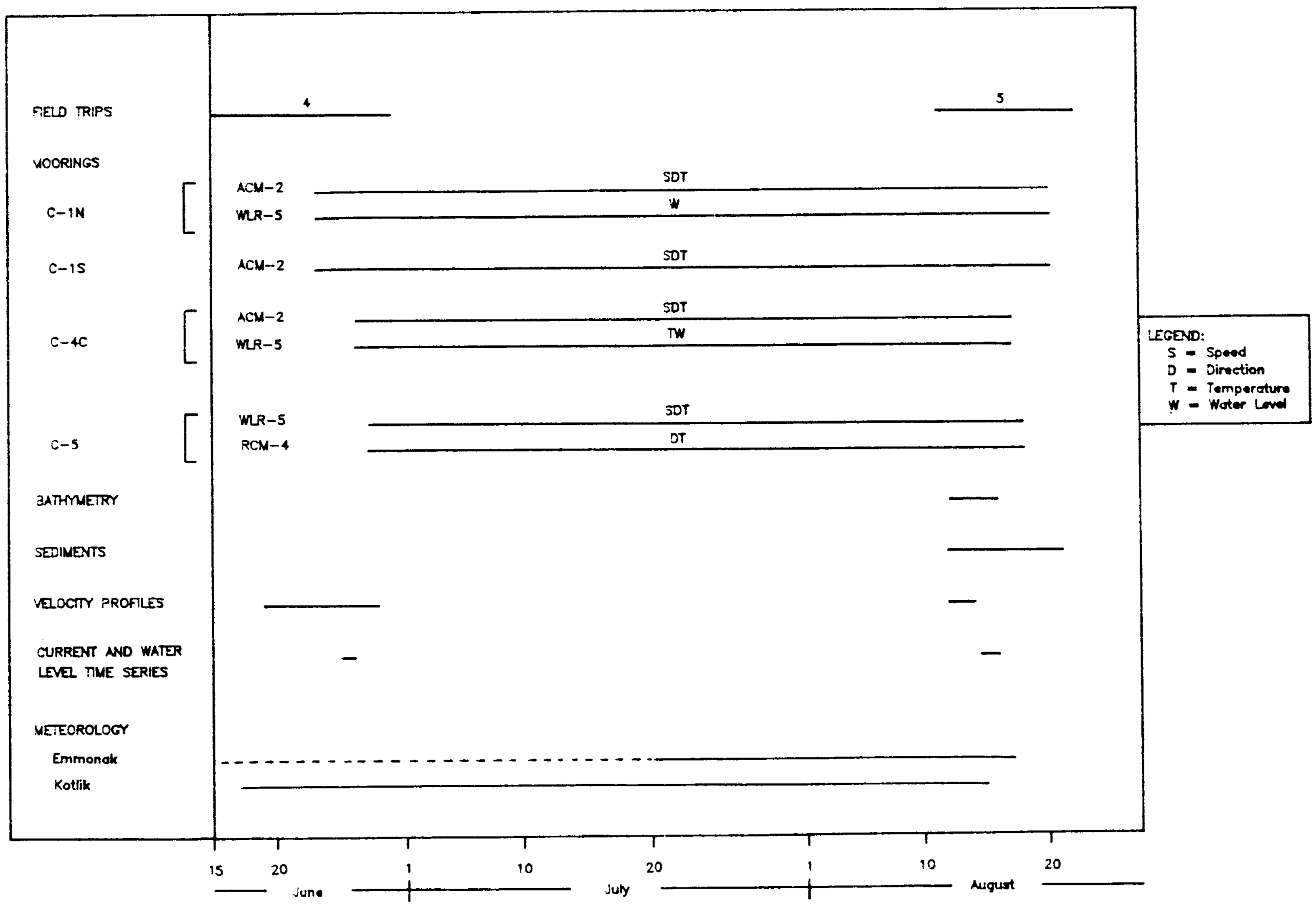


Figure 2-2. Summary of data collection activities on the Yukon Delta during the 1986 measurement program. Dashed lines indicate periods of missing or disqualified data.

46 river transects spaced at 2-mile intervals over the 90-mile length of the river (see Figure 3-1). The second portion of the survey was conducted during the fifth field trip (August 1986) and consisted of 14 transects over the 30-mile length of Kwikpak Pass downstream of Head of Passes (see Figure 3-2). EG&G also conducted several additional bathymetric transects in conjunction with river discharge measurements. These additional surveys were performed at Kobolunuk, Lamont, Kwikpak, Aproka, Hamilton, Apoon Pass, and Okwega Pass during the last four field trips.

On all bathymetric surveys, a Raytheon DE-719B fathometer was used for depth determinations and a Sitex-Codon Loran-C receiver was used to determine the locations of transect terminations. The orientation of each transect was kept roughly normal to the river channel by running the boat on line with range poles established on the banks. Continuous analog records were obtained from each transect, and 30-second annotations were made on the record while the boat was steaming across the river at a constant speed. The Loran-C positions at the ends of the transects provided an accurate measurement of the length of each transect. This technique was tested and verified for accuracy during the first field trip using a Hewlett-Packard 3810B Total Station System.

Surveys in connection with the river discharge measurements were conducted with an Echotech depth sounder and the Sitex Loran-C receiver. In these cases, depths were recorded manually at 5-second intervals while the boat proceeded across the transect line.

Efforts were also made to tie the bathymetric data to four vertical controls located at:

63°02.0'N	163°33.0'W
62°44.0'N	163°55.9'W
62°42.8'N	164°36.5'W
62°05.1'N	163°32.3'W

However, of the several markers found, many had evidently been disturbed since their original establishment. Without expensive equipment and more field time allocated for this aspect of the project, local vertical controls could not be effectively established for the bathymetric data.

After the cruise, the strip chart records and navigation logs were returned to EG&G's Waltham office for digitization and quality control. The first step in processing the bathymetric data was to plot all Loran-C transect end positions on the existing USGS topographic maps (scales 1:633,360 and 1:250,000). This was done for quality control of the navigation data, but it also confirmed field observations that many of the islands and shoals had changed locations and characteristics since the 1952 topographic survey.

Analysis of the Loran-C data also revealed a significant, yet constant, offset in the latitude and longitude positions that were computed from the lines of positions (LOPs) by the Loran-C receiver. This offset of approximately 0.68 nm due west was practically constant over the entire Delta, as verified by comparison with a few prominent landmarks and positions obtained from the inertial navigation system in the NOAA helicopter during subsequent field trips. Aside from this offset, which was easily corrected, the Loran-C proved to be the most reliable method of navigation on the Delta.

All bathymetric records were manually digitized to 1-foot resolution at 30-second annotations, or more often when the bottom relief was changing slope rapidly. On constant, gradual slopes, the 30-second distance between annotations represented approximately 350 feet (107 m) over the bottom. Where the topography was rough, depths were digitized as often as 50 feet (15 m) in the horizontal direction. All bathymetric transects are included in Appendix A of this report, and a discussion of their major features is provided in subsection 3.1.

2.3.2 Moored Current and Water-Level Measurements

Subsurface current/water-level moorings were deployed and recovered principally to obtain time series data of river flow, river height, and offshore currents and tides throughout the 1985-1986 open-water seasons. Other time series data were collected, including information on temperature and conductivity at some of the mooring sites.

The instrumentation consisted of several Neil Brown Instrument Systems (NBIS) ACM-II acoustic current meters, two Aanderaa RCM-4/5 Savonius rotor current meters, and three Aanderaa TG3-A and WLR-5 pressure gauges. All ACM-IIs were provided by NOAA; the RCMs and pressure gauges were provided by NOAA and EG&G. The release equipment consisted of four EG&G 314-A acoustic releases.

The 1985 schedule and locations of moorings in the river and on the Delta front are presented in Table 2-1, and graphically illustrated in Figure 2-3. Since the scope of the project was limited by the availability of moored equipment, the locations of deployment sites were altered for the three deployment periods. Moorings C-1, C-2, C-3 and C-4A were deployed on the first field trip. All of these moorings were successfully recovered in late August during the instrument turnaround phase of the second field trip. Moorings C-1 and C-2 were redeployed on this trip, and a third mooring was deployed at site C-4B. During the 1986 field measurement program, moorings C-1N, C-1S, C-4C and C-5 consisted of a single deployment extending from mid-June through mid-August (Figure 2-4).

Instrument depths and local water depth for each of the moorings are also presented in Table 2-1. Slight changes in the current meter depths occurred between several deployments due to reconfiguration of the mooring components and small changes in mooring locations. These differences in sensor depths between deployments must be taken into account when interpreting the current data because of the presence of strong current shear.

Table 2-1. Summary of instrumentation, water depths, and sampling depths for moorings deployed in the Yukon River and nearshore areas during the summers of 1985 (two deployments) and 1986 (one deployment). Mooring locations are shown in Figures 2-3 and 2-4.

1985 DEPLOYMENT

			Mooring Configuration					Position	
Station	Location	Deployment	Instrument Type	Sampling Rate (min)	Instrument Depth (m)	Water Depth (m)	Measurement Period	Latitude (north)	Longitude (west)
C-1	Kobolunuk	First	ACM-2	1	11.6	17.7	2-21 Aug	62°04'32"	163°28'15"
		First	WLR-5	10	4.0	4.6	9-21 Aug	62°03'49"	163°23'50"
		Second	ACM-2	1	9.5	15.9	21 Aug-2 Oct	62°04'54"	163°28'40"
		Second	TG3-A	15	13.1	15.9	21 Aug-2 Oct	62°04'54"	163°28'40"
C-2	South Mouth	First	ACM-2	1	13.0	16.2	30 Jul-18 Aug	62°35'15"	164°47'48"
		First	TG3-A	15	9.1	10.4	30 Jul-18 Aug	62°35'15"	164°47'48"
		First	RCM-5	10	14.0	18.3	30 Jul-18 Aug	62°35'19"	164°49'56"
		Second	ACM-2	1	10.1	18.0	28 Aug-28 Sep	62°35'34"	164°50'55"
		Second	RCM-4	10	13.4	18.0	28 Aug-28 Sep	62°35'34"	164°50'55"
		Second	TG3-A	15	15.2	18.0	28 Aug-28 Sep	62°35'34"	164°50'55"
C-3	Offshore	First	ACM-2	1	4.9	9.4	31 Jul-26 Aug	62°36'52"	165°32'01"
	South Mouth	First	TG3-A	15	7.9	9.4	31 Jul-26 Aug	62°36'52"	165°32'01"
C-4A	Offshore Middle Mouth	First	RCM-4	10	6.0	10.1	31 Jul-22 Aug	63°02'47"	165°13'54"
C-4B	Middle Mouth	Second	ACM-2	1	6.1	12.2	24 Aug-27 Sep	63°01'04"	164°22'02"
		Second	RCM-5	10	7.0	12.2	24 Aug-27 Sep	63°01'04"	164°22'02"

1986 DEPLOYMENT

			Mooring Configuration					Position	
Station	Location	Deployment	Instrument Type	Sampling Rate (min)	Instrument Depth (m)	Water Depth (m)	Measurement Period	Latitude (north)	Longitude (west)
C-1N	Kobolunuk		ACM-2	1	7.0	13.7	23 Jun-20 Aug	62°05'38"	163°31'37"
			WLR-5	10	9.8	13.7	23 Jun-20 Aug	62°05'38"	163°31'37"
C-1S	Kobolunuk		ACM-2	1	7.0	12.2	23 Jun-20 Aug	62°04'12"	163°32'25"
C-4C	North Mouth		ACM-2	1	4.0	7.3	26 Jun-17 Aug	63°02'39"	163°45'25"
			WLR-5	10	5.0	7.3	26 Jun-17 Aug	63°02'39"	163°45'25"
C-5	Lamont		ACM-2	1	13.0	18.0	27 Jun-18 Aug	62°43'01"	164°20'16"

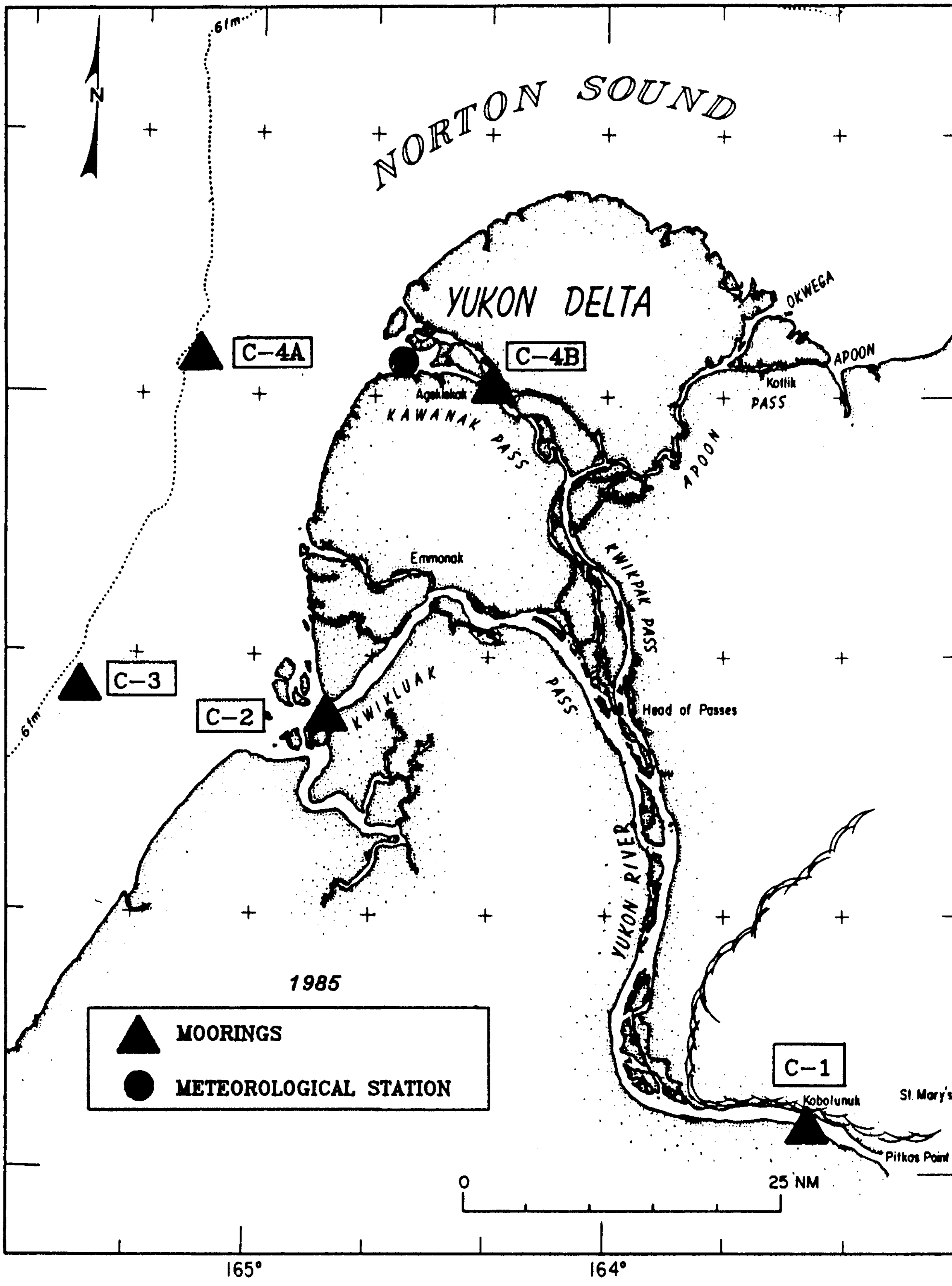


Figure 2-3. Locations of current/water-level moorings and a meteorological station deployed during 1985 field program.

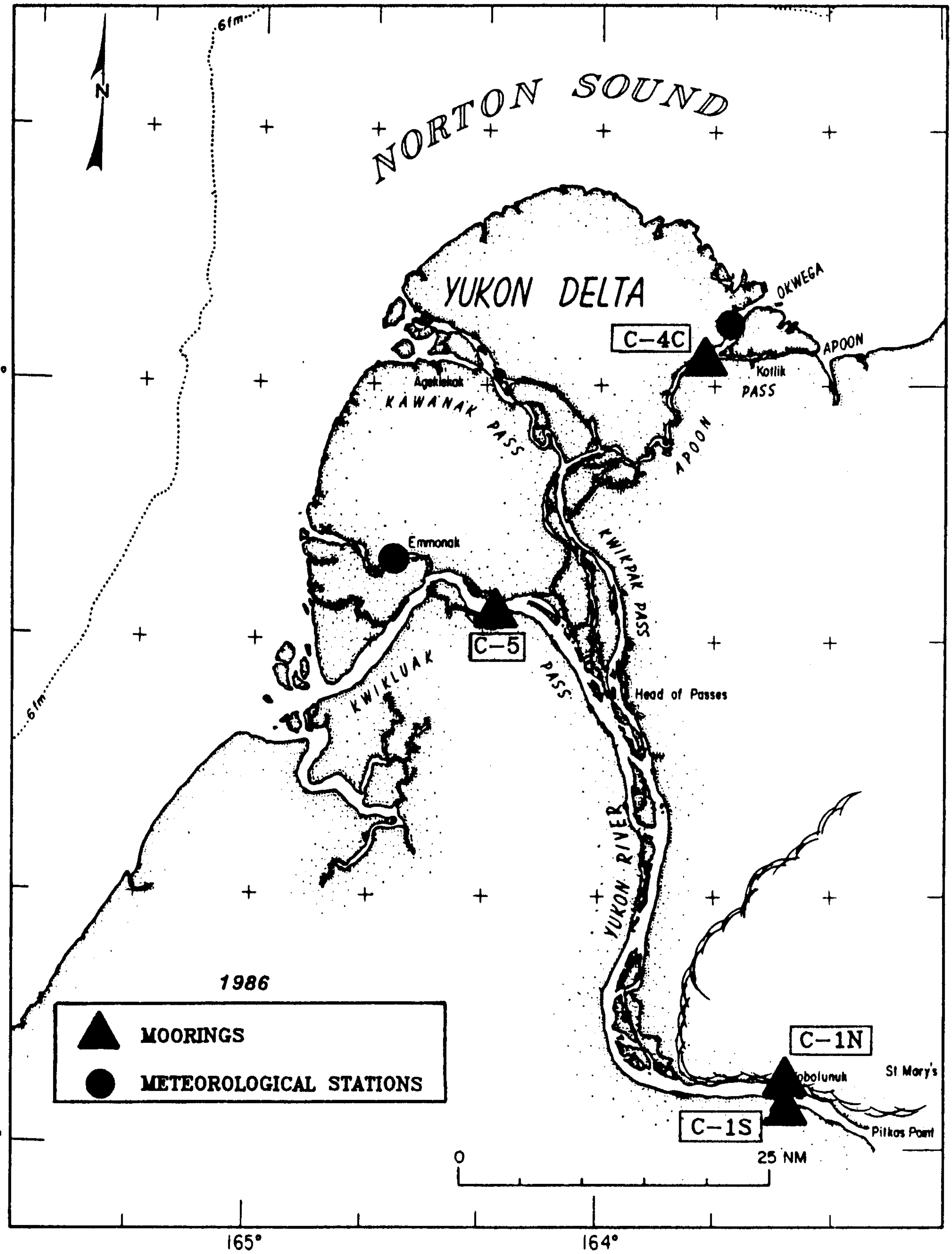


Figure 2-4. Locations of current/water-level moorings and meteorological stations deployed during 1986 field program.

It is important to note that Aanderaa Savonius rotor current meters greatly overestimate current speeds when moored within regions of strong wave activity. The RCM moored 6 m below the surface offshore of Middle Mouth (mooring C-4A) may have overestimated currents during wave events greater than 2 m, but in the absence of wave records, meaningful corrections to the record cannot be made. We suspect, however, that this wave-induced noise in the present record is much smaller than the 1-2 knot current signal at mooring C-4A.

The techniques of instrument deployment and recovery were adapted to environmental conditions and the limitations of the small boat. Robust moorings with 3/8-inch galvanized wire, 1/2-inch shackles, 28-inch diameter steel subsurface buoys, and 600-pound anchors were designed to withstand currents up to 5 knots. The moorings were also designed for ease of deployment and recovery from the 25-foot boat which lacked equipment for lifting the anchors. The anchors were deployed off the boat from a portable ramp, and the moorings were usually recovered by activating acoustic releases. On a few occasions, the release mechanisms were fouled by bottom debris and the moorings had to be recovered by grapling techniques. The design and techniques proved successful; all of the moorings were recovered without loss of equipment.

2.3.3 River Discharge Measurements

Current profiling transects were performed during the last four field trips for the purpose of measuring river discharge within the three major distributaries. Figures 2-5 through 2-8 illustrate the locations of profiling transects on each of the four surveys. Transect locations were selected far enough upstream to avoid contamination by the effects of the tides. Data were gathered regularly at Kobolunuk, Lamont, Kwikpak, and Aproka Passes and at Hamilton. Supplementary data were gathered during

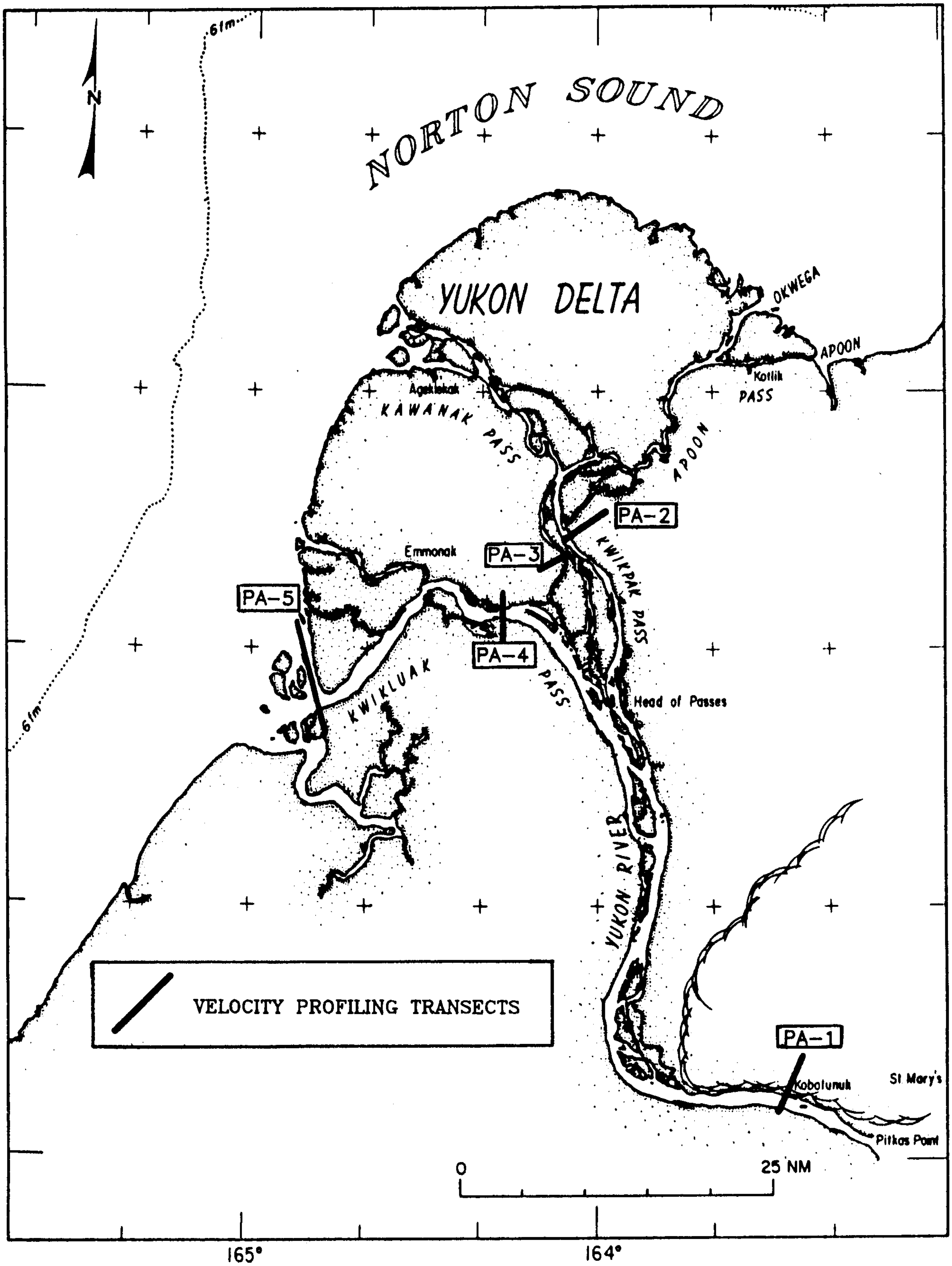


Figure 2-5. Locations of velocity profiling transects occupied during the second Yukon field trip.

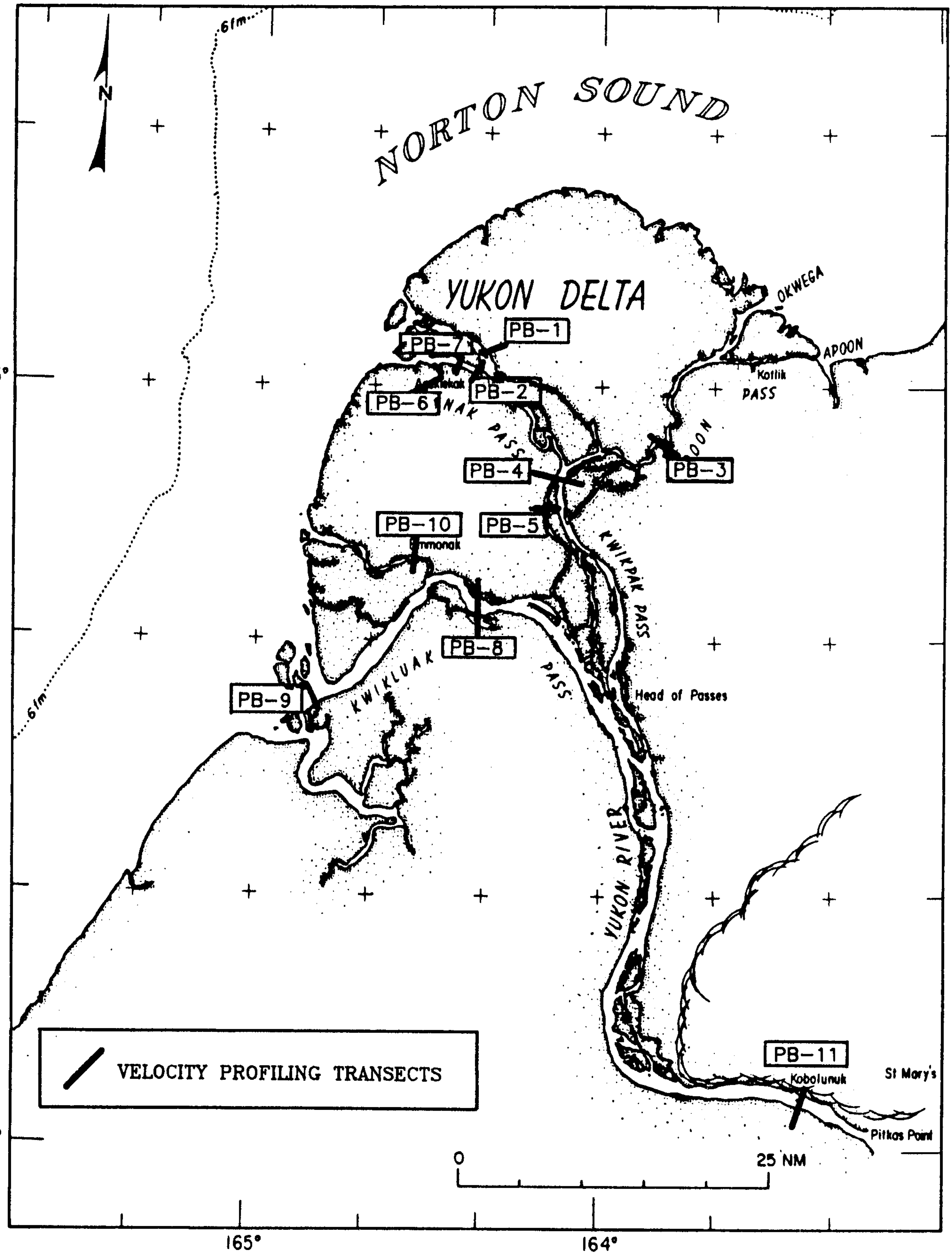


Figure 2-6. Locations of velocity profiling transects occupied during the third Yukon field trip.

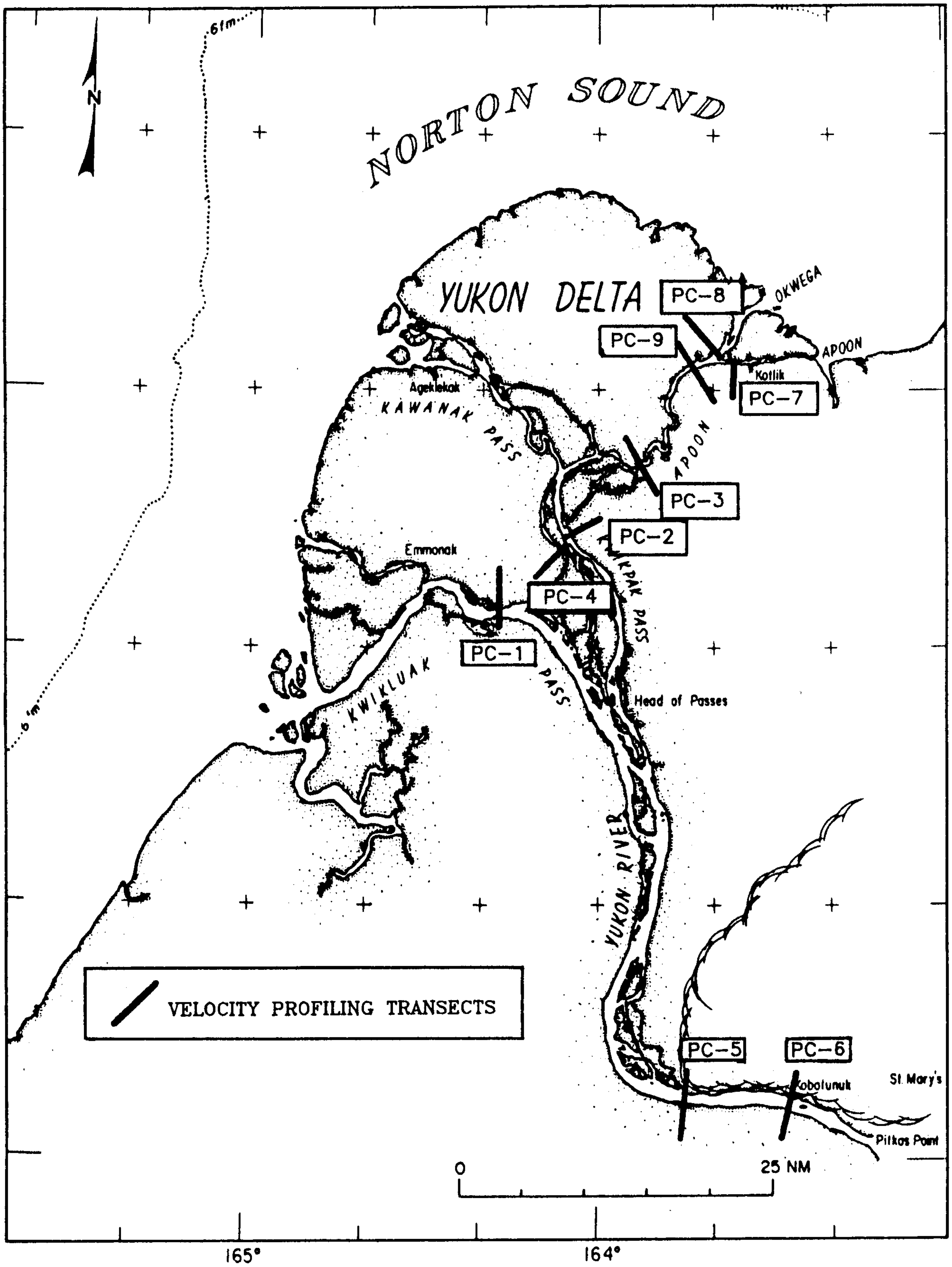


Figure 2-7. Locations of velocity profiling transects occupied during the fourth Yukon field trip.

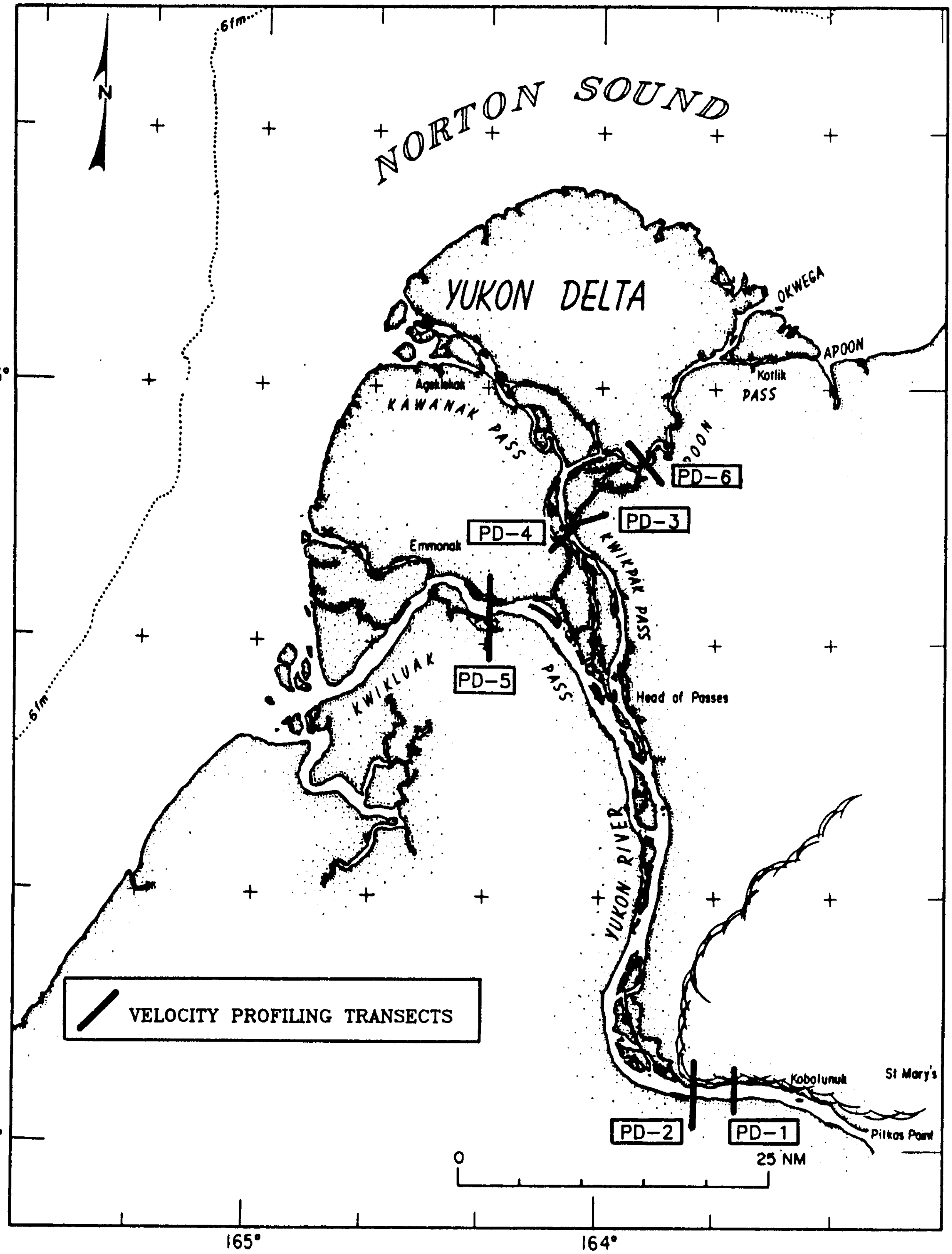


Figure 2-8. Locations of velocity profiling transects occupied during the fifth Yukon field trip.

selected field trips at Mountain Village, Kwikluak Pass, Kawanak Pass, and at Kotlik. A transect at Mountain Village was used to evaluate the effectiveness of the measuring technique by comparing results taken during the same period at Kobolunuk.

Transects performed at South and Middle Mouths during the initial phases of the measurement program were not occupied on subsequent trips because tidal effects made the data difficult to interpret. Flow characteristics within the North Mouth distributary near Kotlik were measured over an 18-hour and a 24-hour period during the fourth and fifth field trips, respectively.

To establish comparable sets of current data at each transect location, a uniform procedure was developed for sampling the two-dimensional current field. At each profiling transect, a bathymetric profile was obtained by running the boat perpendicularly across the river using range marks established on the bank. The results of the profile were then used to select the appropriate sampling positions for the profiling operations. During each profile, the boat was anchored, a stable position was logged, and the Endeco Model 110 direct reading current meter was lowered over the side with the help of the winch. Current readings were made near the surface, near the bottom, and at a number of intermediate depths, depending upon the total water depth. At each measurement level, the current meter was held stationary for at least 2 minutes, or until a stable speed and direction measurement could be obtained from the analog dial of the deck unit.

After the profiling cruises, the current data were manually plotted on vertical sections containing the appropriate bathymetric data. These discrete observations were hand-contoured to provide a complete velocity section across the river. The transect's cross-sectional area was then divided into 100-m^2 (50 m wide by 2 m deep) cells, and an average velocity for each cell was estimated. The total river transport was then computed by adding the individual transport contributions within each cell.

In this process, the actual along-channel velocity component was computed as the product of the current speed and the cosine of the angle between the current direction and the direction normal to the transect. This was necessary because the stations did not lie exactly on the transect line. Also, there was veering of current direction with depth at some stations. Angles of 10 to 40° were not uncommon in the current data.

A detailed discussion of all profile measurements, including an assessment of the Yukon River discharge variability, is provided in subsection 3.4.

2.3.4 Temperature and Salinity Measurements

Temperature and salinity measurements were made with a Neil Brown Instrument Systems (NBIS) MK-III CTD profiling system and Hewlett-Packard Model 85 microcomputer at stations located at the mouths of Kwikluak and Kawanak Passes, and within the subaqeous channels to a distance of 30 km offshore. These stations were conducted during the second and third field trips. The CTD system provided real-time data for analysis of water properties, as well as storage of digital data on HP magnetic tape cartridges. The digital data were returned to EG&G's Waltham, Massachusetts, facility for processing, editing, and generation of data products following each cruise.

Additional salinity measurements were conducted during the fifth field trip near the mouth of Apoon Pass, to a distance of 2 miles offshore, utilizing a Beckman RS5-3 salinometer. This unit provides a direct data readout and all station information was logged manually. A discussion of the water properties and salt intrusion within the subaqeous channels and Yukon distributaries is offered in subsection 3.5.

Water temperature time series were obtained from all moored current meters and water-level recorders. Salinity time series were also obtained from Aanderaa RCM current meters equipped with conductivity sensors. These instruments were deployed in Kwikluak Mouth (C-2), Kawanak Mouth (C-4B), and at the offshore mooring C-4A. These data are discussed in detail in subsection 3.2.

2.3.5 Meteorological Measurements

The purposes for acquiring meteorological data from the Yukon Delta and nearby regions were twofold. First, synoptic data were needed to determine the influence of the mean winds and storm events on the coastal circulation and sea-level variability in the vicinity of the Delta. Second, data were needed to verify the existence (or absence) of a sea breeze that was expected to occur on the Delta during the summer months.

Meteorological data were obtained using an Enviro-Labs weather logger deployed by EG&G on Nokogamiut Island during the 1985 season and on Emmonak Island during the 1986 field season, and from an Aanderaa DL-2 automated weather station established near Kotlik during the 1986 field season. The Enviro-Labs logger was on site from the beginning of August through the end of September 1985. However, due to system hardware problems, only 17 days of good data were obtained (10 in August and 7 in September). More complete records were obtained from the two meteorological stations deployed at Emmonak and Kotlik during the June through August 1986 measurement program.

In addition, hourly measurements of wind speed, wind direction, barometric pressure, and air temperature were obtained from four coastal stations operated by the National Weather Service (NWS) and the U.S. Air Force. Data from stations at Emmonak and St. Marys were obtained for the period June through September 1985. This time window was chosen because it overlapped the period of the EG&G field measurements and provided additional summer data for analysis of the sea breeze. Similar meteorological data from Cape Romanzof and Unalakleet were obtained for the months of July, August, and September 1985.

Since the meteorological data described above were daily observations generally obtained from early morning to late afternoon, a cubic spline algorithm was used to interpolate over gaps of less than 24 hours for barometric pressure and 12 hours for air temperature in the initial interpretation of the data. The cubic spline procedure was effective because fluctuations in barometric pressure typically have time scales of several days, and the diurnal air temperature extremes (maximum and minimum daily values) normally occurred during the observation window. The interpolation of the wind data utilizing a cubic spline was less effective due to the random variability and high-frequency content of the wind components. For this reason, gaps in the wind data were filled only if they were 3 hours or less.

2.3.6 Bottom and Suspended Sediment Measurements

The geological component of the Yukon Delta study included collecting and analyzing both suspended and bottom sediment samples from various positions in the lower Yukon River and nearshore regions around the Delta. The results were used to identify the following sedimentary characteristics:

- regional variations in suspended sediments within the river and nearshore areas;
- regional variations in bottom sediments within the river and nearshore areas; and
- temporal fluctuations in suspended sediment load and total sediment transport in the Yukon River.

Bottom Sediments

During the first field trip, bottom sediment samples were collected in conjunction with the bathymetric survey from Pitkas Point to Kwikluak Mouth and the offshore region of South Mouth.

At 8-mile intervals, a bottom sample was obtained from the main river channel. In all, 23 river samples and six offshore samples were collected in July 1985. An additional 18 samples were collected during subsequent field trips: six during the third trip (September 1985); six during the fourth trip (June 1986); and six during the fifth trip (August 1986). Samples were not collected from the offshore region of Middle Mouth because of adverse sea conditions and logistical constraints. Samples were collected using either a modified Ponar grab or a small pipe dredge. The grab was useful in the nearshore areas of the Delta front, while the dredge was more effective in sampling the harder substrates of the river channels and bars.

A total of 22 samples were analyzed at two laboratories. Ten of the samples taken during the first and third field trips (July and September 1985) were analyzed by Dr. A.S. Naidu of the Institute of Marine Science (IMS) at the University of Alaska, while 12 of the samples collected during the first, third and fifth field trips (August 1986) were analyzed by Dr. G.A. Jones of the Woods Hole Oceanographic Institution (WHOI). The methods included grain size analysis by the sieve and pipette method and computation of the conventional grain size statistical parameters (e.g., meansize, sorting, etc.; gravel-sand-silt-clay percentages). Estimates of carbon content were attained using two slightly different loss on ignition techniques. The IMS results included estimates of organic and inorganic carbon, while the WHOI results were limited to estimates of organic carbon only. The x-ray diffraction of the clay fractions performed by the WHOI team on seven samples used the techniques described by Jones (1983). The results for the clay analysis were expressed in Biscaye values (Biscaye, 1965).

<u>Suspended Sediments</u>

Water samples were collected for suspended sediment analysis in conjunction with bottom sediment samples. At each station during the first and third trips, a 1-liter water sample was collected at the surface and 1 m above the bottom using a Niskin bottle. During the third trip, all of the collected samples were analyzed in Emmonak using a Hach model 4140 Turbidimeter. Turbidity readings, in NTU units, were obtained for five 50-ml subsamples of each sample. All values were recorded 10-20 seconds after the sediments in each of the samples was resuspended. Average values of turbidity and their respective standard deviations were calculated for each of the suspended sediment samples.

After comparing the results from near-bottom and surface samples from both the first and third field trips, no differences were noted. Subsequent suspended sediment samples were taken at the surface only during the remaining sampling periods and analyzed with the Hach Turbidimeter.

To calibrate the turbidity values of the suspended sediment samples, 22 of the samples were also analyzed for sediment concentration at the EG&G facility in Waltham. From each of the 500-ml samples, five 100-ml subsamples were individually filtered through dried and preweighed Type A glass fiber filters. Each filter was then dried and weighed again in order to determine the concentration of the subsample. For each sample, the average and the standard deviation were calculated from analysis of the five subsamples.

Additionally, 10 of the samples were analyzed at an independent facility, Arnold Greene Testing Laboratories, for suspended sediment concentrations using the same techniques. The results compared favorably with those made at the EG&G facility.

3. DISCUSSION OF RESULTS

3.1 BATHYMETRY

3.1.1 General Discussion

Detailed topographic maps of the Yukon Delta, at scales of 1:63,360 and 1:250,000, have been prepared by the U.S. Geological Survey from surveys conducted in 1952. These maps illustrate the sinuous nature of the lower Yukon, as well as the complex system of distributaries, islands, and sloughs which transect the Delta. "Minor revisions" were made to these maps in 1971 and later years, but the bathymetric survey conducted during the present program revealed that the maps do not accurately portray the lower Yukon as it is today. The largest distributary, Kwikluak Pass, has the serpentine nature shown on the maps, but its banks are often displaced hundreds of meters from where they appear on the maps. Major islands still exist as shown, but smaller islands and exposed bars can be found in places where channels existed during the earlier surveys. Similarly, navigable waters were found in a few places where small islands were shown on the maps.

Regardless of the availability of topographic maps for the Yukon Delta, it must be recognized that there have been no bathymetric surveys of the lower Yukon prior to this program. One might expect that the river is navigable from bank to bank, but this is not the case at many places between Pitkas Point (near the mouth of the Andreafsky River) and the mouth of Kwikluak Pass. At many locations, a broad depositional bar had developed adjacent to one bank, such that the navigable transect had to begin at distances up to 1 km from the river bank. Many other transects were characterized by two deep channels separated by a central bar or shoal that could not be crossed.

Another prominent feature of the lower Yukon is the existence of "cut banks," which are regions where intense flow had caused major erosion of the river bank. Deep channels, which lie adjacent to these cut banks, convey most of the river flow in close proximity to the bank, thus sustaining the erosion. This process is self-supporting because the strong flow carries away the collapsed banks and erosion proceeds. The most active cut banks are found near river bends, and it is at these locations that the topographic maps differ most from present day conditions.

The most striking result of the lower Yukon bathymetric survey was the intricate system of erosional channels that make their way along the river bottom. These pronounced topographic features, which have considerable downstream length scales, may persist for years until altered by the slow process of deposition, or a catastrophic erosional event due to an ice jam and diversion of the river during spring breakup. Year-to-year variability in bottom topography is expected to be small, as confirmed by local fisherman who travel within the channels without the aid of depth sounders, and also anchor their gill nets at the same place along the river bank each year.

The Yukon's system of erosional channels extends offshore from the mouths of the three major distributaries. These features persist as subaqueous channels that wind across the shallow flats surrounding the Delta. Although the bathymetric survey did not extend beyond the mouth of Kwikluak Pass, these subaqueous channels had to be followed during the present program in order to reach offshore sites for mooring deployment and CTD profiling. In Section 5, it is recommended that bathymetric surveys be conducted offshore of the three major distributary mouths because little is known about the paths by which offshore pollutants would approach the Delta.

3.1.2 Lower Yukon and Kwikluak Pass

Figure 3-1 indicates the locations of 46 bathymetric transects between Pitkas Point and South Mouth that were surveyed during July 1985. Figure 3-2 presents locations of an additional 14 transects that were surveyed in Kwikpak Pass (downstream and northward of Head of Passes) during August 1986. The start and end positions of each transect illustrate that navigable water was sometimes found where the outdated topographic map indicated shoreline. In other locations, the transects could not extend to existing river banks because of bars or water less than the 2-foot draft of the survey vessel.

NOAA had specified that bathymetric transects be surveyed at 2-mile intervals along the length of the river in order that the data can be used (under separate contract) as a basis for numerical modeling of the lower Yukon. This spacing was adequate for resolution of the major topographic features of the river, such as islands, large bars, and major channels. There was, however, much variability between transects, and more detailed surveying at a few locations revealed that river profiles can differ significantly when separated by only a few hundred feet in the downstream direction.

Bathymetric profiles from all 60 river transects are presented in Appendix A. Inspection of adjacent profiles reveals the high degree of variability that is observed over short distances. Figure 3-3 presents bathymetric profiles from four locations between Pitkas Point and South Mouth; transect postions are shown in Figure 3-1. These transects exemplify the various profile types that were observed along the lower Yukon and in Kwikluak Pass. At Pitkas Point, a deep channel lies adjacent to the right (north) bank, and a shallower but distinct channel exists on the left side of the river (looking downstream). Near Mukialik, 24 miles downstream of Pitkas Point, moderately deep channels are found on both sides of the river, separated by a

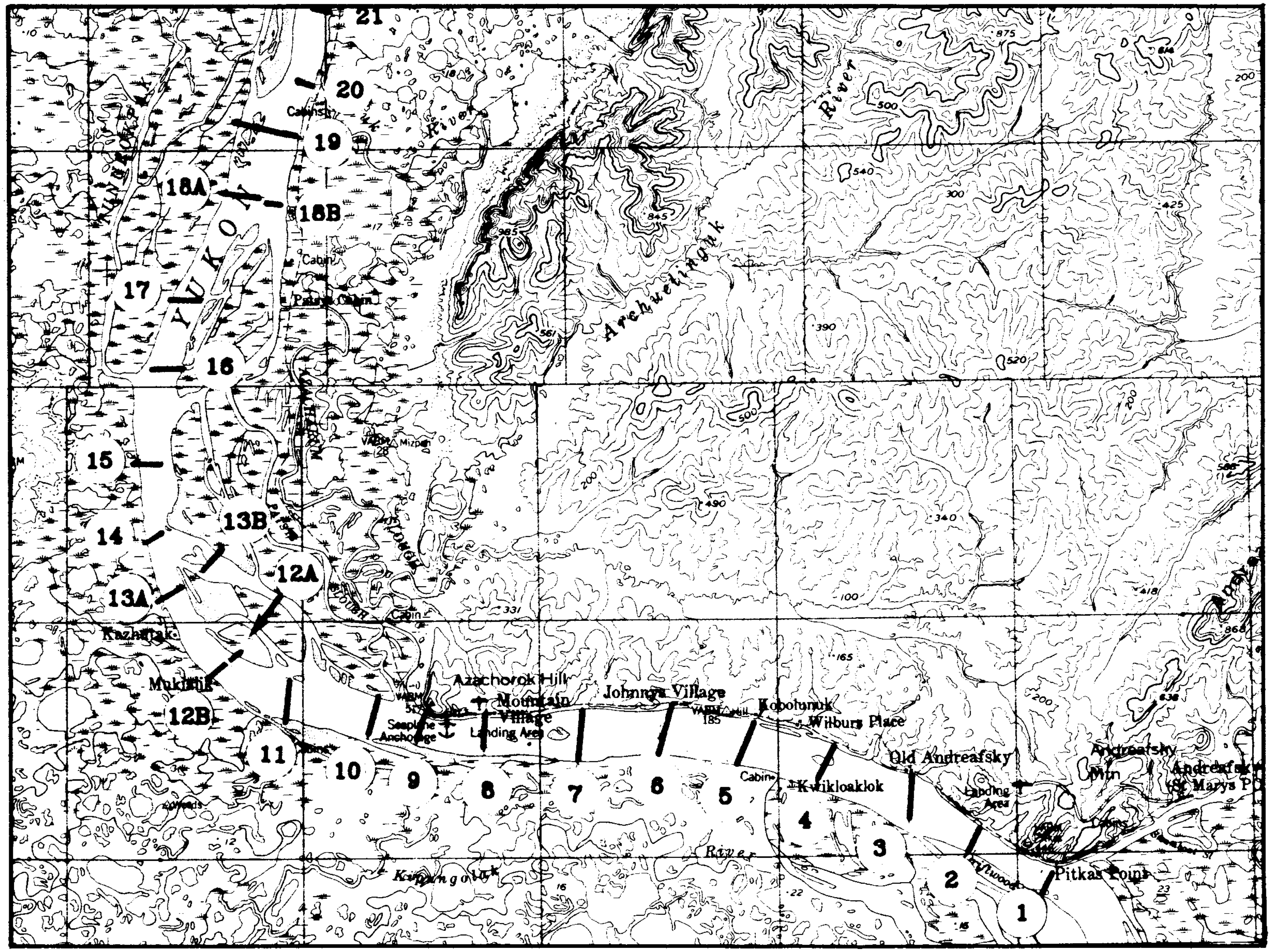


Figure 3-1a. Location of bathymetric transects 1 to 21 surveyed during the first Yukon field trip in July 1985. Positions are based upon corrected Loran-C navigation.

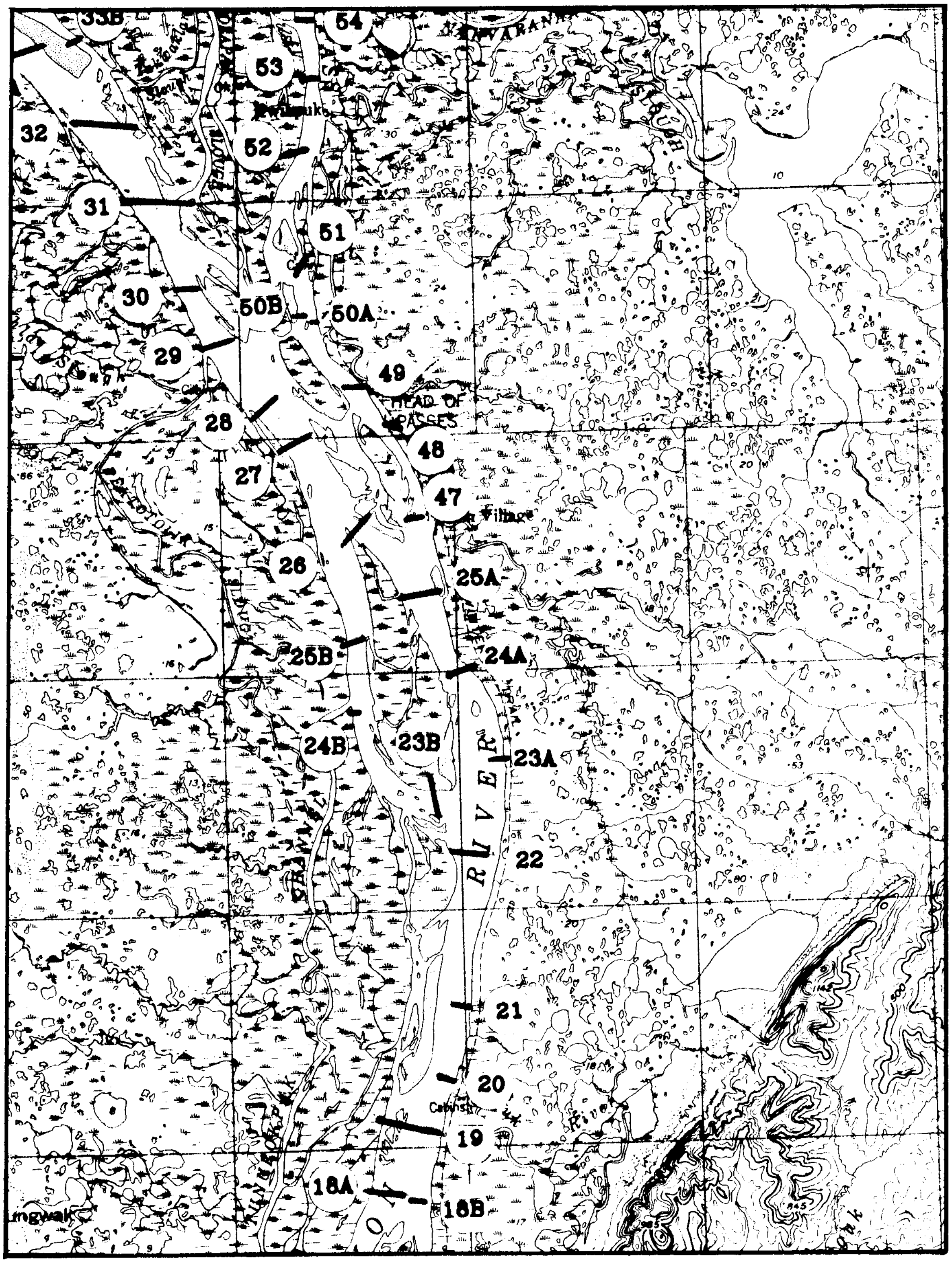


Figure 3-1b. Location of bathymetric transects 18 to 32 surveyed during the first Yukon field trip in July 1985. Positions are based upon corrected Loran-C navigation.

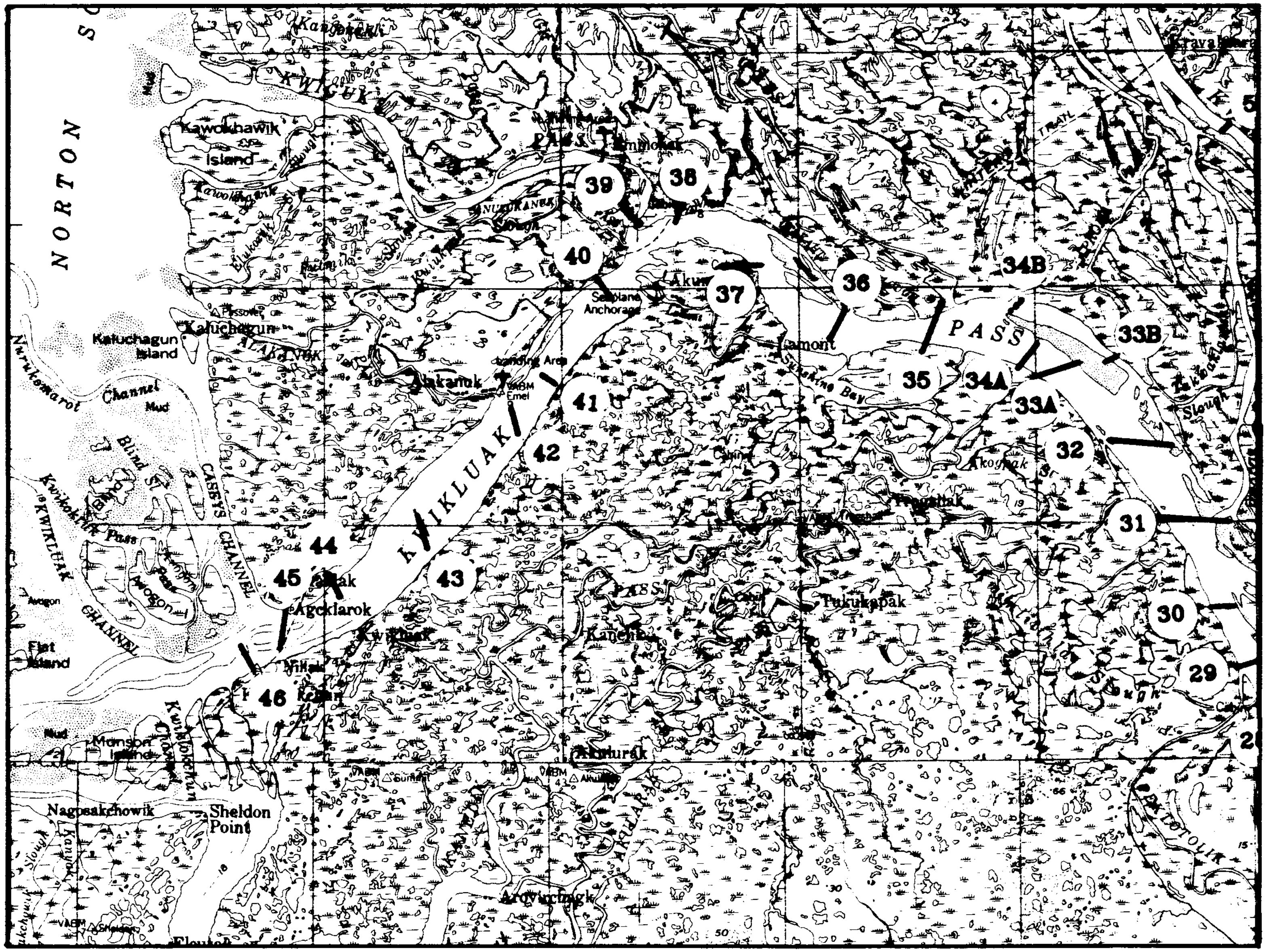


Figure 3-1c. Location of bathymetric transects 29 to 46 surveyed during the first Yukon field trip in July 1985. Positions are based upon corrected Loran-C navigation. The dashed transect (34B) represents the best-known position since Loran-C data are questionable.

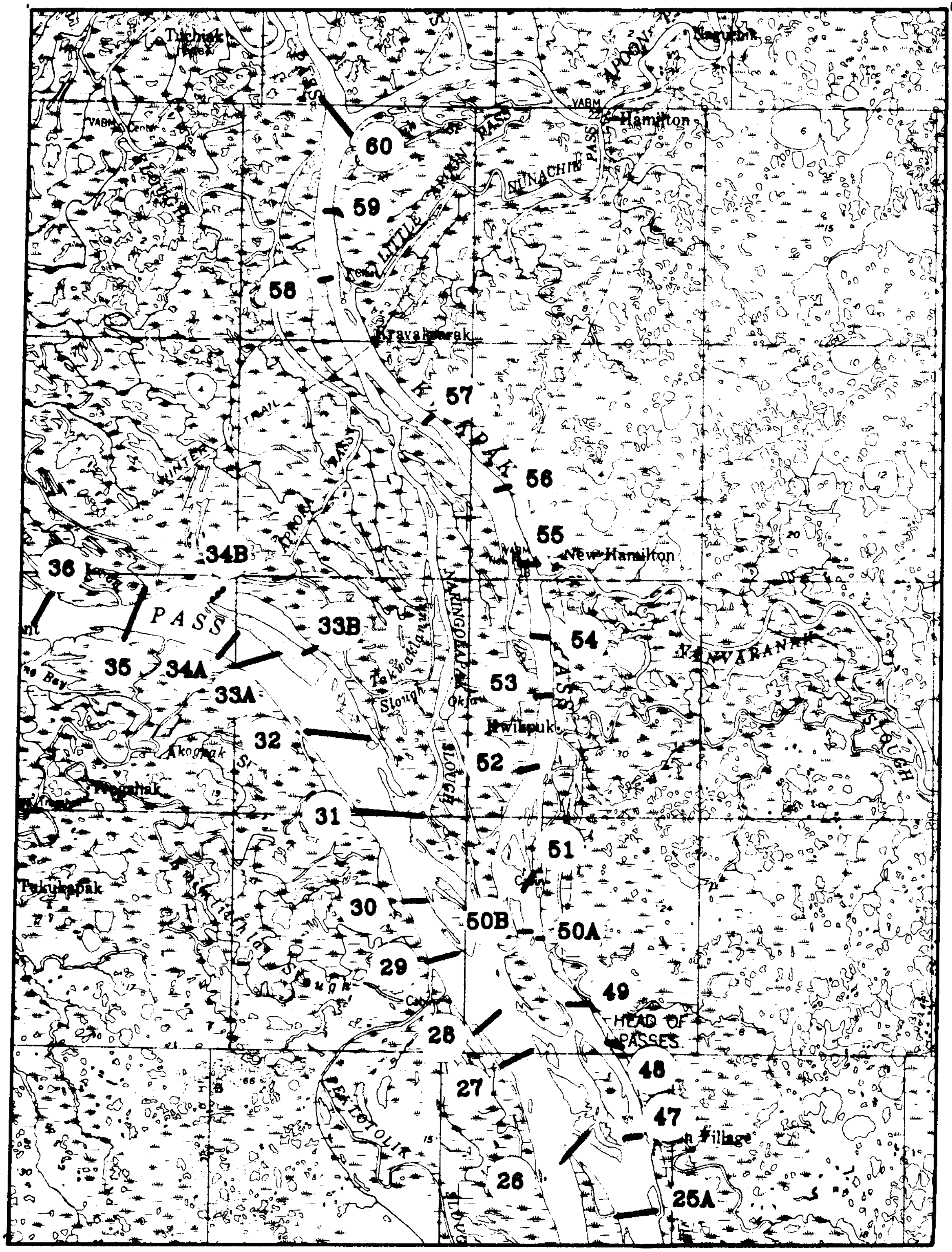


Figure 3-2. Location of bathymetric transects (47 to 60) surveyed in Kwikpak Pass during the fifth Yukon field trip in August 1986. Transect numbers are provided for reference to other figures and tables.

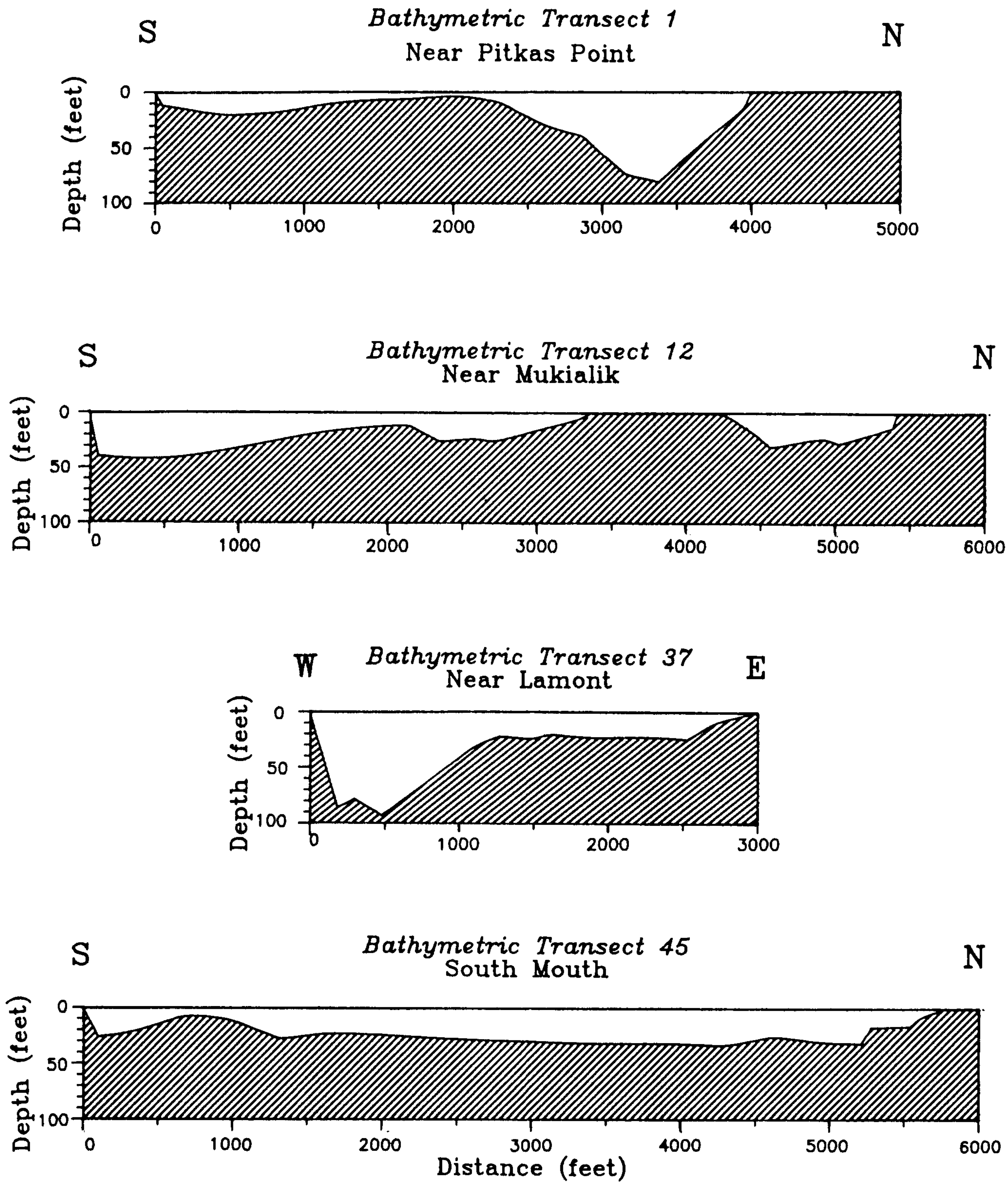


Figure 3-3. Bathymetric transects at four locations along the Yukon River between Pitkas Point and the mouth of Kwikluak Pass. Transect locations are shown in Figures 3-1a to 3-1c. Transects are presented looking downstream.

bar. The two-channel characteristics of these two transects were observed at many locations along the survey region.

Transect number 37, located near Lamont, revealed a 93-foot channel adjacent to the left bank. Depths decreased rather sharply with distance across the river, and a large bar was encountered roughly 1/2 mile from the left bank. No secondary channel existed at this transect location.

Transect number 45, located near the mouth of Kwikluak Pass, exhibited navigable waters over a river width of more than 1 mile, but the maximum channel depth was only 34 feet (10 m). Note, however, that adjacent transects at South Mouth were much narrower and exhibited deep channels on opposite sides of the river.

Although there is much topographic variability between river transects, it is possible to categorize each into one of five bathymetric profile types. Figure 3-4 presents schematic diagrams of five types of channel profiles; water depth and transect length are secondary factors. Profile type 1 is characterized by two channels separated by a middle shoal. The channels may have equivalent depths, but in most cases, one channel is considerably deeper than the other. Type 2 also has two channels, but they are separated by an island or exposed bar.

Profile types 3 and 4 are characterized by a single, deep channel adjacent to one bank. They differ only by the relative width of the deep channel. Type 5 represents transects where a broad, relatively flat channel extended across the entire length of the transect. These five profile types are used in Table 3-1 to characterize each of the 46 transects from Pitkas Point to South Mouth. Also given in this table are the length of each transect, the maximum depth of pronounced channel(s), and for type 1 profiles, the minimum shoal depth between channels. The existence of a bar or island is noted for type 2 profiles. Distances from the position of maximum channel depth to the

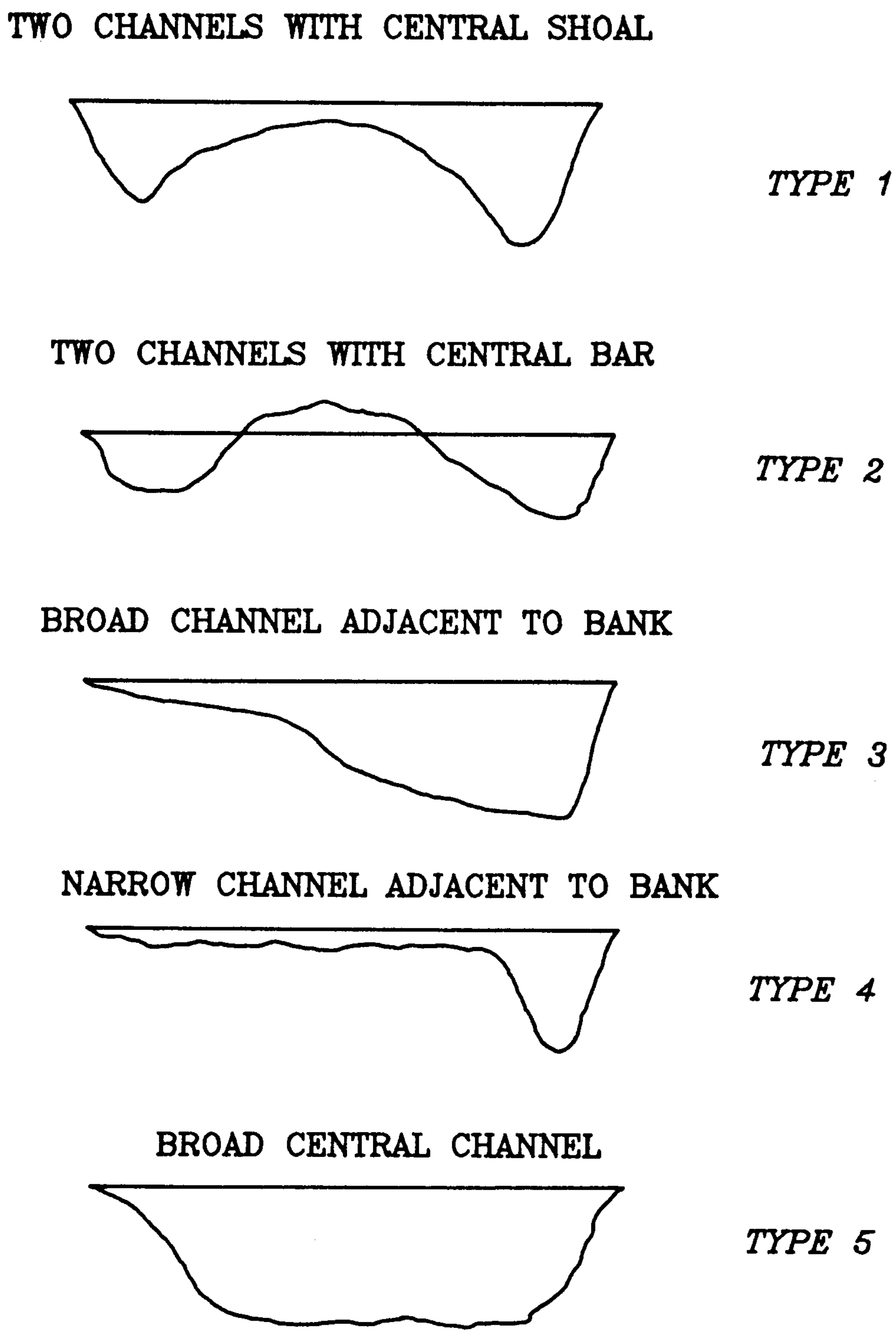


Figure 3-4. Typical profile types for bathymetric transects across the lower Yukon.

Table 3-1. Summary of bathymetric characteristics for transects surveyed between Pitkas Point (transect 1) and South Mouth (transect 46) during July 1985. Transect locations are shown in Figures 3-1a through 3-1c; profile types are illustrated in Figure 3-4. Transect lengths and distances to the river bank refer to the ends of the navigable transects (depth <2 feet) rather than the actual river banks.

			Left Channel			Right Channel	
Transect	Length (ft)	Profile Type	Max Depth (ft)	Dist. to Bank (ft)	Min Shoal Depth (ft)	Max Depth (ft)	Dist. to Bank (ft)
1	4,002	1	21	475	3	81	625
2	3,831	1	15	325	8	45	575
3	7,227	1	28	1,275	10	33	375
4	6,080	1	39	1,750	5	61	730
5	6,683	1	36	500	5	51	805
6	6,688	1	65	150	9	20	105
7	6,981	1	34	1,075	12	58	605
8	4,984	1	32	175	3	53	1,280
9	3,370	1	13	195	5	62	1,425
10	4,914	5				43	2,000
11	5,976	1	50	200	5	15	1,325
12	5,417	2	43	304	Bar	31	854
13	3,355	2	49	608	Island		
13B	3,100					28	489
14	2,492	5				67	870
15	3,526	3	58	1,050			
16	5,229	5	35	2,775			
17	5,107	5				28	395
18	8,511	2	41	601	Bar	34	431
19	8,451	1	40	200	9	41	1,125
20	2,004	5				38	835
21	1,946	5	45	710			
22	6,080	5	31	3,040			
23	2,614	2	45	1,442	Island		
23B	5,222					25	556
24	4,073	2	63	3,917	Island		

Table 3-1. Continued

Transect	Length (ft)	Profile Type	Left Channel Max Depth (ft)	Left Channel Dist. to Bank (ft)	Min Shoal Depth (ft)	Right Channel Max Depth (ft)	Right Channel Dist. to Bank (ft)
24B	1,701					52	1,550
25	5,411	2	34	666	Island		
25B	2,983					19	583
26	4,925	1	54	1,180	9	40	1,775
27	4,370	1	32	1,330	13	39	530
28	5,404	1	26	125	19	37	2,850
29	5,046	5	31	775			
30	4,312	3	40	670			
31	8,454	1	35	3,425	11	39	540
32	8,502	1	40	3,924	7	20	1,526
33	11,665	2	39	3,604	Island	15	433
34	9,437	2	33	3,886	Island	23	877
35	7,216	1	34	330	5	42	1,220
36	5,280	3				47	1,865
37	2,976	4	93	480			
38	3,101	4				97	350
39	2,553	5				50	420
40	3,400	5				56	600
41	2,800	5	49	680			
42	4,322	3				35	1,910
43	3,339	3	27	210			
44	3,412	3				51	370
45	5,775	1	26	100	7	34	1,485
46	3,704	3	72	925			

nearest end of the navigable transect are given for profile types 1 through 4.

Excluding transects of type 2 (having central bars or islands), the average length of transects was roughly 4,800 feet. This is significantly less than the average distance from bank to bank (5,400 feet) which is obtained from measurement of the existing topographic maps. This difference can be attributed to the wide shoals that lie adjacent to the river banks; at many of the transect locations, a broad shoal lies on one side of the river while a deep channel is found on the other side. This balance of erosion on one side and deposition on the other represents the mechanism for creation of river meanders, and the delta formation.

Table 3-1 indicates that the greatest water depth can lie on either side of the river, and, in fact, it often alternates from side to side in downstream distances of less than 2 miles. For transects between Pitkas Point and South Mouth, the average of the maximum transect depths was 49 feet (14.9 m); the minimum and maximum depths of the deepest channel were 27 (8.2 m) and 97 feet (29.6 m), respectively.

Secondary channels were observed at 26 of the 46 transects; 40 feet (12.2 m) was the maximum depth observed within any of the secondary channels.

The tendency for deep channels to lie adjacent to the river bank is exemplified by the relatively short distances from the maximum channel depth to the end of the navigable transect. Table 3-1 indicates that channel depths greater than 50 feet (15.2 m) are often observed within 800 feet of the river bank. Where these horizontal distances are small, there is always a cut bank. The most extreme case is at transect 38 (near Kwiguk Pass, the entrance to Emmonak), where a depth of 97 feet (29.6 m) was observed at a distance of 350 feet from the cut bank. This corresponds to an average bottom slope of 15°. Bottom slopes approaching 45^{o} are not uncommon over short distances next to active cut banks; 30-foot (9 m) depths were often observed within a few tens of feet from cut banks.

Table 3-2 summarizes the number of transects of each characteristic profile type. From Pitkas Point to South Mouth, 18 of 46 transects (39%) were of type 1, having two distinct channels with a middle shoal. Another eight had two channels, but were separated by an island or bar. Thus, more than half of all river transects had two channels. Roughly another quarter of the transects had a single broad channel (type 5) which extended across the entire transect. The remaining nine transects had a single channel adjacent to one bank (types 3 and 4).

To graphically illustrate the complex nature of the erosional channels within the lower Yukon, it is necessary to look at a downstream sequence of bathymetric profiles. Figure 3-5 has been constructed to illustrate river width, expressed as the distance to either side of the river axis, as well as the contoured depth along the river. The Pitkas Point transect lies at the bottom and South Mouth is at the top, such that downstream river flow would be directed upward on the page. This type of presentation effectively removes the meandering of the river, while emphasizing variations in the width and depth of the river.

The width of the river varies considerably, as seen by the constrictions of less than 3,000 feet (transects 14, 21 and 37 to 41) and broad areas with central islands and bars (transects 23 to 25 and 31 to 35) having overall widths in excess of 8,000 feet. In simple terms, mid-river islands and bars exist only where the river is wide.

The most interesting characteristic of Figure 3-5 is the spatial coherence of the erosional channels. Despite the downstream variability, the channels can be contoured with a high degree of confidence. In general, where the river is wide,

Table 3-2. Summary of bathymetric profile types surveyed along the lower Yukon River and Kwikluak Pass (transects 1 to 46 from July 1985), and in Kwikpak Pass (transects 47 to 60 from August 1986). Figure 3-4 illustrates each profile type.

Profile Type	Characteristics	Yukon River and Kwikluak Pass	Kwikpak Pass
1	Two channels with middle shoal	18	6
2	Two channels with bar or island	8	1
3	Single broad channel adjacent to either bank	7	3
4	Single narrow channel adjacent to either bank	2	0
5	Single broad channel	11	4
	Total transects:	46	14

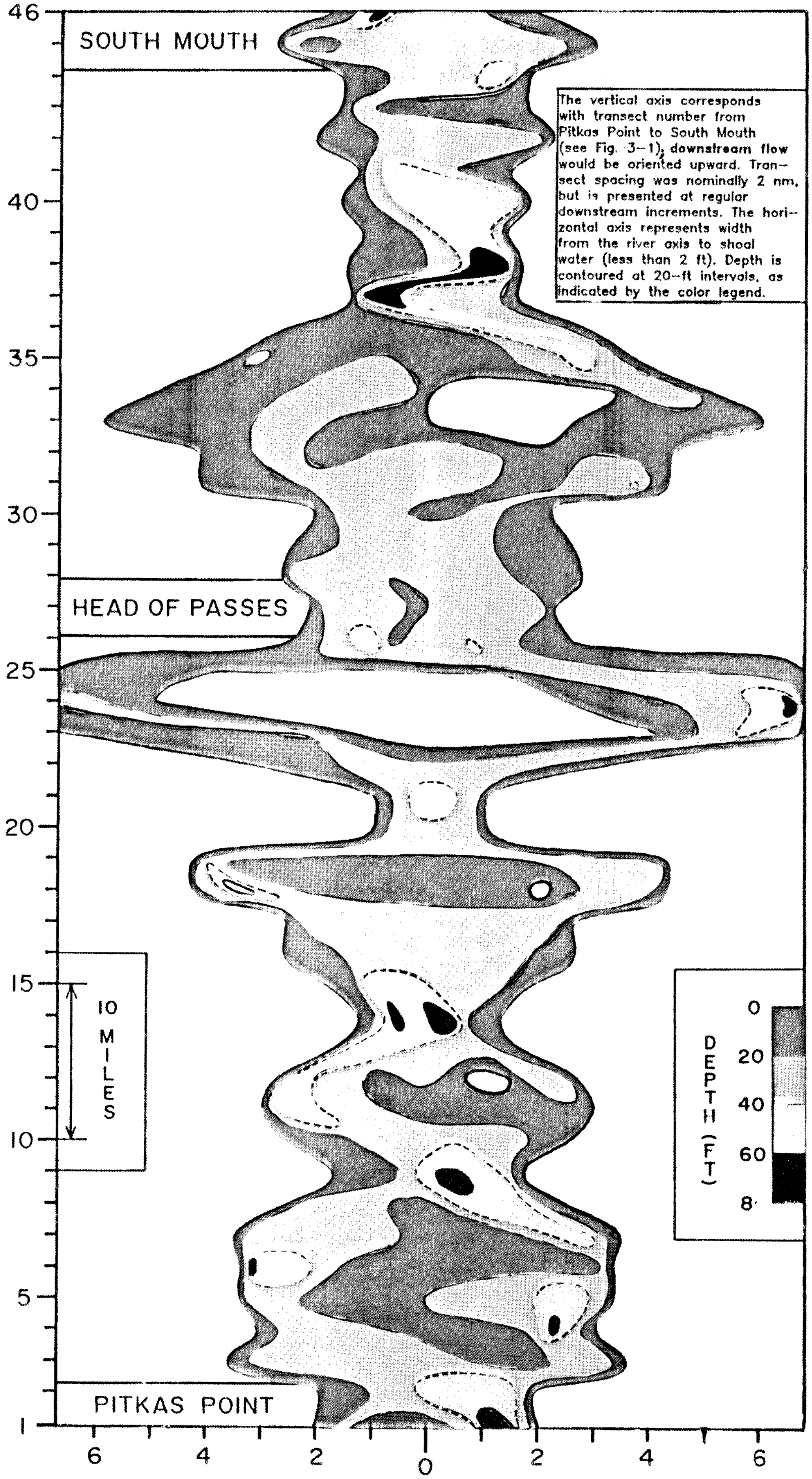


Figure 3-5. Composite of bathymetric transects from the lower Yukon River.

channels are found on each side of the river. When the river narrows, the two channels often meet, and a single channel passes through the constricted region. The 40-foot depth contour is the best indicator of deep channel, and 30 of the 46 transects have water of this depth or greater. Water depths greater than 60 feet exist at nine of the transects, and depths exceeding 80 feet were seen at only three locations. The deepest channel within the entire survey region passed through transects 37 and 38, in the vicinity of Kwiguk Pass, which is the main entrance to Emmonak. The river meanders sharply in this area, and the deep channel traverses from bank to bank over a downstream distance of less than 2 miles.

It is interesting to note that the 97-foot channel axis at transect 38 lies where there was delta highground at the time of the topographic surveys. Navigation errors were suspected as the cause of this discrepancy, but this was ruled out because the site is now the main entrance to Kwiguk Pass. This is clear proof that the cut bank had migrated many hundreds of feet to the north during the past three decades.

3.1.3 Kwikpak Pass

In addition to the bathymetric survey of Kwikluak Pass, 14 bathymetric transects were surveyed in Kwikpak Pass during August 1986. This survey region extended northward from Head of Passes to the branch where Kawanak and Apoon Passes begin. Positions of each transect are shown in Figure 3-2.

In general, bathymetric characteristics within Kwikpak Pass were similar to those observed in the lower Yukon and Kwikluak Pass. Table 3-3 presents the length, profile type and depth characteristics of each of the 14 transects in Kwikpak Pass. In general, Kwikpak Pass was about half the width of Kwikluak Pass; excluding transect 60, which crossed Kawanak and Apoon Passes,

Table 3-3. Summary of bathymetric characteristics for transects surveyed between Head of Passes (transect 47) and the north end of Kwikpak Pass (transect 60) during August 1986. Transect locations are shown in Figure 3-2; profile types are illustrated in Figure 3-4. Transect lengths and distances to the river bank refer to the ends of the navigable transects (depth <2 feet) rather than the actual river banks.

			Left Channel		Min	Right Channel	
Transect	Length (ft)	Profile Type	Max Depth (ft)	Dist. to Bank (ft)	Shoal Depth (ft)	Max Depth (ft)	Dist. to Bank (ft)
47	2,720	5				19	780
48	1,405	3				36	155
49	3,205	1	28	162	4	14	139
50	3,830	2	28	1,555	Bar	42	355
51	2,160	5				37	790
52	2,300	3	40	412			
53	2,080	1	18	294	4	61	142
54	1,920	5				38	890
55	2,355	1	28	318	18	30	304
56	1,752	3				52	180
57	1,960	1	46	210	20	29	314
58	1,870	5				40	490
59	2,250	1	48	160	10	22	88
60	6,080	1	38	550	12	36	400

the average transect length in Kwikpak Pass was 2,300 feet compared to 4,800 feet in Kwikluak Pass. Similarly, Kwikpak was shallower than Kwikluak Pass; the average of the maximum transect depths was 40 feet (12.2 m); the minimum and maximum depths of the deepest channel were 19 (5.8 m) and 61 feet (18.6 m), respectively. Secondary channels existed at seven of the 14 transects, with the deepest being 36 feet.

Table 3-3 illustrates that the profile types in Kwikpak Pass are similar to those found in Kwikluak Pass. This comparison is shown in Table 3-2, which indicates that profile type 1, having two channels with a central shoal, is the most common structure. Only one transect contained a bar (profile type 2). Types 3 and 5, having a single channel either adjacent to the bank or in the center of the river, make up the remainder. Although the bathymetric surveys did not extend into the passes leading to North and Middle Mouths, we suspect these passes are generally too narrow to possess two channels (profile types 1 and 2). Only in parts of Kawanak Pass that are wider than 2,000 feet would we expect two channels.

3.2 MOORED CURRENT MEASUREMENTS

One of the primary objectives of the Yukon Delta measurement program was to obtain time series records of river currents in conjunction with offshore current measurements from various sites around the Delta. Prior to the measurement program, it was recognized that the study region comprised three characteristically different flow regimes: first, an upstream region where flow is strictly hydraulic, and tides or other oceanic processes are absent; second, a dynamically rich region at the mouths of the major distributaries, where river flow is dominant during the open-water season, but oceanic processes can affect the flow characteristics; and third, the nearshore regions around the Delta which can be affected by oceanic processes and/or river discharge, the balance between these processes varying with distance offshore.

This regional characterization is, however, greatly oversimplified because temporal variations in Yukon River flow have a major effect upon the dynamics at the river mouths and in the nearshore regions. For example, when river discharge drops rapidly in autumn, salt water can be expected to penetrate into the river mouths and the flow, which was primarily governed by river discharge, becomes increasingly controlled by tides and other oceanic processes. Likewise in the nearshore regions, the shallow flats surrounding the Delta are covered by river water in summer, but later in the year, salt water is likely to be ubiquitous and oceanic processes are dominant.

The complexity of the flow regime around the Yukon Delta can also be attributed to the large differences in flow among the three major distributaries. As will be shown in subsection 3.4, Kwikluak Pass discharges roughly two-thirds of the Yukon flow from South Mouth, whereas the discharge from North Mouth is less by a factor of eight. Thus, for a given Yukon flow rate, there is no doubt that the dynamics within South Mouth are much different from those at North Mouth, where oceanic processes will, relatively speaking, have a much greater effect upon the local dynamics.

In light of these spatial and temporal factors, one recognizes the difficulty in attempting to monitor the flow regime around the entire Delta region using the limited resources (three or four current moorings) that were allocated to the present program. Our approach was to dedicate at least one mooring to upstream flow measurements, while the remaining moorings were placed in the mouth of one or more of the major distributaries. Offshore measurements were planned for all deployment periods, but sea conditions prevented offshore work on all but the first deployment.

Results from the moored current measurements are presented in the following three subsections, corresponding to the major flow regimes of the Delta. In the absence of any prior current measurements from this area, much information has been gained from this program, but longer deployment periods and additional offshore measurements are highly recommended (Section 5). This program also proved that Eulerian current measurements can be made in the lower Yukon if strong hardware is used on subsurface moorings; all instruments were recovered from the 11 moorings deployed during the program. NBIS acoustic current meters, which have no moving parts, proved to be the most reliable for use in the river. Aanderaa current meters deployed in the river mouth became jammed with organic matter shortly after deployment. These and other field experiences will be helpful for future measurement programs in this region.

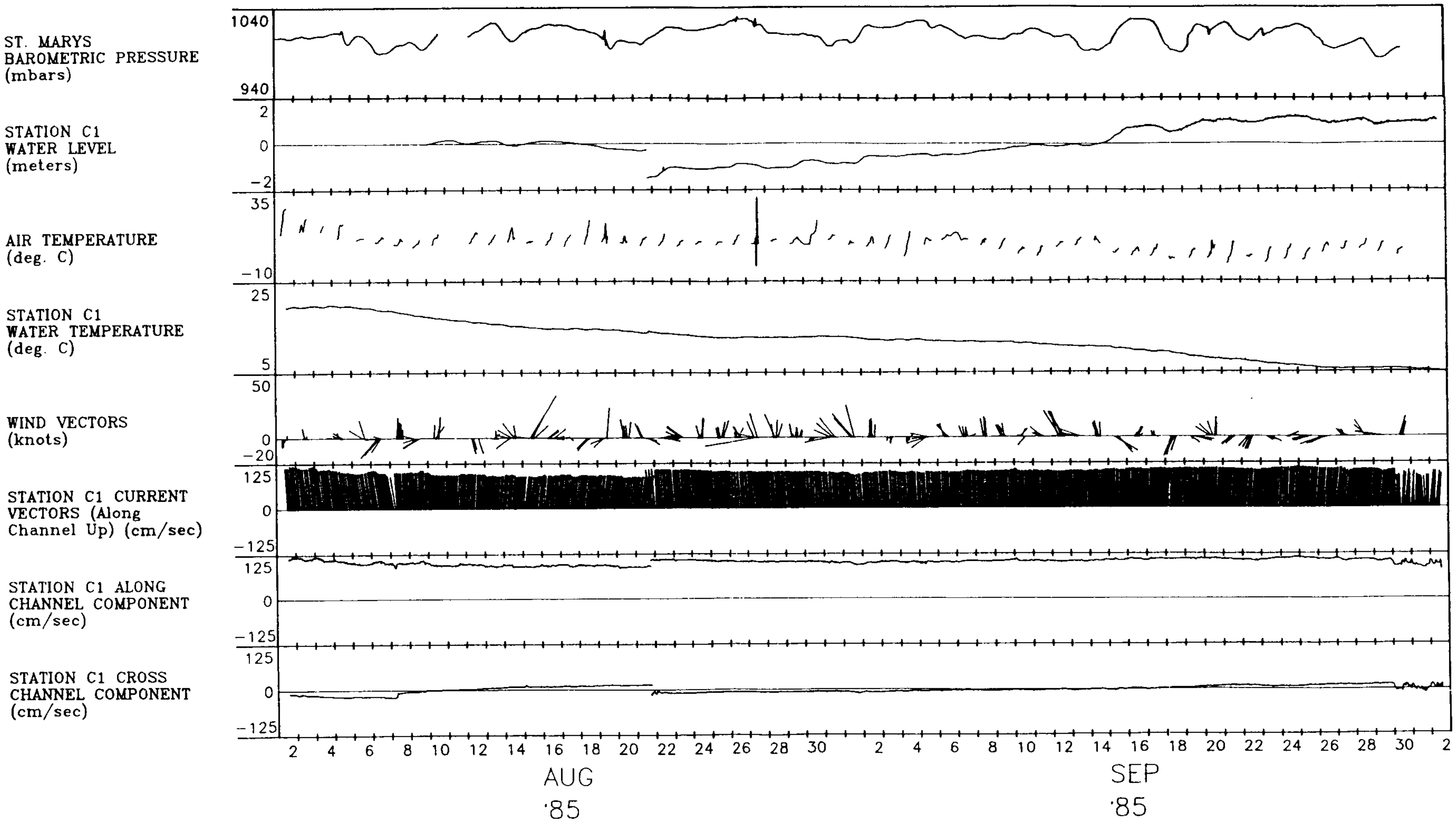
3.2.1 Upstream Measurements

Kobolunuk, located 11 miles downstream of Pitkas Point, was chosen as the site for upstream current measurements throughout the Yukon Delta measurement program. This site (see Figure 2-3) proved adequate because it was far enough downstream of the Andreafsky River influx that the Yukon flow was free of disturbances as it approached the Delta region. A current meter mooring was deployed in the northern channel at Kobolunuk for both deployment periods in 1985 and during the single deployment in 1986. An additional mooring was placed in the southern channel at Kobolunuk during the 1986 deployment (see Figure 2-4) to resolve the partition of flow between the two major erosional channels.

The northern channel mooring at Kobolunuk included a water-level recorder for all three deployment periods. Instrument problems at the beginning of the first deployment resulted in 7 days of lost data, but good water-level records were obtained for the remainder of the program. The water-level time series is discussed in subsection 3.3.

Figure 3-6 presents a composite time series plot of moored measurements from Kobolunuk and concurrent meteorological measurements from the airport at St. Marys during the 1985 field measurement program. Although the meteorological measurements were taken at 364 feet above sea level, the airport is located within 6 miles of the mooring, and the observations are believed to be representative of Kobolunuk. As discussed in subsection 3.6, the St. Marys meteorological data are not continuous because observations are made manually and only during hours of aircraft traffic.

Figure 3-6 also presents time series records of water level, water temperature, and currents from the Kobolunuk site. Current data are shown as along-channel current vectors and as individual along- and cross-channel current components. The along-channel current direction was determined from vector averages of data from the individual deployments: 306°T and 318°T for the two deployments, respectively.



Composite time series plot of meteorological data from St. Marys and oceanographic data from mooring C-1 near Kobolunuk for the period 2 August through 2 October 1985. Equipment servicing and redeployment was performed on 21 August. Wind vectors are plotted according to the meteorological convention.

Figure 3-6.

Inspection of Figure 3-6 reveals that, upstream in the Yukon River, currents are very steady and characterized by a highly polarized along-channel flow; the average along-channel and cross-channel current components and their standard deviations during the 1985 deployment period were 103.9 and 5.0 cm/sec and 0.2 and 6.5 cm/sec, respectively. The abrupt changes in current speed and direction on 21 August were associated with mooring recovery, servicing, and redeployment. The abrupt speed increase of about 20% (from 90 to 110 cm/sec) and counterclockwise directional rotation of 20° was a result of mooring relocation and changes in sensor depths. Mooring C-1 was first deployed in 18 m of water with the current sensor at 12 m. During the second 1985 deployment, mooring C-1 was placed in water 16 m deep (approximately 130 m westward of the first deployment location) with the current sensor at 9 m. Since the river is characterized by strong vertical and horizontal current shear, and large variations in bottom topography over distances of 100 m, this change in sensor depth and mooring location was, undoubtedly, the cause of the abrupt change on 21 August.

Near the end of the record (29 September), currents became more variable in both along-channel and cross-channel components. These high-frequency fluctuations may have been a result of obstructed flow near the acoustic current sensors of the ACM-2 caused by river debris.

Figure 3-6 also illustrates that water temperatures decreased monotonically from 20°C at the beginning of August to about 5°C on 2 October. This smooth decrease is related to large-scale seasonal cooling of the Alaska region, as supported by the gradual trend of decreasing air temperatures observed at St. Marys. It is interesting to note that, at any time during the 1985 measurement program, the Yukon River water was significantly colder than the local average daily air temperature (~26°C in early August, and 18°C in late September). This large difference indicates that Yukon River temperatures are mainly controlled by the distant, upstream characteristics of the tributaries and high-elevation runoff which contribute to the Yukon. Local convective heating and insolation in the vicinity of the Delta is insufficient to raise the river water to air temperature levels because, at 100 cm/sec flow speeds, a water parcel can transit the entire Delta region (roughly 100 miles) in less than 2 days.

As indicated in Figure 3-6, the river level remained relatively constant from the beginning of the record (2 August 1985) until the mooring turnaround on 21 August. From the date of the turnaround until 24 September, however, the water-level at Kobolunuk rose 2.8 m. Climatologically, this rise in water level is sometimes observed in late summer and early fall, and in 1985, was apparently related to the high rainfall which occurred during the measurement period. The profiling transects conducted at Kobolunuk (see subsection 3.4) indicated a 43% increase in river discharge from 22 August (9,200 m^3/sec) through 1 October (13,120 m^3/sec), concurrent with the observed rise in water level. A detailed discussion of the upstream water-level measurements, and a comparison with concurrent measurements taken by USGS, is presented in subsection 3.3.

Figure 3-7 presents a composite of time series records obtained from two moorings deployed near Kobolunuk during the 1986 field measurement program. During this period, one mooring (C-1N) was placed in the northern channel, near the site of the 1985 deployment, and a second mooring (C-1S) was deployed near the axis of the southern channel. While there was no significant change in the along-channel current component in the north channel (C-1N) from the beginning of the deployment until 24 July, there was a significant reduction in the south channel current (C-1S), which began on 4 June.

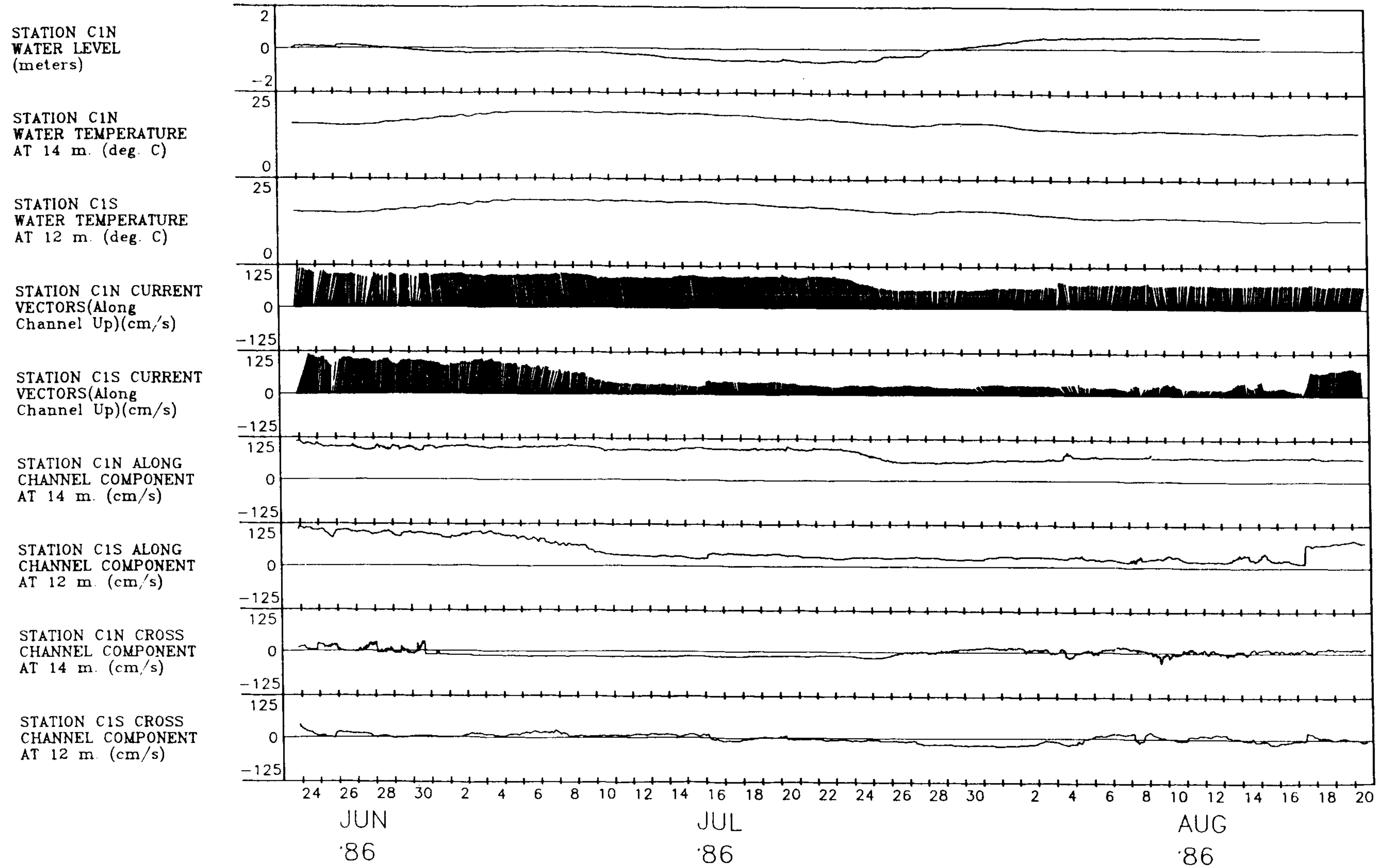


Figure 3-7.

Composite time series plot of oceanographic data from moorings C-1N and C-1S near Kobolunuk for the period 23 June through 20 August 1986.

Figure 3-7 also exhibits a 0.6 m decrease in water level on mooring C-1N from the beginning of the deployment (23 June) until 24 July, concurrent with the significant reduction of the current observed in the south channel. During the period from 25 July through the end of the deployment (20 August), the river level at Kobolunuk rose 1.1 m, but the current remained relatively weak in the south channel until an abrupt increase was experienced on 17 August. Instrument problems were suspected as being the cause of this discontinuity, but, upon recovery, the instrument was found in good working order. Although we cannot be sure, it is likely that some river debris had collected on the current meter and caused low readings until it washed clear of the instrument. Unfortunately, there is no way to determine how early in the deployment the current meter began to record erroneous speeds. Inspection of the along-channel and cross-channel speed records from mooring C-1S does not reveal any abrupt change in the character of the time series that may suggest the time when debris was first introduced. Velocity profiling conducted near moorings C-1N and C-1S on 12 August did, however, confirm that the current meter at C-1S was providing low speeds while the meter in the north channel agreed with the profiling current meter.

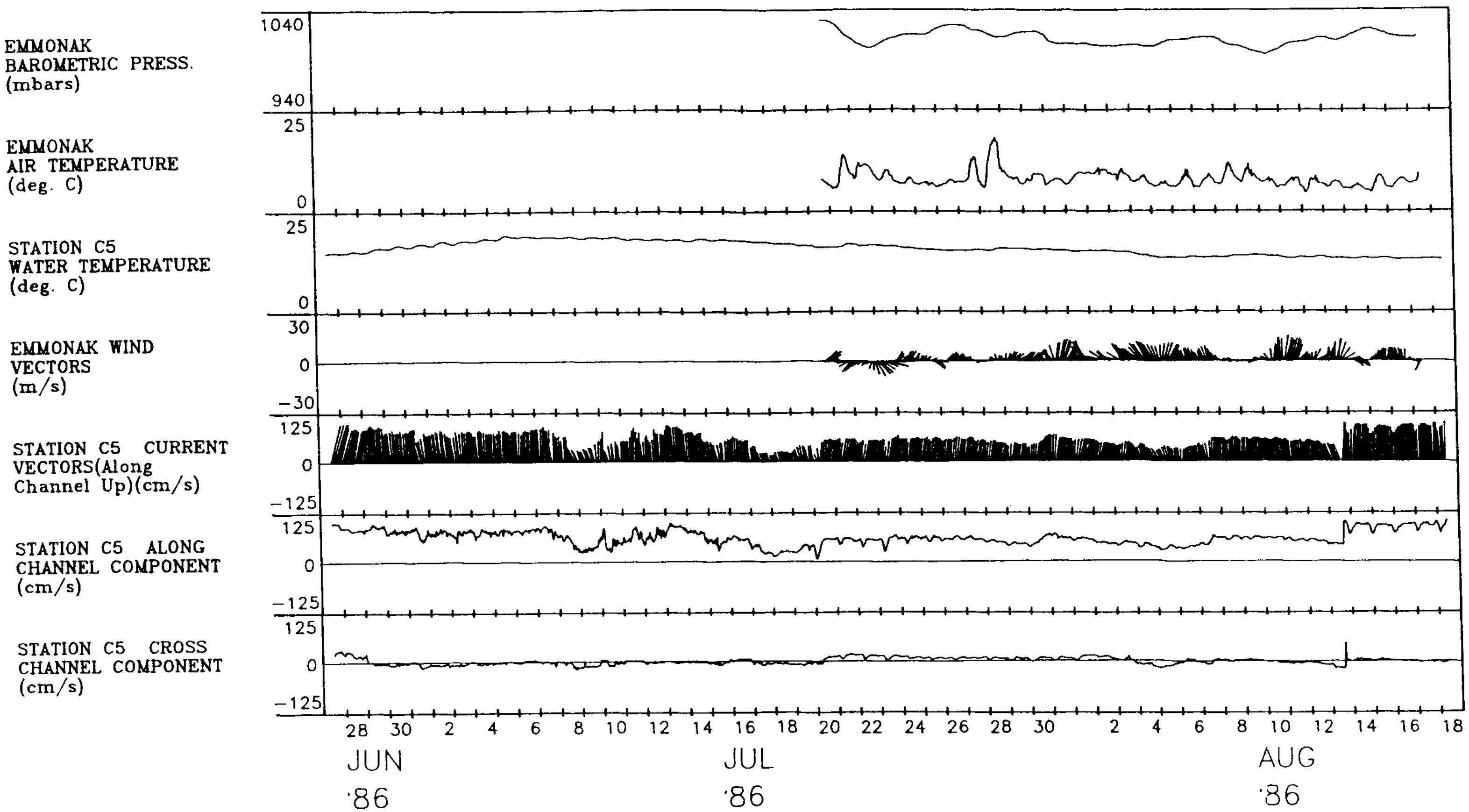
Figure 3-7 illustrates a 47% reduction (97 cm/sec to 51 cm/sec) in the north channel current from 23 through 26 July. Considering that the profiling surveys and resulting discharge calculations exhibited no significant change between June and August 1986 in the north channel, the reduction in current speed indicated by mooring C-1N is surprising. The reduction may be attributed to sensor fouling or a cross-channel translation of the velocity field placing the sensor within a less intense region of the flow. The latter explanation seems more plausible, since the current profiling data obtained at Kobolunuk during the fourth (27 June) and fifth (12 August) field trips are in good agreement with the moored current records from the north channel.

Water temperature records from moorings C-1N and C-1S appear identical, exhibiting a gradual increase from the beginning of the 1986 deployment through about 6 July when maximum temperatures near 19°C were observed at both sites. From mid-July until the end of the deployment (20 August) water temperatures decreased gradually. Although the average water temperature during the 1986 deployment period at site C-1N (16.02°C) was about 0.4°C warmer than the average at C-1S (15.59°C), we suspect most of this difference is due to absolute calibration differences between instruments, rather than horizontal or vertical temperature gradients within the river. This is further supported by the result that maximum and minimum temperatures at C-1N exceeded those at C-1S by 0.54°C and 0.32°C, respectively, suggesting a consistent calibration offset between instruments.

River water temperatures at the beginning of the 1985 deployment (2 August) were roughly 20°C compared to 15°C on the same day in 1986. By 20 August, however, comparison of the water temperatures from year to year showed agreement to within 1°C.

During the 1986 field program, an additional upstream mooring was deployed in Kwikluak Pass near Lamont, a distance of 2-1/2 miles upstream of the entrance to Kwiguk Pass, which leads to Emmonak. Figure 3-8 presents a composite of time series records from the Lamont mooring (C-5) and meteorological data collected by a remote station deployed in Emmonak by EG&G. The meteorological station was located approximately 8 miles to the west-northwest of the mooring and should be representative of the conditions at the mooring site.

The current data presented in Figure 3-8 reveal the highly polarized flow field that was observed farther upstream at Kobolunuk, but the record from Lamont exhibits a great deal more variability in the along-channel velocity component. Major velocity fluctuations are observed on 8 and 17 July, followed by a period of relatively constant velocities until an abrupt increase



Composite time series plot of meteorological data from Emmonak (20 July through 17 August 1986) and oceanographic data from mooring C-5 near Lamont (27 June through 18 August 1986). Wind vectors are plotted according to the meteorological convention.

Figure 3-8.

on 13 August. Cross-channel current veering cannot be the cause of this since the cross-channel velocity component was relatively constant throughout the record. It is interesting to note that these fluctuations occurred when the northernmost mooring at Kobolunuk exhibited little variability. One might first hypothesize that there exists a complex two-channel flow system at Lamont, but this is not the case; the mooring was placed in the axis of the single, 60-foot channel that exists at this location.

The abrupt speed increase that was observed on 13 August is most likely related to removal of debris around the moored velocity sensor. This again raises the question of when the sensors became obstructed, and at what point in the record do the data become suspect. Note that this jump occurred 4 days prior to the similar velocity discontinuity that was observed at mooring C-1S, thus precluding the possiblity of an actual increase in river flow that would have had to originate upstream.

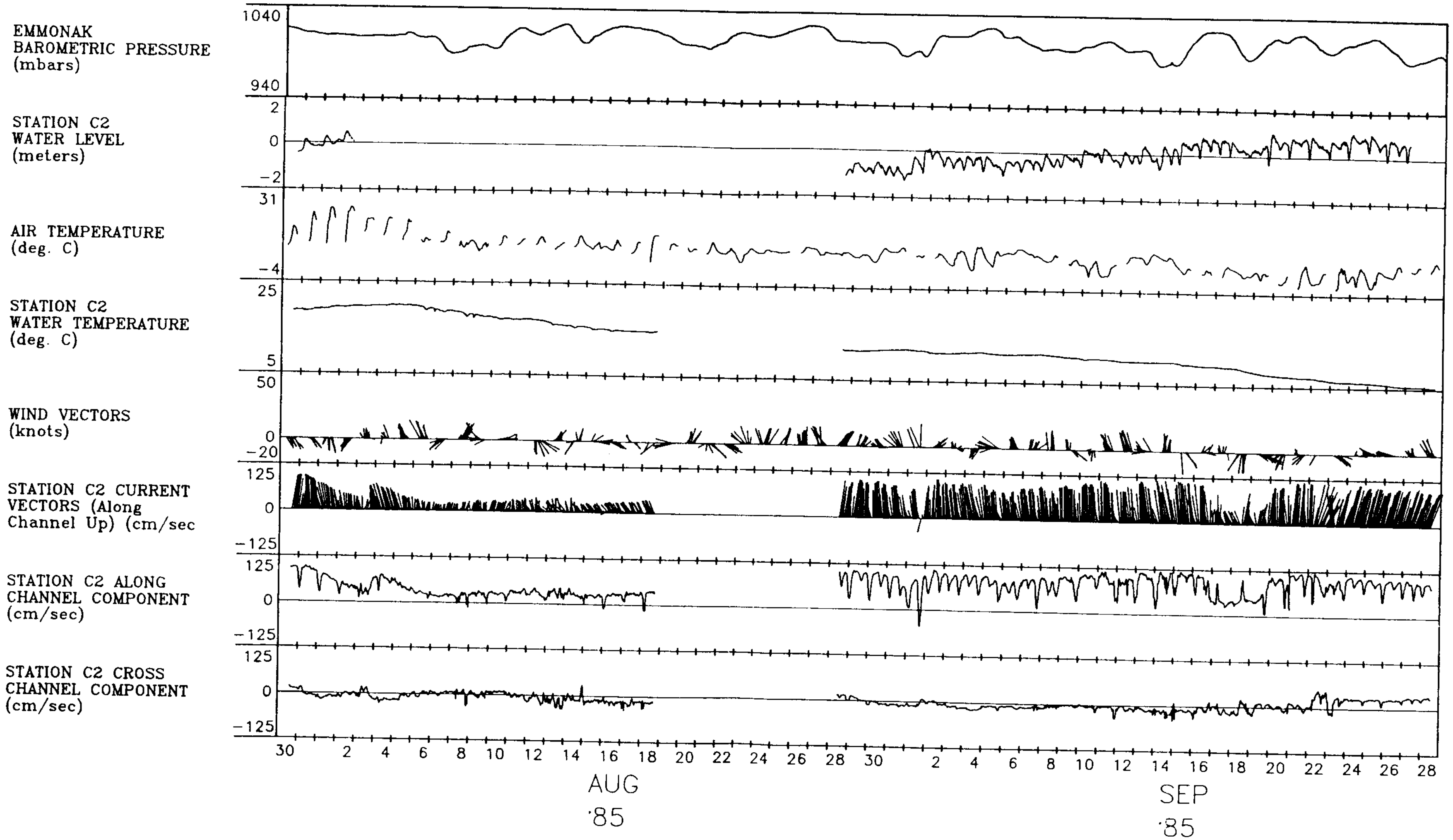
After 13 August, the Lamont current record remains relatively constant near 90 cm/sec, with the exception of a noticeable diurnal speed reduction in the along-channel component that persists over the last 5 days of the record. This is qualitatively similar to the diurnal fluctuations that can be seen from 20 through 23 July. The rapid drop in barometric pressure at Emmonak on 21 July indicates the passage of an extra-tropical storm, which may have caused the diurnal fluctuations in river flow. Coincident with the passage of this atmospheric low, large diurnal air temperature fluctuations were evident, as well as a sudden wind shift from northeastward to southwestward winds. (Wind vectors in Figure 3-8 are plotted in the oceanographic convention to indicate the direction toward which the wind is blowing.) Curiously, southward winds were not observed at Emmonak until 14 August when diurnal river fluctuations were again observed. Further analysis will be required to determine whether these fluctuations are truly a function of the local wind field, and why they were not observed in simultaneous records from Kobolunuk.

3.2.2 River Mouth Measurements

Current meters and water-level (pressure) recorders were deployed in the mouths of the three major distributaries, but limited hardware resources prohibited simultaneous measurements from all three distributary mouths and the upstream site. The deployment strategy was to occupy each distributary mouth during at least one of the three deployment periods (two in 1985 and one in 1986). Deployment dates and instrument depths are presented in subsection 2.3. In summary, mooring C-2 was deployed in South Mouth during both deployments of 1985 (late July through September); mooring C-4B was deployed in Middle Mouth during the second deployment of 1985 (late August through September); and mooring C-4C was deployed in North Mouth from late June through the middle of August 1986.

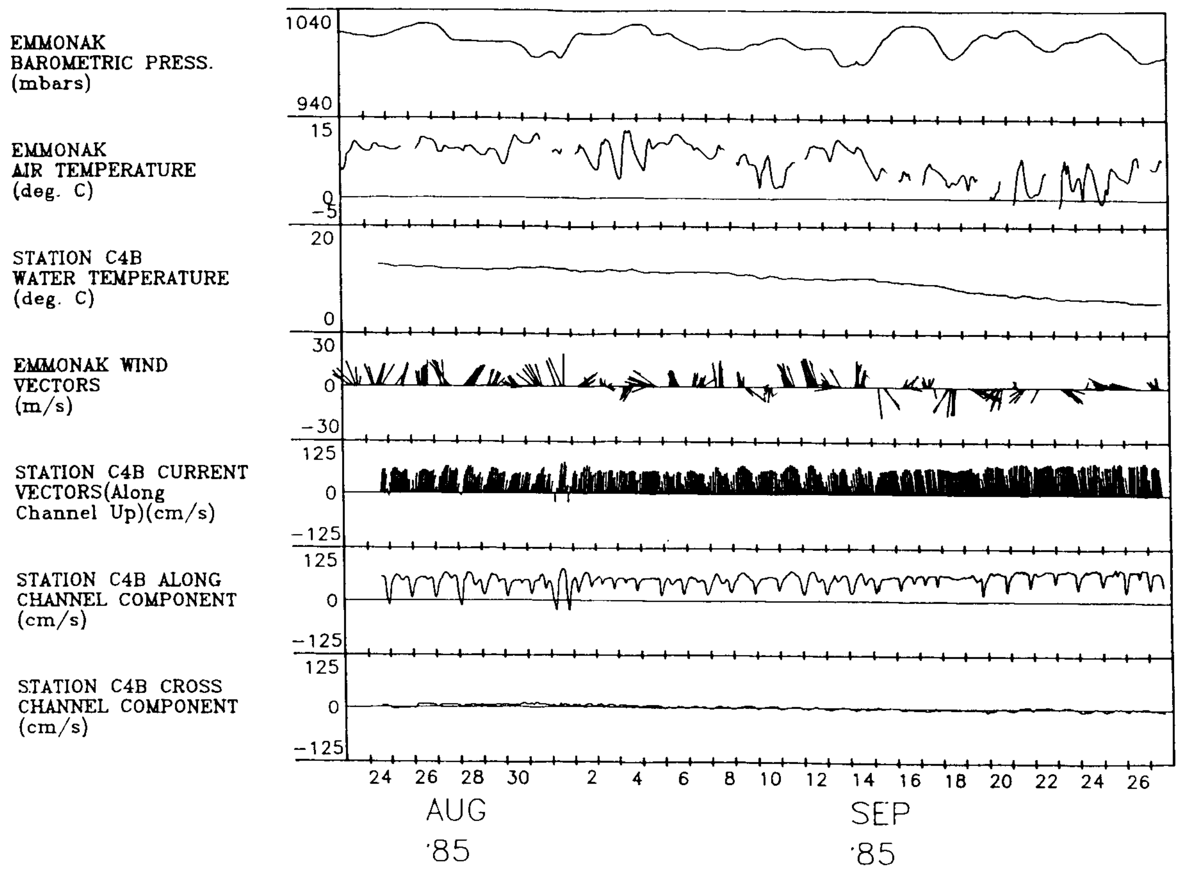
Figures 3-9 through 3-11 present composite time series plots of meteorological data obtained at Emmonak and Kotlik, and current meter data obtained from moorings deployed in the South, Middle, and North Mouths. Each plot presents time series of barometric pressure, water level, air temperature, water temperature, wind vectors, current vectors, and along-channel and cross-channel current components. The water-level record is absent from Figure 3-10 because no water-level recorder was deployed on the current mooring (C-4B) in Middle Mouth.

Moored data from stations C-2 and C-4B, obtained during summmer 1985, are accompanied by meteorological data that were collected by NWS observers in Emmonak (see subsection 2.3 for a discussion of gaps in the meteorological data). Moored data collected in North Mouth (station C-4C) during summer 1986 are concurrent with meteorological data collected by EG&G using a remote station installed near Kotlik.



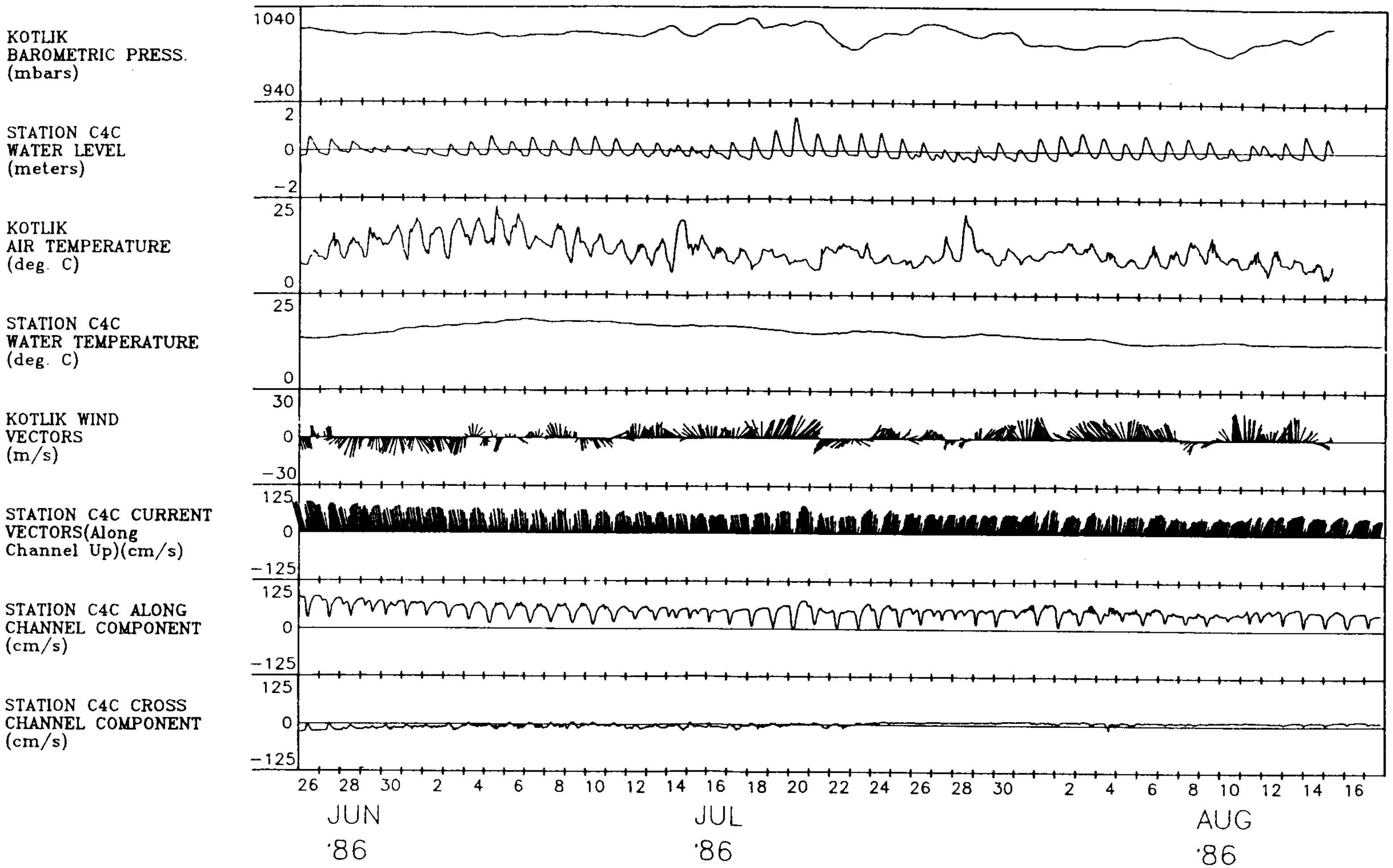
Composite time series plot of meteorological data from Emmonak and oceanographic data from mooring C-2 near South Mouth for the period 30 July through 28 September 1985. Moored equipment was recovered on 18 August for servicing and redeployed on 28 August. Wind vectors are plotted according to the meteorological convention.

Figure 3-9.



Composite time series plot of meteorological data from Emmonak and oceanographic data from mooring C-4B near Middle Mouth for the period 23 August through 27 September 1985. Wind vectors are plotted according to the meteorological convention.

Figure 3-10.



Composite time series plot of meteorological data from Kotlik and oceanographic data from mooring C-4C near North Mouth for the period 26 June through 17 August 1986. Wind vectors are plotted according to the meteorological convention.

Figure 3-11.

The current records from the three distributary mouths all reveal a highly polarized along-channel flow which is a combination of intense Yukon River flow and tidal currents. Other processes, such as storm surge and the effects of coastal currents, introduce non-periodic, short-term variability on the current and water-level records.

Current data from South Mouth (mooring C-2), presented in Figure 3-9, cover the period from 30 July through 28 September 1985, excluding the 9-day gap in late August associated with instrument servicing. Currents during the first deployment period exhibited two periods of significant along-channel current reduction: 1 through 3 August, and 4 through 7 August. The water-level recorder on mooring C-2 experienced hardware problems after only a few days, but a nearby water-level recorder deployed by NOAA RU 660 did not exhibit any significant change in water level during this period. Also, the current records from Kobolunuk indicate that the Yukon discharge was relatively constant during this period. For this reason, we must regard the current data from the first deployment at C-2 as suspect, probably due to fouling of the sensors by river debris.

Good quality current data were obtained during the second deployment at South Mouth (C-2). As indicated in Table 3-4, the average along-channel current speed from 28 August through 28 September was 80.3 cm/sec; the maximum along-channel speed and the standard deviation were 121.2 cm/sec and 25.6 cm/sec, respectively. In contrast, the average cross-channel speed was near zero, with a maximum of 47.8 cm/sec. The magnitude of the cross-channel standard deviations (15.3 cm/sec) was significantly less than that of the along-channel current. The water-level data are discussed in detail in subsection 3.3.

Water temperatures during the two deployments in South Mouth are not significantly different from those measured at Kobolunuk:

Table 3-4. Statistical summary of current meter observations from moorings located in the mouths of the three main Yukon River distributaries. Deployment periods and instrument depths are given in Table 2-1.

	Along-Channel Component			Cross-Channel Component		
Station	Max. (cm/s)	Avg. (cm/s)	Std. (cm/s)	Max. (cm/s)	Avg. (cm/s)	Std. (cm/s)
C-2 (South Mouth)	121.2	80.3	25.6	47.8	0.3	15.3
C-4B (Middle Mouth)	77.3	50.4	16.6	10.7	0.5	3.9
C-4C (North Mouth)	83.3	46.7	14.8	12.8	0.1	8.3

temperatures decreased monotonically from a maximum of 20°C in early August to values near 5°C at the end of September.

Although there were significant tidal components in the current and water-level records from South Mouth during the 1985 measurement program, the extremely smooth water temperature record strongly suggests that seawater did not enter South Mouth with the tidal excursions. Offshore seawater temperatures in early August were 5 to 10°C colder than the Yukon discharge, but by late September, the Yukon was significantly colder than the nearby sea water. Nevertheless, it is highly unlikely that seawater would reach the site of mooring C-2 yet not be evident in the time series of water temperature. The absence of seawater penetration into South Mouth during the 1985 measurement period is confirmed by the conductivity record that was obtained from a conductivity sensor mounted on an Aanderaa current meter near the bottom of mooring C-2. Non-zero salinity readings were obtained from this instrument, but careful analysis revealed that the maximum observed readings, which ranged between 0.10 and 0.16 ppt, were not significantly different from zero. These readings may simply be a result of background conductivity in the sediment-laden river water. Despite the threshold uncertainties of the Aanderaa conductivity sensor, we can be sure that this instrument would have detected salinity levels of a few parts per thousand if sea water had actually entered South Mouth.

Figure 3-10 presents water temperature and current data obtained from mooring C-4B deployed in Middle Mouth during the second deployment period of 1985 (24 August through 27 September). Also shown are meteorological data from Emmonak (same as those included in Figure 3-9). The current records from this site, which was located approximately 9 miles upstream from the seaward edge of the Delta, exhibit less high-frequency and cross-channel fluctuations than were observed at South Mouth. Along-channel speeds are smoothly varying, yet exhibit a clear diurnal tidal component with a lesser semidiurnal component. On several occasions, 24 August, 28 August, and twice during 1 September, the current in the river actually reversed, apparently in phase with the tide. Near constant water temperatures and near-zero conductivity readings from an Aanderaa conductivity sensor located at the base of the mooring strongly suggest that sea water did not penetrate into Middle Mouth during these events.

The current reversal on 1 September is related to a storm surge event, as discussed in subsection 3.6. Although EG&G did not deploy a water-level recorder at this site, a concurrent water-level record was obtained from a nearby site by NOAA RU 660. These data have been analyzed and included in subsection 3.3 for interpretation of tides in Middle Mouth.

Statistics of the along-channel and cross-channel currents observed at Middle Mouth are also presented in Table 3-4. The average along-channel speed at Middle Mouth (50.4 cm/sec) is significantly less than that observed at South Mouth (80.3 cm/sec) during roughly the same time period. These reduced currents, in combination with the relatively small cross-sectional area of Kawanak Pass, result in a much smaller discharge from Middle Mouth than South Mouth. This will be quantified in subsection 3.4, which presents results of the velocity profiling surveys and discharge calculations.

Figure 3-11 presents moored data from North Mouth during the 1986 field measurement period. Mooring C-4C was located roughly 8 miles upstream from the seaward edge of the Delta, the same relative position as mooring C-4B in Middle Mouth. Meteorological data were collected by a remote station installed near Kotlik by EG&G.

The along-channel current record from North Mouth exhibited little high-frequency variability; fluctuations were primarily a result of slowly varying river discharge and a predominantly diurnal tidal current. The semidiurnal tide was much less conspicuous than in current records from Middle and South Mouths. The water-level record from mooring C-4C confirmed the mixed, predominantly diurnal characteristics of this location, and a complete tidal analysis of all three distributary mouths is presented in subsection 3.3.

The meteorological data collected near Kotlik reveal large diurnal variations in air temperature, which may be related to sea breeze processes (see subsection 3.6). The wind time series from late June through mid-August exhibits numerous reversals on time scales of a few days to a week, but upon inspection, there appears to be no correlation between wind fluctuations and along-channel currents. This is not surprising, since only moderate wind speeds (15 to 20 knots) were observed during the deployment period, and wind effects may be unable to penetrate below 1 or 2 meters depth in cases of strong river flow. Note that current meters were situated at least 4 m below the surface at all mooring sites. Shallower instrument deployments would be required to determine the wind-current correlation within the river, but this deployment strategy may result in significant loss of equipment due to floating debris and fishing activity.

Inspection of water-level fluctuations at mooring C-4C (subsection 3.6) also indicated that there were no significant storm surge events during this summer deployment of 1986. We expect, however, that during fall and winter of any year, storm surge and meteorological forcing would have a noticeable effect upon the flow in North Mouth, especially since river discharge rates normally would be greatly reduced during these periods.

3.2.3 Offshore Measurements

Although there is much information about tidal amplitudes and phases within Norton Sound and the eastern Bering Sea, there have been no prior current measurements in the nearshore regions around the Yukon Delta. We expect tidal currents westward of the

Delta to be much different from those to the north of the Delta (at the southern boundary of Norton Sound) due to the large spatial gradients that exist for both the K_1 diurnal and M_2 semidiurnal tidal constituents. The northward tendency of the general circulation along the eastern boundary of the Bering Sea is also much different than the circulation in the Sound to the north of the Delta. Another important difference between the west and north sides of the Delta is related to the wind-driven circulation. For a strong northerly wind, nearshore currents north of the Delta would be primarily onshore, with a small westward component; however, northerly winds along the western margin of the Delta would result in strong alongshore currents with a significant offshore, surface circulation due to Ekman dynamics. In contrast, a strong southerly wind would result in onshore flow at South and Middle Mouths, while the nearshore flow would be primarily offshore at North Mouth.

To resolve the spatial characteristics of the general circulation, tidal currents, and the wind-driven flow in the vicinity of the Yukon Delta would require simultaneous current measurements from a number of sites around the Delta during both the summer and fall open-water seasons. Because hardware resources were limited, EG&G had proposed to deploy moorings offshore of South and Middle Mouths during the summer of 1985 to determine the large-scale circulation, tidal current characteristics, and the spatial correlation between currents offshore of two major distributaries. A single mooring was to be deployed offshore North Mouth during 1986 to observe the circulation along the southern margin of Norton Sound.

Good quality current, water temperature, salinity and water-level data were obtained from the moorings deployed to the west of the Delta during the period from late July through late August 1985. Unfortunately, rough sea conditions prohibited a second offshore deployment in late August. Consequently, all moorings had to be placed within the river. Likewise, an attempt was made to deploy a mooring offshore of North Mouth in June 1986, but bad weather again prevented the field party from traveling the 20-mile distance to reach water depths of 30 feet that were required for the mooring deployment. Had a larger vessel been available for the mooring work, it may have been possible to deploy additional moorings offshore of the Delta, but navigating across the shallow tidal flats of the Delta front would have become more of a problem.

The offshore measurements in 1985 consisted of one mooring (C-3) located approximately 16 miles west of South Mouth, and another (C-4A) situated 15 miles west of Middle Mouth. The moorings were placed at water depths of 32 and 33 feet, respectively, westward of the shallow flats that surround the Delta. At mooring C-3, current and water temperature measurements were obtained from an ACM-2 moored 19 feet below the surface. An Aanderaa water-level recorder was situated at the base of the mooring. Salinity, water temperature, and current measurements were obtained at mooring C-4A using an Aanderaa current meter that was also situated 19 feet below the surface.

Figures 3-12 and 3-13 present composite time series plots of moored data from sites C-3 and C-4A, as well as concurrent meteorological data from Emmonak for the period from 31 July through 26 August 1985. Both moorings were recovered on 26 August, but the Aanderaa meter stopped recording on 22 August. Although these records are relatively short for resolution of the coastal circulation, which may have time scales of weeks to a few months, there are many interesting features which are evident in the time series of the different variables.

Inspection of the time series reveals two distinct flow regimes. The first, extending from 31 July until 6 August, consists of a rotary tidal current with major axis parallel to the coast and mean speeds of about 40 cm/sec. During this time

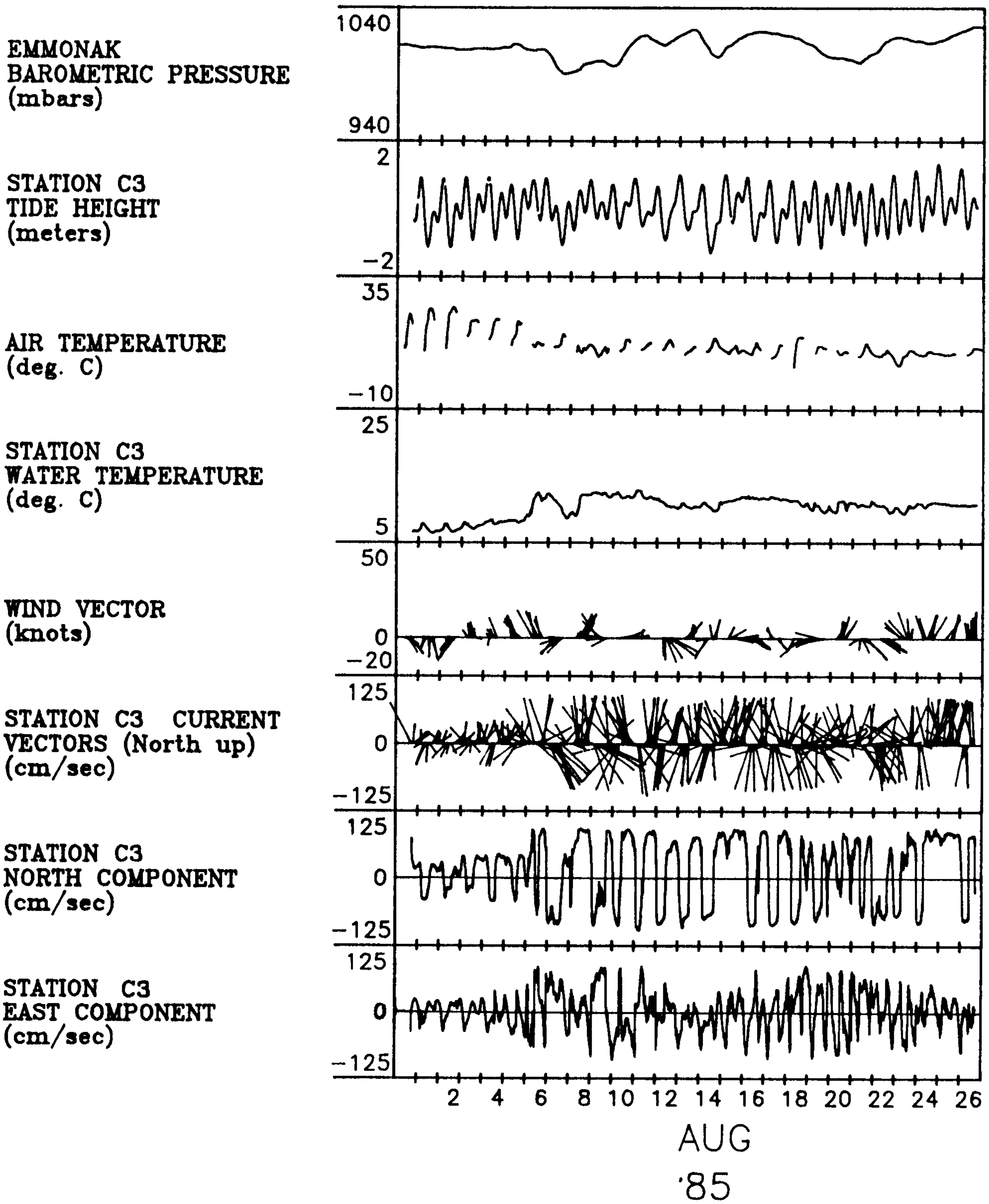


Figure 3-12. Composite time series plot of meteorological data from Emmonak and oceanographic data from mooring C-3 offshore South Mouth for the period 31 July through 26 August 1985. Wind vectors are plotted according to the meteorological convention.

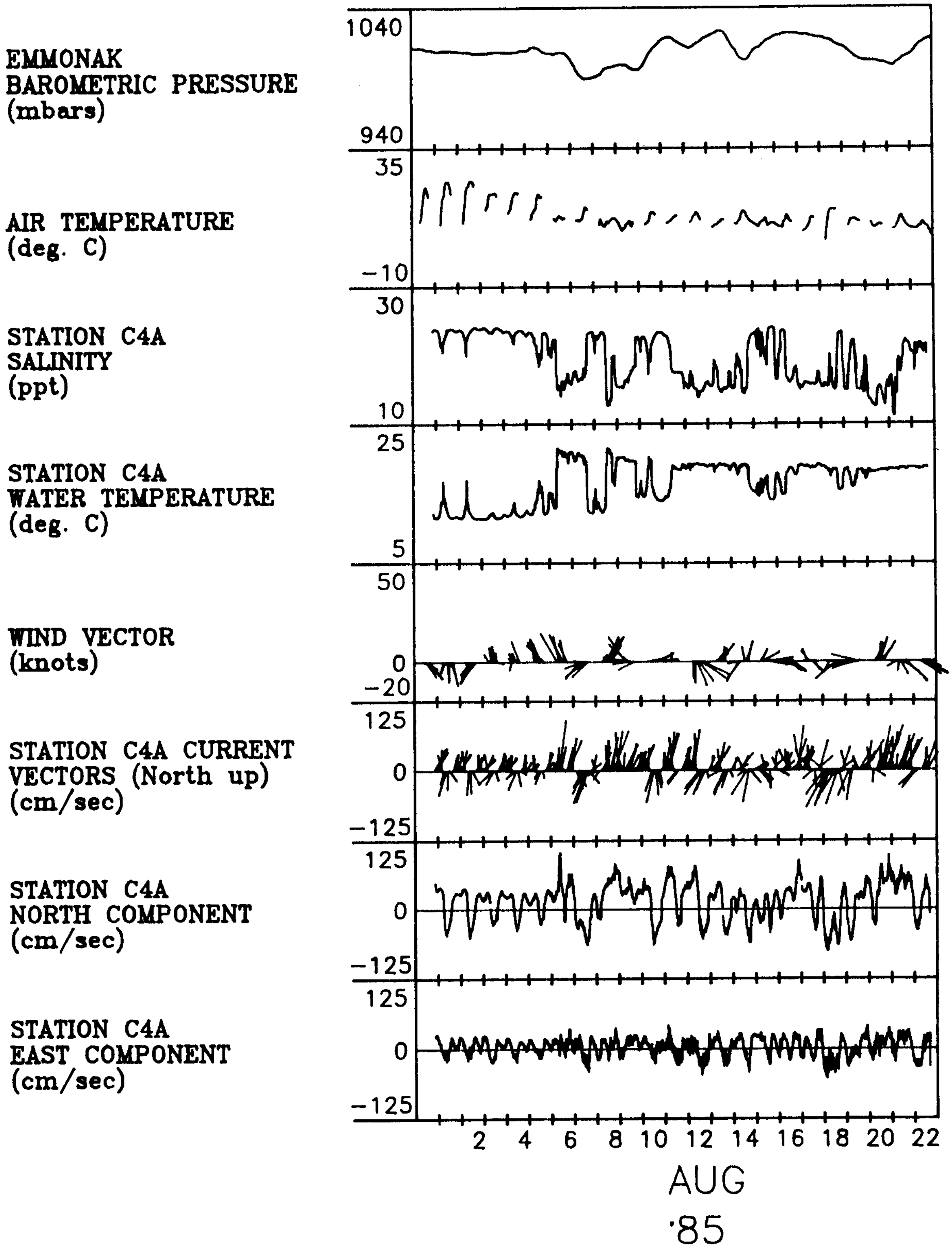


Figure 3-13. Composite time series plot of meteorological data from Emmonak and oceanographic data from mooring C-4A offshore Middle Mouth for the period 31 July through 22 August 1985. Wind vectors are plotted according to the meteorological convention.

period, the salinity and temperature at mooring C-4A were relatively steady with mean values of about 24 ppt and 12°C, respectively. The water temperature at C-3, however, was much colder, with average values of about 6.5°C.

A temperature/salinity profile obtained during the deployment of mooring C-3 on 31 July revealed a thin, surface layer of relatively fresh water overlying cold, saline Bering Sea water; at a depth of 3 feet, temperature and salinity were 11.6°C and 12.9 ppt, respectively, whereas from a depth of 9 feet to the bottom, temperature and salinity exhibited no depth dependence. In this lower, oceanic layer, temperature and salinity ranges were 5.2 to 5.9°C and 25.8 to 27.2 ppt, respectively. Due to poor weather conditions and darkness, T/S profiles could not be conducted at the time of deployment at mooring site C-4A. A discussion of the CTD data collected in September 1985 during the recovery of moorings C-3 and C-4A is provided in subsection 3.5.

The second regime, extending from 6 August until the end of the deployment (26 August), was characteristically different and much more energetic. The flow again exhibited a rotary pattern of diurnal period, but speeds of 80 to 90 cm/sec were common through the end of the deployment at C-3, and speeds were only slightly less at C-4A. This energetic period was accompanied by a significant temperature increase at both mooring sites. At C-3, temperatures increased to about 12°C and exhibited moderate variability through the end of the record. At mooring C-4A, excursions in temperature and salinity were large and visually correlated to each other; temperature oscillations of 10°C were accompanied by salinity variations of up to 9 ppt, and warm waters were relatively fresh while colder waters were more saline.

To illustrate the large excursions in temperature and salinity that were observed at mooring C-4A during the passage of the Yukon River plume, Figure 3-14 presents a T/S diagram constructed from 10-minute samples of each variable. The pronounced linear segments, which have temperature ranges up to $10^{o}C$, represent individual events where the mooring witnessed the passage of the front between warm river water and cold, saline ocean water. The large number of points connecting the two extrema indicate that the two distinct water types have undergone extensive mixing, such that the front between the two has moderate property gradients. Further speculation about the characteristics of this front is not possible because one cannot distinguish between horizontal and vertical excursions of water masses past a single moored, subsurface sensor. For instance, a fresh, surface lens of river water may pass the mooring site, whereas the subsurface instrument may detect low salinities only when the lens becomes thick enough to reach the depth of the instrument.

The current and water property time series clearly indicate that both moorings were located at the fringe of the Yukon River plume. Prior to 6 August, the moorings were lying on the ocean side of the front, and cool, saline Bering Sea water resided at both sites. Soon after, the front moved farther offshore, placing mooring C-4A in water that, on a salt basis, was a mixture of roughly five parts Bering Sea water to two parts fresh Yukon River water. Since the Aanderaa was moored well below the sea surface, it is likely that fresher, less dense waters lie within a surface lens that could not be sampled by the subsurface instruments.

The offshore advection of the river plume was most likely caused by a low pressure storm that entered the area on 6 August. (Note that river discharge during this period was relatively constant, as shown in Figure 3-6.) The Emmonak meteorological data presented in Figures 3-12 and 3-13 illustrate that, on this day, the barometric pressure dropped, the average daily air

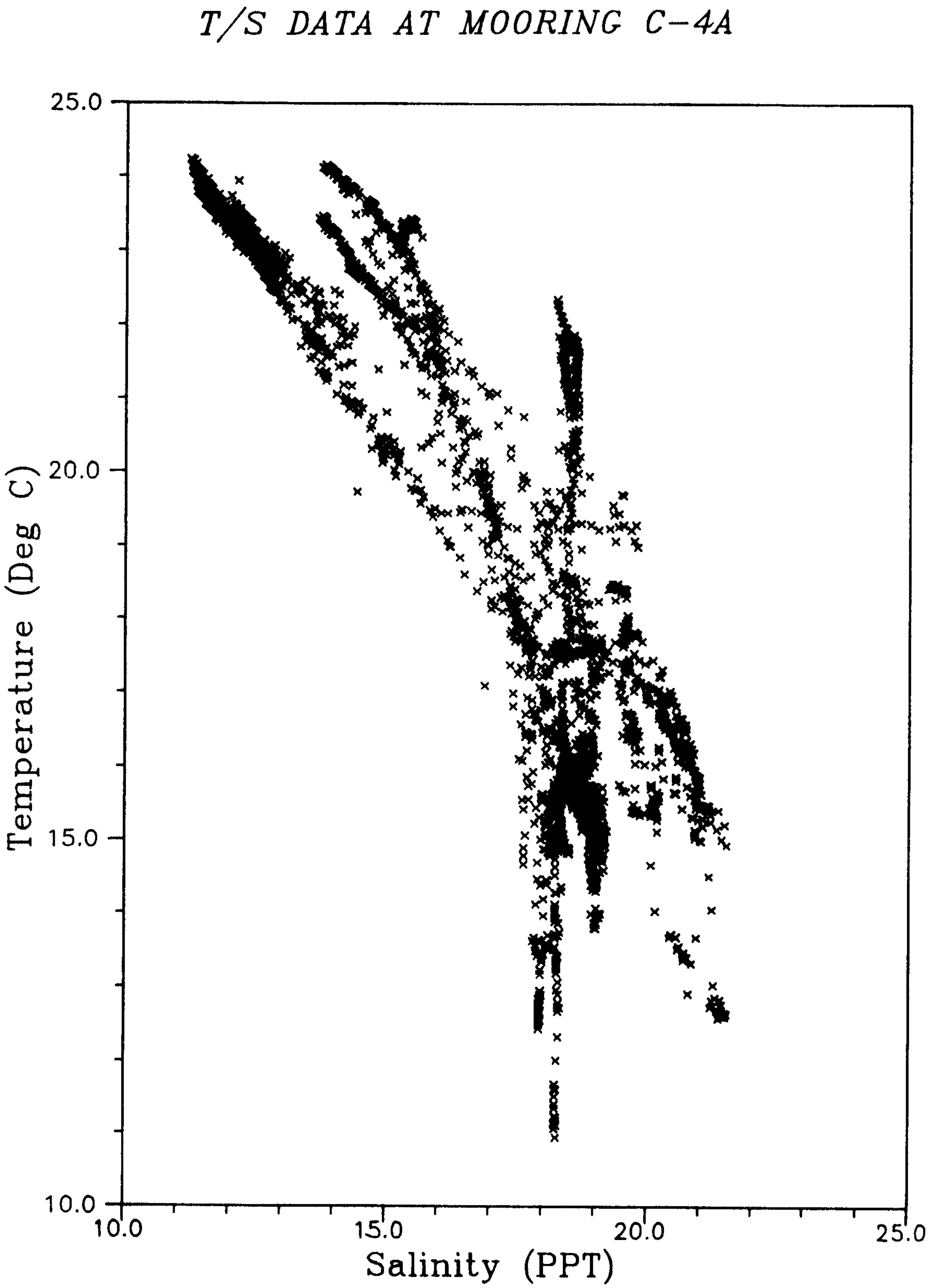


Figure 3-14. Temperature/salinity scatter plot of 10-minute samples measured by a current meter on mooring C-4A offshore Middle Mouth for the period 31 July through 22 August 1985.

temperature decreased, and diurnal oscillations in the air temperature were greatly damped (probably due to an increase in clouds accompanying the storm). Winds during this period appear to be stronger than on previous days, but with the gaps in the NWS observations at Emmonak, it is difficult to resolve the true wind field during this period. The strong southwestward winds on the morning of 7 August would be favorable for an offshore surface flow, based upon Ekman dynamics, but verification of this transport process is not possible with the available information. A further account of the evolution of this storm, and another which affected the Delta on 8 August, is given in subsection 3.6.

Progressive vector diagrams (PVDs) generated from current data at sites C-3 and C-4A (Figures 3-15 and 3-16, respectively) illustrate that the two sites were affected by the same north-northeastward drift for the 3-week deployment period. A net drift of roughly 260 km over the first 22 days of each record resulted in an average speed of 12 km/day, or 12 cm/sec. This is in close agreement with Drury et al.'s (1981) estimate of a 10- to 15-cm/sec northward drift along the westward side of the Yukon Delta. Unfortunately, the limited length of the recent offshore measurements precludes estimation of alongshore drift during other seasons of the year.

The PVDs also provide evidence that the flow regime was related to the meteorological events that occurred during the measurement period. Both PVDs indicate that from the beginning of the deployment (lower left corner) until 6 August, relatively small counterclockwise tidal excursions were superimposed on a north-northeastward drift. In contrast, from 6 August until the end of the deployment, the PVD from mooring C-3 is characterized by much larger counterclockwise oscillations and a much stronger northward drift.

The PVD from mooring C-4A was significantly different from that of mooring C-3 after 6 August. At C-4A, there were periods

STATION C3, YUKON DELTA, ALASKA

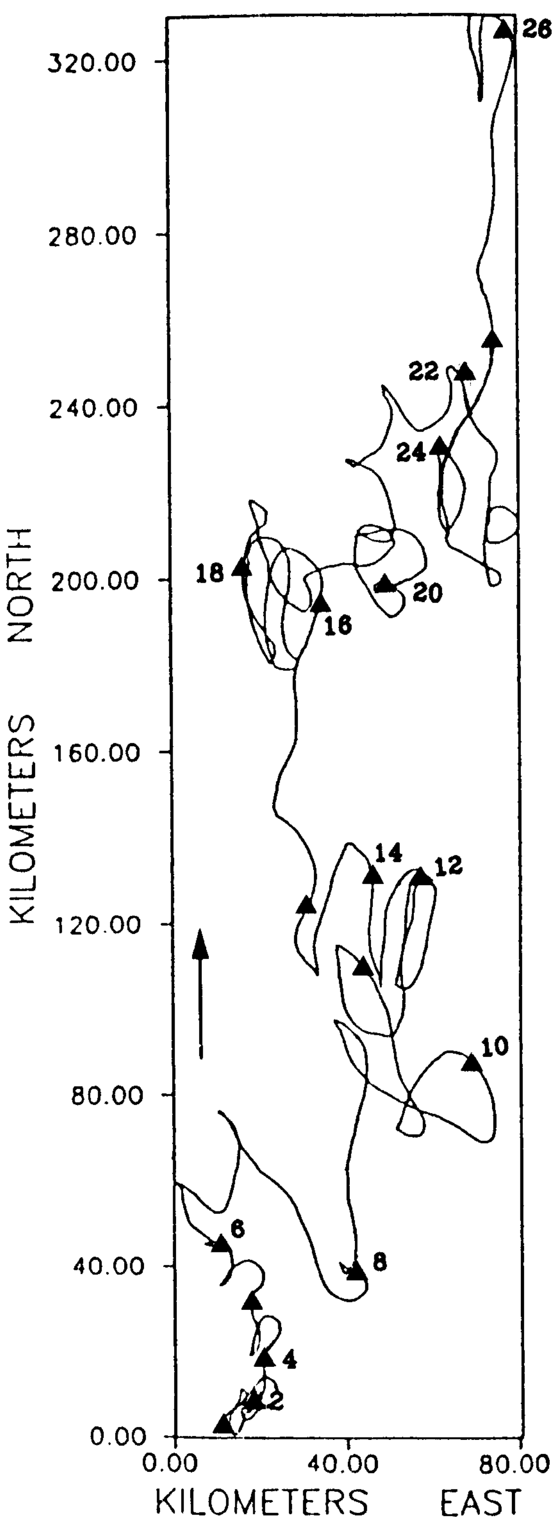


Figure 3-15. Progressive vector diagram of currents from mooring C-3 offshore South Mouth. The trajectory begins on 31 July 1985 (lower left) and ends on 26 August 1985 (upper right).

STATION C4, YUKON DELTA, ALASKA

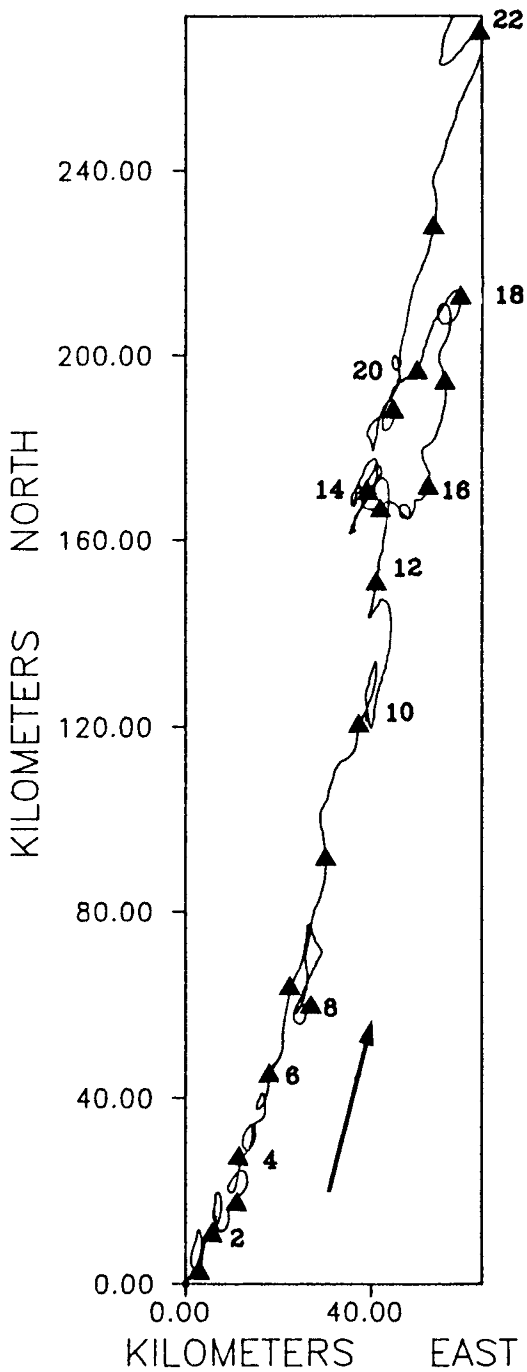


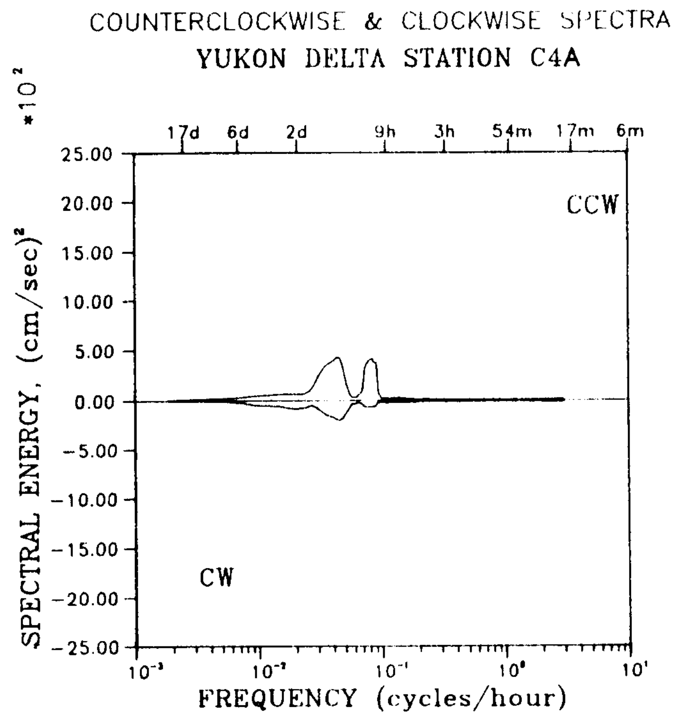
Figure 3-16. Progressive vector diagram of currents from mooring C-4A offshore Middle Mouth. The trajectory begins on 31 July 1985 (lower left) and ends on 22 August 1985 (upper right).

of strong northward drift, as observed at C-3, but there were other periods when the northward flow decreased and tidal oscillations were dominant. Analysis of the temperature and salinity data from C-4A reveals that strong northward flow was observed when the instrument was immersed in the warm, low salinity plume of Yukon River water, whereas the predominantly tidal regime occurred when cold, saline water was present. This result indicates that the water mass boundary between Yukon River water and Bering Sea water also represents a dynamic boundary for current generating processes.

It is interesting to note that Norton Sound, which is 280 km long with an average depth of approximately 18 m, has a resonant period of nearly 24 hours. This may provide a mechanism by which atmospheric forcing can generate diurnal seiches in Norton Sound. This mechanism is consistent with the observed diurnal current amplification that was observed in the current records after the arrival of the storm on 6 August 1985.

For further analysis of the oscillatory component of the currents at moorings C-3 and C-4A, variance conserving plots of rotary spectra, including the counterclockwise (top half) and clockwise (bottom half) components for each record, are presented in Figure 3-17. At mooring C-3, most of the spectral energy is contained in the counterclockwise component: a broad peak at diurnal periods, a lesser peak at the semidiurnal frequency, and small but noticeable energy at higher harmonics. In the clockwise component, all energy is confined to periods of 1 day or longer. At periods longer than 2 days, the flow has no preferred sense of rotation, but since the records are only a few weeks long, it is likely that this analysis greatly underestimates the energy content of processes having periods greater than 1 week.

The rotary spectra at C-4A exhibit roughly five times less energy in the diurnal counterclockwise current component than was observed at mooring C-3. The counterclockwise semidiurnal



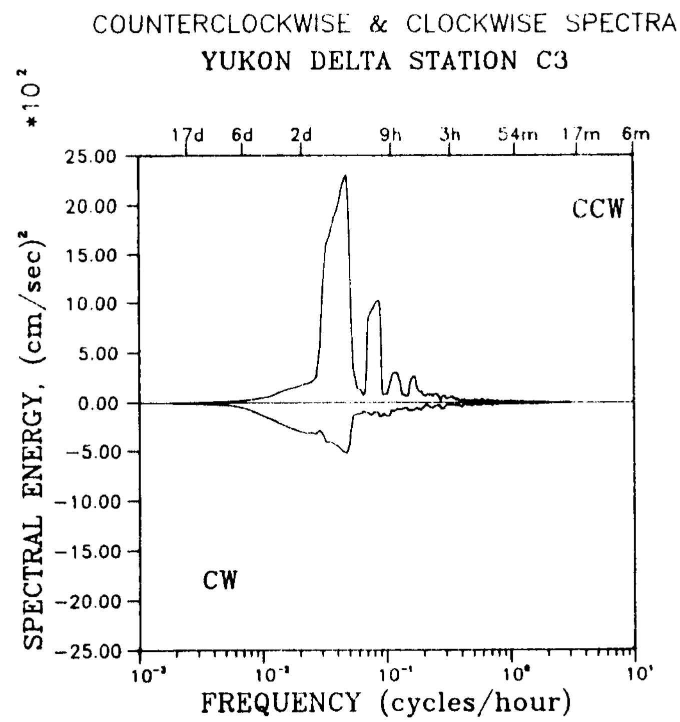


Figure 3-17. Variance conserving rotary spectra of current data from mooring C-4A offshore Middle Mouth (lower panel) and mooring C-3 offshore South Mouth (upper panel) for the period 31 July through 22 August 1985.

component at C-4A was also less than at C-3, but only by a factor of two. It is very surprising that the diurnal counterclockwise currents differ by this amount over the 26-mile distance between the two mooring sites, especially since the range of the diurnal tide should be roughly the same at both sites.

Pearson et al. (1981) indicate that both the K_1 diurnal and M_2 semidiurnal tidal constituents, which are the predominant barotropic tidal constituents in this area, have a counter-clockwise sense of rotation in the region to the west of the Delta. The large counterclockwise diurnal current at C-3 is definitely not a result of inertial effects, because at this latitude, inertial currents would have a period near 13 hours, and their sense of rotation would be clockwise. Nor would we suspect the large diurnal amplitude at C-3 to be a result of some local topographic effect, because bathymetric contours to the west of the Delta are smooth and oriented north-south, such that mooring C-3 is located in the same topographic regime as mooring C-4A. Both moorings lie on the gradual slope which lies offshore of the shallow flats of the Delta platform.

We suspect the high energy at C-3 to be a result of baroclinic processes which are related to the Yukon River plume. The time series of currents and water temperature at C-3 (Figure 3-12) indicate that the large amplitude diurnal currents were present when water temperatures were relatively high. When the plume of fresh, less dense river water advances offshore, large density gradients will form at the boundary with the cold, saline, and dense seawater. These density fronts will occur along the horizontal boundary of the plume, as well as at the vertical boundary between the two layers of different density. This baroclinic structure will be very susceptible to excitation by the more energetic processes of the region, namely the diurnal and semidiurnal barotropic tides. The apparent result that baro-clinic motions are not excited at mooring C-4A may be due to a less intense front between the two water types at that location. Since the Yukon discharge from South Mouth (inshore of C-3) greatly exceeds that at Middle Mouth (inshore of C-4A), it is likely that waters at C-4A are well mixed compared with those at C-3.

The available data are insufficient to resolve the two-dimensional field of mixing in this region, but there appears to be major differences in the extent of vertical mixing at the two sites. At C-4A, the plume of relatively fresh water (15 to 20 ppt) often penetrates to the 19 foot (5.8-m) depth of the instrument, but at C-3, which lies closer to the major river discharge point, warm river waters never reached the 19 foot (5.8-m) depth of the instrument. We may conclude that the plume is subjected to vertical mixing as it is advected northward along the Delta coast, and vertical gradients between water types were much weaker to the north of mooring C-3. Although highly speculative, this scenario is consistent with both water properties and the dynamics of the current regime.

Coherence analyses were also performed upon the north and east current components from the two moorings (Figure 3-17a). No significant coherence was detected in the eastward current component, but coherence was significant in the northward current component at diurnal periods and in the 2- to 10-day band. The observed 150^{o} phase lag (where C-3 leads C-4A) is consistent with the counterclockwise tidal wave.

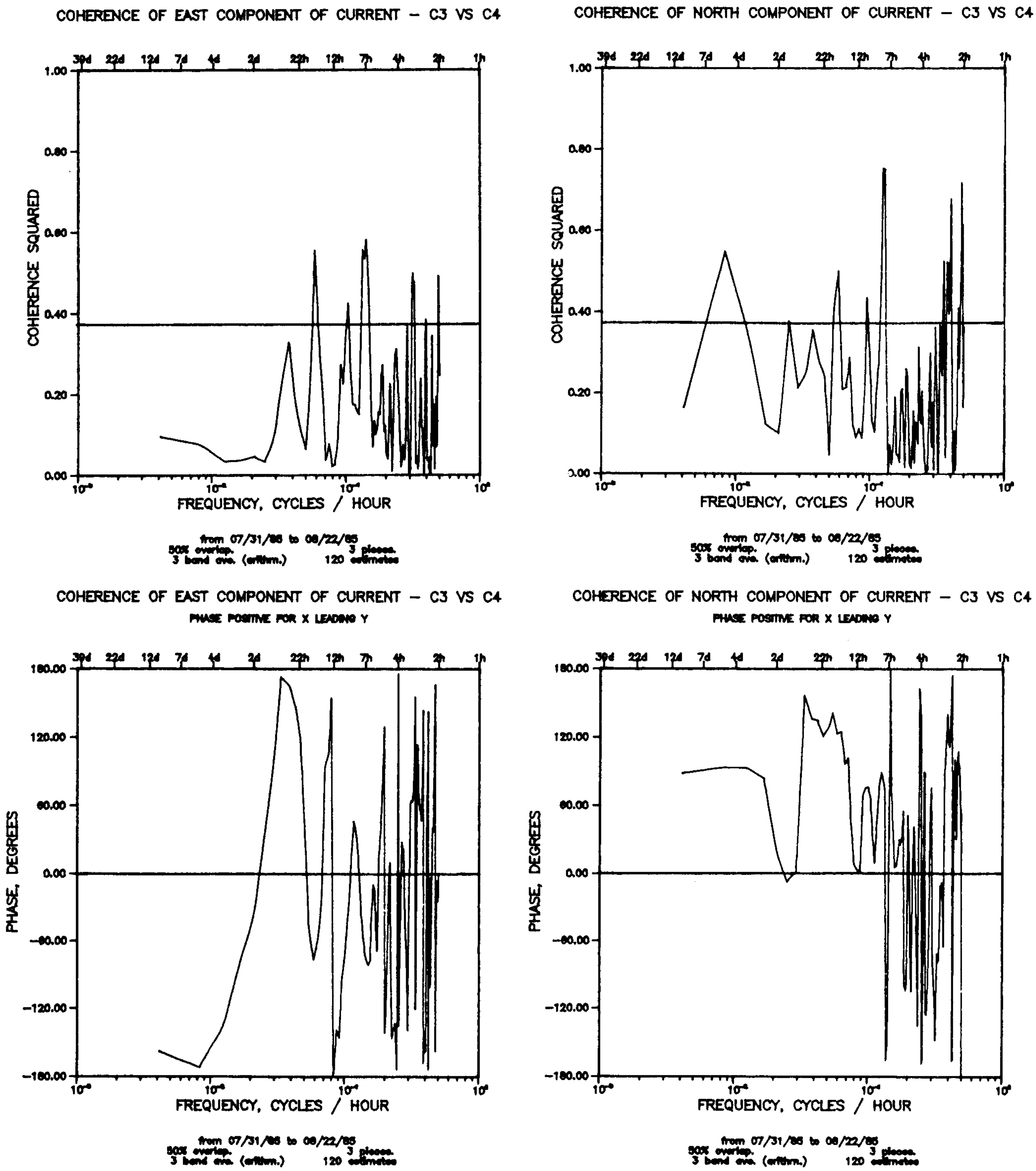


Figure 17a. Coherence squared and phase between east and north components of current velocity at mooring C-3 offshore South Mouth and C-4A offshore Middle Mouth for the period 31 July through 22 August 1985. Horizontal line indicates level of zero time coherence at 95% confidence. Positive phase indicates C-3 leading C-4A.

3.3 WATER-LEVEL MEASUREMENTS

Water-level (pressure) measurements were obtained at various sites during the Yukon Delta measurement program in order to meet three objectives. First, upstream time series of water-level were obtained in conjunction with the current measurements to monitor the height of the river during the summer season when river discharge and water level changed significantly. Second, offshore water-level measurements were made to determine the predominant tidal characteristics and relate these results to the flow regime. Third, water-level measurements were made in the distributary mouths to determine whether tides penetrate into the river and alter the rate of river discharge. The water-level measurements from the distributary mouths and offshore sites were also useful for identification of storm surge events. An analysis of the surge results is provided in subsection 3.6, as it relates closely to the meteorological results.

To supplement the water-level measurements obtained during the present program, additional water-level data have been obtained from a variety of sources. For the analysis of river level, time series of river height were acquired from government-operated stations at Russian Mission and Yukon Bridge, which are located 90 and 670 miles upstream of Pitkas Point, respectively. At the mouth of the three major distributaries, tidal characteristics change greatly over small spatial scales, and it was necessary to obtain additional water-level records collected during summer 1985 as part of NOAA RU 660, the fisheries investigation of the Yukon Delta. Water-level records from three sites around the Delta shoreline were also available from a past NOAA study conducted by EG&G. Using all of these data sources, it has been possible to resolve the tidal regime within the distributary mouths and nearshore areas.

3.3.1 Upstream River Height

As previously discussed in subsection 3.2, water-level measurements were obtained at Kobolunuk during the 1985 and 1986 field programs. The 1985 water-level time series (see Figure 3-6) exhibited a gradual drop in water level from late July to mid-August, followed by a 2.8-m rise in river height from 22 August until the end of the deployment period on 2 October. This rise was apparently related to the relatively high rainfall that occurred throughout Alaska during this period. The velocity profiling transects conducted at Kobolunuk during the second (August 1985) and third (October 1985) field trips indicated a 43% increase in river transport, concurrent with the rise in river level.

This autumn rise in water level was so large that it was initially suspected to be an instrument calibration problem. Upon EG&G's request, NOAA sent the government-furnished water-level recorder (TG-3) used at Kobolunuk (station C-1) to the Northwest Calibration Center in Seattle for post-deployment instrument calibration. The time series of water level was reprocessed using the new calibration coefficients, and the resulting time series revealed a 4% decrease in water level compared with the initial analysis. Although the magnitude of the rise was thus reduced to 2.7 m, this recalibration proved that the measurements were credible.

As an independent check, concurrent water-level data were acquired from a USGS station at Russian Mission, which is located 90 miles upstream from Kobolunuk. During the period 30 August through 25 September 1985, the water level at Russian Mission rose 1.94 m, while the measurements at Kobolunuk indicated a 1.85-m water-level rise during the same time period. Figure 3-18 illustrates the good agreement between the water-level measurements obtained by EG&G at Kobolunuk (continuous line) during the period 22 August through 30 September 1985, and the concurrent

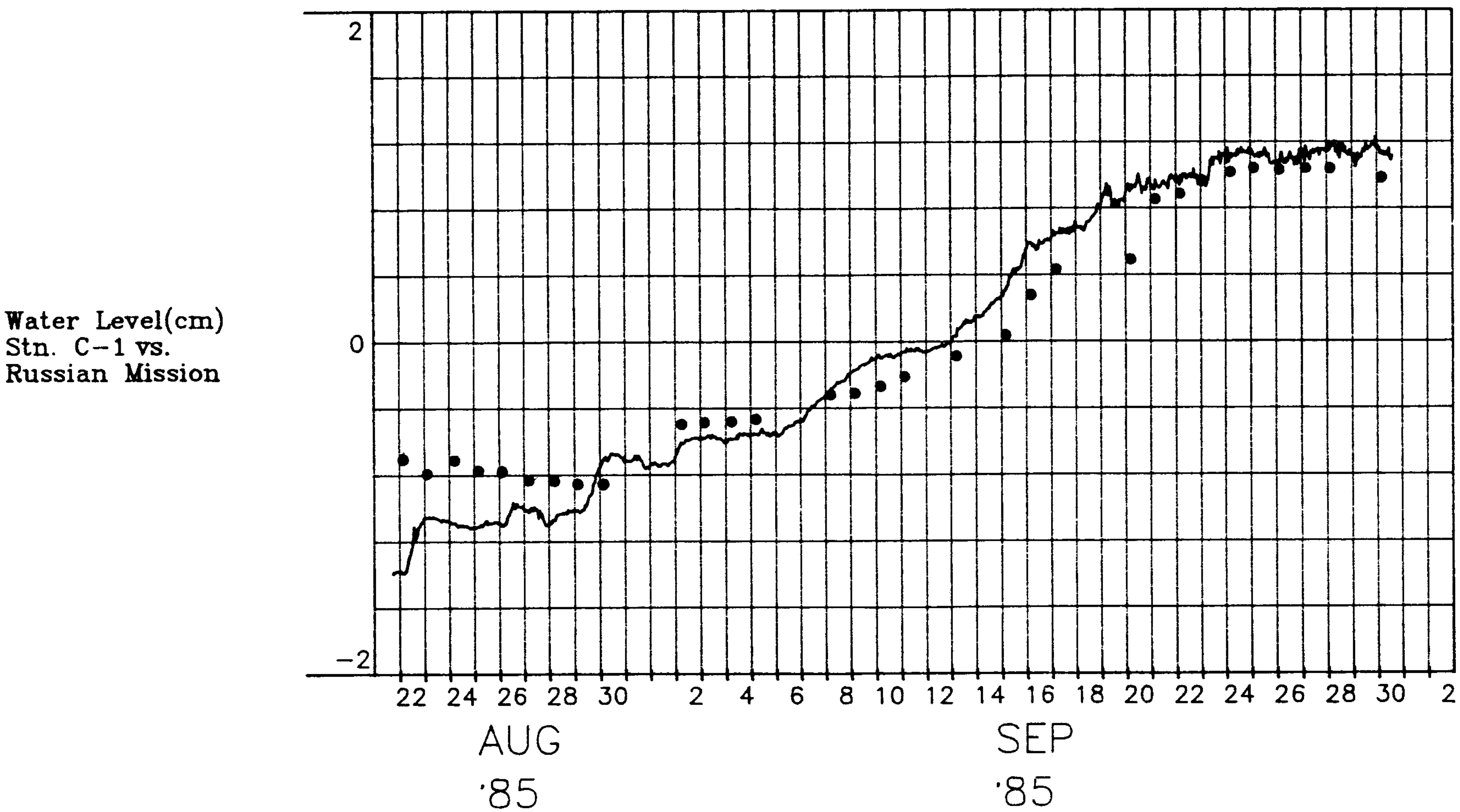


Figure 3-18. Comparison of water-level time series obtained for a gauge moored near Kobolunuk (continuous line) versus daily water-level measurements from a USGS station at Russian Mission (solid circles) during August and September of 1985. Russian Mission is located 100 miles upstream of Kobolunuk.

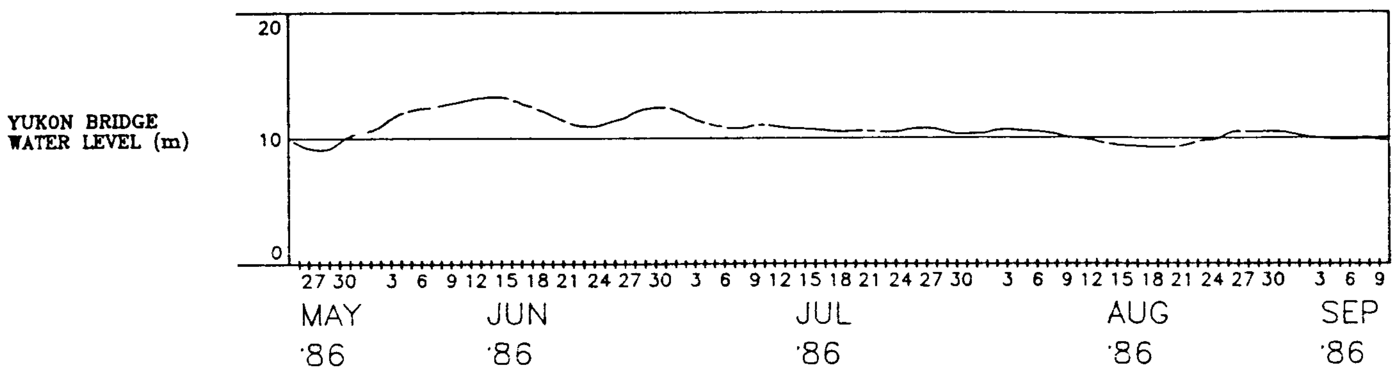
daily water-level measurements from Russian Mission (solid circles). These results confirm the rise in water level that was observed at Kobolunuk.

It should be noted that all water-level records are plotted relative to a mean water-level datum computed for the length of the record in question. Absolute water-level comparison between sites is not possible because the moored records obtained by EG&G and other NOAA Research Units were not vertically surveyed with respect to USGS benchmarks.

For comparison with the Kobolunuk water-level data, a time series of river level has been obtained from a USGS station at Yukon Bridge, which is located in the Yukon Flats, 670 miles upstream of Kobolunuk. During 1985, good quality water-level data were obtained from early June through late October (Figure 3-19). This represents the period when the Yukon, at this location, was ice free. From this time series, peak river flow and water level apparently occurred in early June, and water level dropped consistently until the end of the open-water season. Note that in late August and mid-September, water level at Yukon Bridge did rise for periods of a few days.

Also shown in Figure 3-19 is the 1986 time series of water level from Yukon Bridge. This record begins on 25 May, but does not extend to the end of the open-water season (late October) because the data were not available at the time of this analysis. In 1986, the peak river level was less than observed in 1985, and occurred roughly 1 week later. The river also exhibited a second rise at the end of June 1986, followed by near-constant levels through the first week of September. A small rise in late August appeared similar to that observed in 1985.

Figure 3-20 presents a composite of water-level time series from Yukon Bridge, Kobolunuk, and a number of sites on the Yukon Delta. Two water-level records were available from South Mouth;



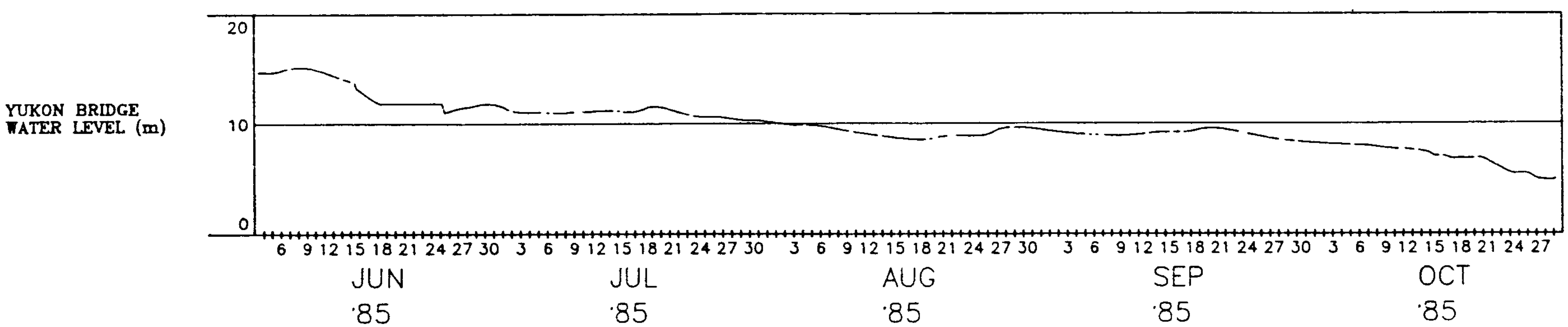


Figure 3-19. Time series plot of USGS water-level data from Yukon Bridge (located 670 miles upstream of Kobolunuk) for the periods 4 June through 29 October 1985 and 25 May through 10 September 1986.

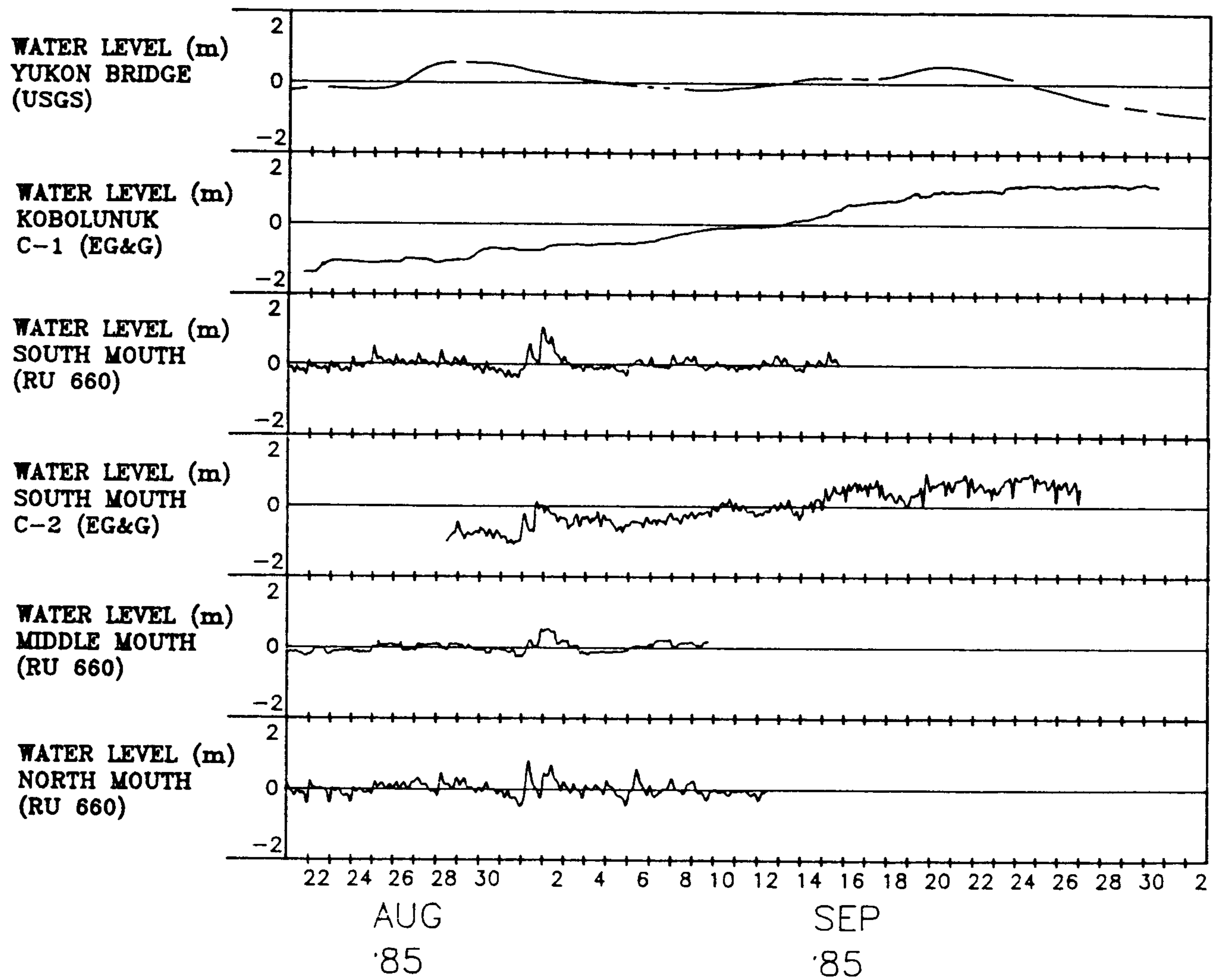


Figure 3-20. Composite time series plot of water-level data from Yukon Bridge, Kobolunuk, and various sites around the Yukon Delta for the period 21 August through 2 October 1985. Water levels are referenced to the mean level determined over the length of each record. Locations of measurement sites on the Delta are shown in Figures 2-3 and 3-27.

a single record was available from both Middle and North Mouths. The moored records were obtained either by EG&G or NOAA RU 660.

This figure illustrates that the increase in river height observed at Kobolunuk from 28 August through 26 September 1985 was also observed at Naringolapak during the same time period. However, the river level at Yukon Bridge was not correlated with the river level at Kobolunuk. This is not surprising, since Yukon Bridge is located over 600 miles upstream of Kobolunuk and much of the Yukon drainage area lies between these two sites. During summer and early fall, the precipitation patterns over interior and coastal Alaska also differ significantly.

Unfortunately, the water-level records from Middle and North Mouths are too short to allow comparison with the EG&G record from South Mouth, but it appears that they do not significantly diverge from a mean water level during mid-September 1985. The South Mouth record from NOAA RU 660 also appears to have a steady mean level, although there may be a gradual rise during the period 5 through 15 September 1985. In contrast, the EG&G record from South Mouth exhibits a strong rise of well over 1 m. We believe the instrument was working properly and that this is not the result of a drift in calibration. Nevertheless, the magnitude of the rise exceeds the increase to be expected from the hydraulic effect of an increased river discharge at a point so close to the ocean boundary. This impression is reinforced by the steady mean levels which appear in the records from the North and Middle Mouths. It is possible that there may have been some settling of the mooring due to anchor scour.

Water-level measurements at Kobolunuk were also obtained during the 1986 field program, from late June through mid-August. Figure 3-21 presents time series of water level at Kobolunuk and North Mouth, which were obtained by EG&G in addition to the water-level record from Yukon Bridge. The time series at Kobolunuk exhibits a 0.6-m drop in the river level from the

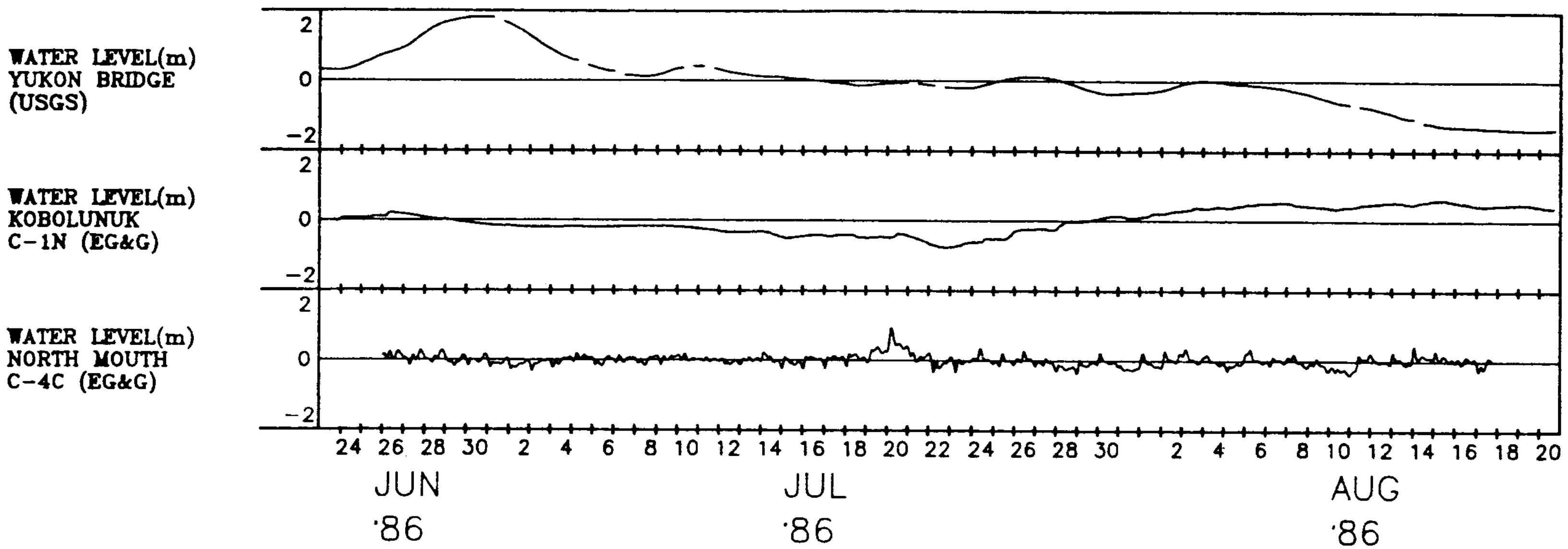


Figure 3-21. Composite time series plot of water-level data from Yukon Bridge, Kobolunuk, and North Mouth on the Yukon Delta for the period 23 June through 20 August 1986. Water levels are referenced to the mean level determined over the length of each record.

beginning of the deployment (23 June) until 22 July 1986. Soon after, the river rose 1.2 m in a period of 2 weeks, then began to drop again at the end of the deployment.

The 1986 water-level records from Yukon Bridge and North Mouth exhibit no correlation with the record from Kobolunuk. As during 1985, the Yukon Bridge record exhibited a peak in June, followed by a gradual decrease in water level during July and August. At North Mouth, only small, short-term fluctuations were observed around a mean water level, again similar to the observations from 1985.

3.3.2 Tides

Astronomical tides are an important physical process in the vicinity of the Yukon Delta because they are responsible for periodic fluctuations in the water level around the Delta, as well as oscillatory currents at offshore sites and flow reversals within the river distributaries. Tidal analyses have been performed on time series of water level and currents obtained at two offshore moorings, in addition to moorings deployed at the mouths of the three major Yukon distributaries. Both tide height and tidal current data have been analyzed using the response method, as developed by Munk and Cartwright (1966). The predicted tide height, or tidal current, is calculated as the response to the astronomical forcing; that is, the predicted tide is the convolution of the astronomical forcing with a set of complex weights which have been determined so that the predicted tide is a least-squares fit to the observed records. This procedure can be used on any length data set (preferably a minimum of 15 days), and the principal outputs are the amplitudes and phases of the harmonic constituents for either the tide height or tidal current.

The following subsections present results of the tidal analyses. First, the tidal characteristics at the offshore sites and in the mouths of the three major distributaries are described, using the recent EG&G measurements as a basis for the analyses. This is followed by analyses of additional water-level records that were acquired during other investigations of the Yukon Delta. Subsection 3.3.2.4 provides a summary of the tidal characteristics around the Delta, using all sources of data.

3.3.2.1 Offshore Tidal Characteristics

Pearson et al. (1981) have presented a summary of the tides within the eastern Bering Sea and Norton Sound region, based upon a large number of observations and comparison with tidal models. Their results indicate that along the western shore of Alaska, tides are mixed, predominantly semidiurnal, except within Norton Sound where diurnal amplitudes are largest. The majority of the tidal energy is contained in two semidiurnal constituents, M_2 and N_2, and two diurnal constituents, K_1 and O_1. The S_2 constituent, which is normally the second-most energetic semidiurnal constituent, is small within the Bering Sea. In the vicinity of the Yukon Delta, the semidiurnal and diurnal tidal currents both rotate in a counterclockwise sense.

According to Pearson et al. (1981), the predominant M_2 tide has an amphidrome in Norton Sound, and large amplitudes in Kuskokwim Bay (>100 cm) and Bristol Bay (>200 cm). Amplitudes for the M_2 constituent are shown to range from 40 cm near South Mouth to about 15 cm in the vicinity of North Mouth. Amplitudes for the N_2 constituent are relatively small (on the order of 10 cm) around the Delta.

The most dominant diurnal constituent, K_1, has amphidromes near Nome and south of Nunivak Island (west of Kuskokwim Bay), and amplitudes between 30 and 40 cm around the Delta. It is expected that K_1 amplitudes at North Mouth are greater than at Middle and South Mouths, since a local maximum (>40 cm) is located at the head of Norton Sound. Amplitudes of the O_1 tide are between 10 and 20 cm around the Delta.

Pearson et al. (1981), using data from numerous offshore and coastal stations (eight stations within Norton Sound and one record from Yukon South Mouth), constructed co-tidal charts of the eastern Bering Sea for the four major tidal constituents (K_1, O_1, M_2, N_2). From inspection of these charts, it is possible to estimate the amplitude and phase of the tide at various positions offshore of the Delta. At the site of mooring C-3, offshore of South Mouth, the amplitude and phase (referred to Greenwich) of the K_1, O_1, M_2 and N_2 tidal constituents are estimated to be 35 cm and 330^o, 15 cm and 290^o, 40 cm and 20^o, and 10 cm and 300^o, respectively.

Table 3-5 presents the results of the tidal analysis performed on the water-level time series record obtained from mooring C-3 during 1985. Tidal amplitude and phase for seven principal constituents are shown in this table. In general, the constituent parameters are in excellent agreement with Pearson's results. Tidal phases agreed to within 20^o for each constituent, while amplitudes generally agreed to within about 6 cm, with the exception of the M_2 constituent, which was about 11 cm greater than the Pearson estimate. This difference is not surprising, since the M_2 co-range lines are closely spaced at this location and relatively large variations can occur over small distances.

Spatial variations of tidal characteristics within the eastern Bering Sea can be demonstrated by the ratio between the sum of amplitudes of the principal diurnal constituents K_1 and O_1, and the sum of amplitudes of the principal semidiurnal constituents M_2 and N_2 (Pearson et al., 1981). From the recent measurements offshore of South Mouth, the local value of this ratio is determined to be 0.94. This value characterizes the tide at Station C-3 as mixed, predominantly semidiurnal, with two high and two low waters per day, and large diurnal inequalities in heights. This description is in good agreement with the observed tide height.

Table 3-5. Principal harmonic tide height constituents determined from water-level records within Yukon distributaries and offshore of the Delta. Tidal phase is referred to Greenwich.

		Station C-3 Offshore South Mouth		Station C-2 Within South Mouth		Station C-4C Within North Mouth	
Constituent	Period (hours)	Amplitude (cm)	Phase (degrees)	Amplitude (cm)	Phase (degrees)	Amplitude (cm)	Phase (degrees)
Q_1	26.87	3.9	296	2.4	50	5.2	56
O_1	25.82	20.8	302	5.2	50	16.3	73
K_1	23.93	36.8	346	12.6	93	19.3	118
μ_2	12.87	7.6	307	2.0	107	1.0	106
N_2	12.66	9.8	304	3.6	122	4.0	157
M_2	12.42	51.2	13	16.6	113	12.6	174
S_2	12.00	8.0	83	0.9	154	3.0	60

Tidal analysis of current meter data, on the other hand, is more difficult than tide height analysis due to the variety of physical processes which affect currents in nearshore regions. As indicated in subsection 3.2, the offshore current measurements were subjected to two different flow regimes on account of the mooring location relative to the Yukon River plume. For instance, the arrival of a storm on 5 August 1985 caused the water mass boundary to advance farther offshore, placing the moorings inside the river plume. The translation of the front was accompanied by a much stronger northward net drift and an amplification of the diurnal current variability, especially at mooring C-3. As previously mentioned, atmospheric forcing may induce diurnal seiches in Norton Sound, and baroclinic processes at the front between the Yukon plume and the Bering Sea water may also result in oscillations at tidal frequencies.

For the above reasons, the offshore current records contain very strong nontidal fluctuations in the diurnal frequency band. Considering that, for the purpose of tidal analysis, any nontidal component is regarded as noise, the current records have a very low signal-to-noise ratio. Since most of the noise is contained in the diurnal band, the accuracy of the tidal current predictions were seriously affected by this low signal-to-noise ratio.

Figure 3-22 presents time series plots of the observed, predicted, and residual tidal height and tidal currents at station C-3 during the 1985 measurement period. The upper three tiers illustrate that the predicted tide closely matches the observed water-level record, and the residual water level (the difference between the observed and predicted records) exhibits relatively small nonperiodic fluctuations. The lower six tiers in Figure 3-22 present tidal analyses of the north and east current components from mooring C-3. Tidal currents are mixed, predominantly semidiurnal, at this site. Nontidal residual currents have much larger amplitudes than the tidal currents,

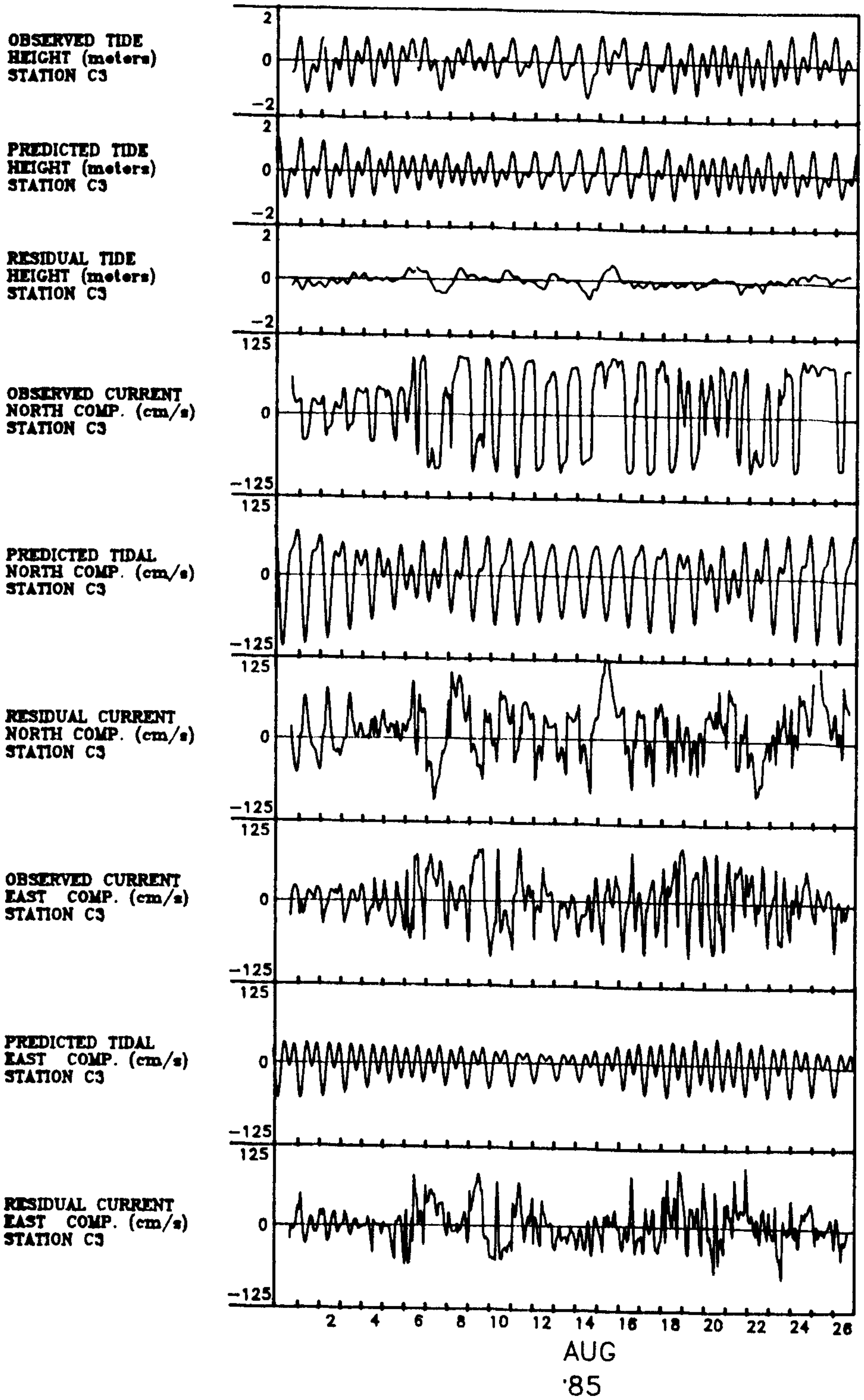


Figure 3-22. Tidal analysis of water-level and current data obtained from mooring C-3 located 16 nm offshore of South Mouth for the period 31 July through 26 August 1985. The upper three tiers present the observed water level (mean removed), predicted tide height, and the residual (observed minus predicted) water level. The lower six tiers present tidal analysis for individual (north and east) current components.

suggesting that the accuracy of the tidal analysis may be questionable due to the dominance of nonperiodic processes. Consequently, the amplitudes of the individual harmonic constituents determined from the tidal current analysis are questionable and have not been presented here.

Aside from the absolute accuracy of the tidal current analysis, Figure 3-22 clearly indicates that the north component of the tidal current is roughly twice that of the east tidal current component. The result is a tidal current ellipse with the major axis oriented northward, roughly along bathymetric contours, in agreement with Pearson et al. (1981).

Figure 3-23 presents the tidal current analysis for mooring C-4A, which was located offshore of Middle Mouth. As for mooring C-3, tidal currents are of the mixed, predominantly semidiurnal type, nontidal residual currents are much larger than the predicted tidal currents, and the northward tidal current is significantly greater than the eastward component. Both tidal current components at mooring C-4A were, however, much smaller than at mooring C-3. This northward decrease in tidal current amplitude was expected for the M_2 semidiurnal tide, but not for the K_1 diurnal tide, which, according to Pearson et al. (1981), should have the same magnitude at all nearshore sites west of the Delta. However, in the absence of a moored water-level record from mooring C-4A, accurate tidal constituent amplitudes cannot be determined, and further speculation is not warranted.

3.3.2.2 Tides within River Distributaries

Tides around the Yukon Delta and within the river distributaries are characterized by extremely large spatial variations. Not only are the tidal characteristics different at the mouths of the three major distributaries, but large tidal amplitude and phase variations occur over small distances within the river. For instance, the diurnal/semidiurnal amplitude ratio, as defined above, changes from about 1 at South Mouth to over 2 at North

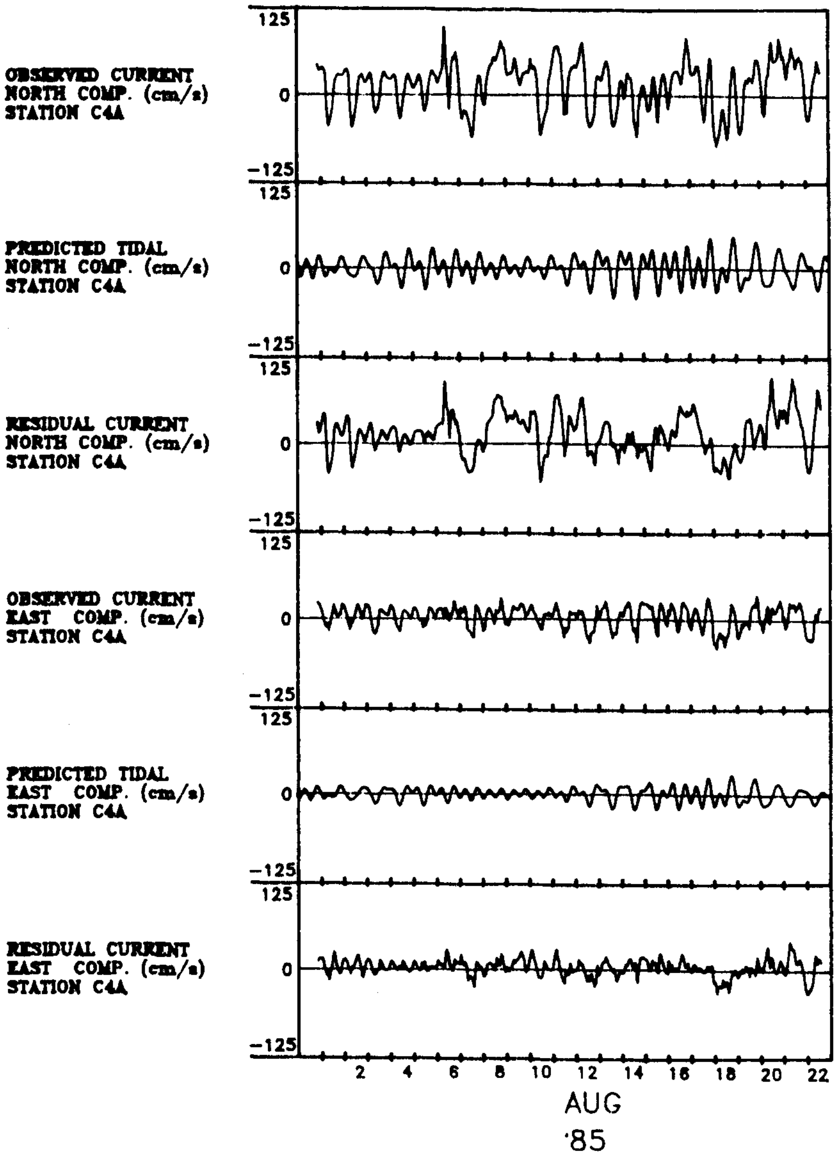


Figure 3-23. Tidal analysis of north and east current components obtained from mooring C-4A located 15 nm offshore of Middle Mouth for the period 31 July through 22 August 1985. The observed current, predicted tidal current, and residual (observed minus predicted) current are presented for each current component.

Mouth. As shown below, tide height fluctuations and tidal current amplitudes decay very rapidly over short distances upstream from the distributary mouth. The presence of tidal amphidromes in Norton Sound and the large dissipation of tidal energy on the shallow tidal flats surrounding the Delta are major contributors to the intense spatial variability of the Yukon Delta tides.

Tidal analyses have been performed on water level and current records obtained from moorings C-2 (South Mouth), C-4B (Middle Mouth), and C-4C (North Mouth). The results of these tidal analyses are illustrated in Figures 3-24 through 3-26 as composite time series plots of observed, predicted, and residual tide height and tidal currents from moorings C-2, C-4B and C-4C, respectively.

Inspection of the tidal analyses for mooring C-2 in South Mouth (Figure 3-24) indicates that the water level is influenced by a mixed, predominantly semidiurnal tide. The amplitudes of the harmonic tidal constituents determined from this analysis of the water level are presented in Table 3-5. Amplitudes of the M_2 and K_1 constituents were 16.6 and 12.6 cm, respectively, with much less energy contained in the other constituents.

Similarly, the tidal analysis of current data from South Mouth illustrates a mixed, predominantly semidiurnal, tidal current that is primarily contained within the east component (roughly parallel with the channel axis). Nontidal current residuals are much greater than the tidal currents for both directional components due to variations in river discharge and meteorological forcing.

The tidal current amplitude and phase for the seven most predominant constituents are presented in Table 3-6, based upon the analysis of South Mouth data during the 1985 deployment. As

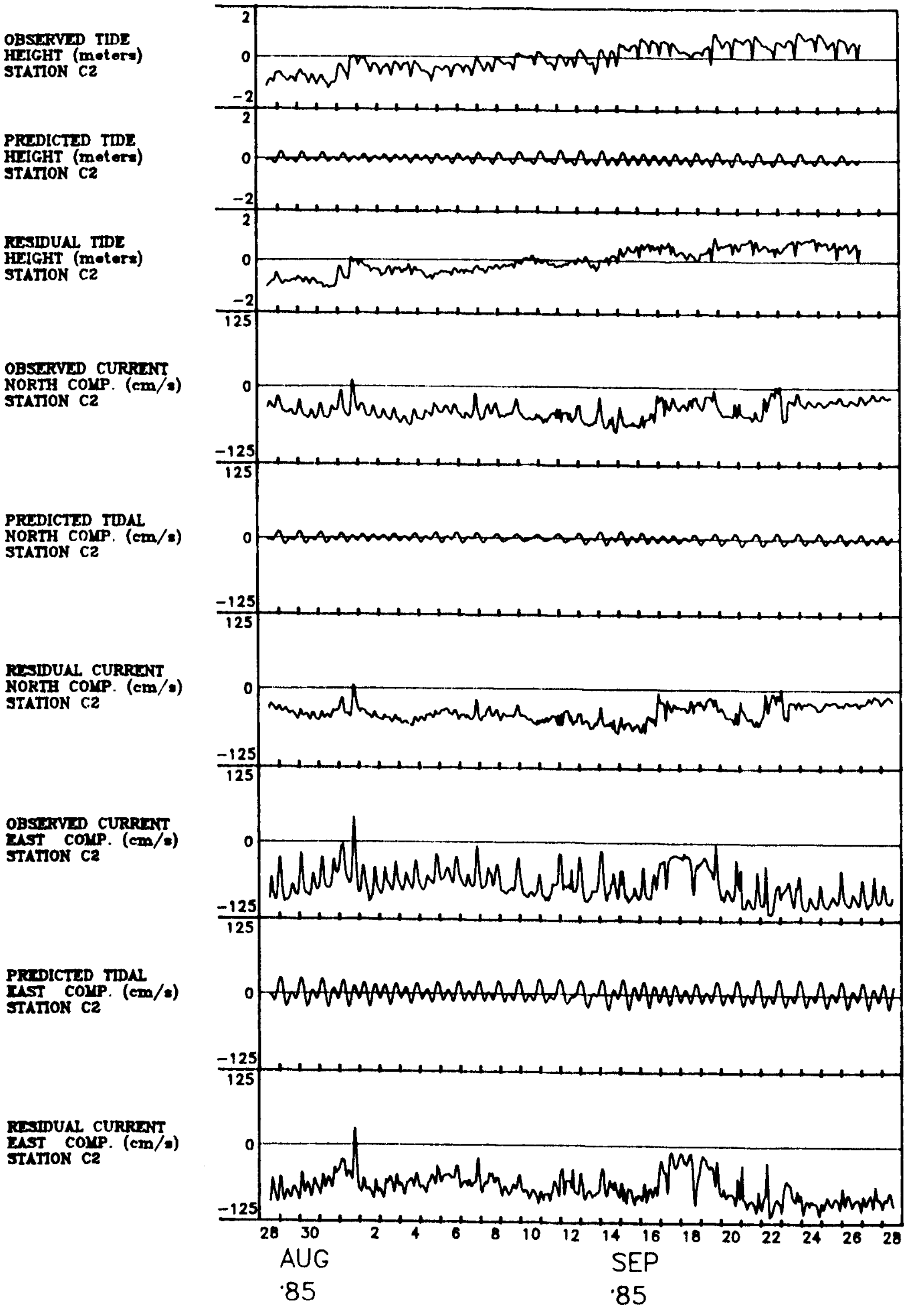


Figure 3-24. Tidal analysis of water-level and current data obtained from mooring C-2 located within South Mouth during the period 28 August through 28 September 1985. The upper three tiers present the observed water level (mean removed), predicted tide height, and residual (observed minus predicted) water level. The lower six tiers present the tidal analysis for individual (north and east) current components.

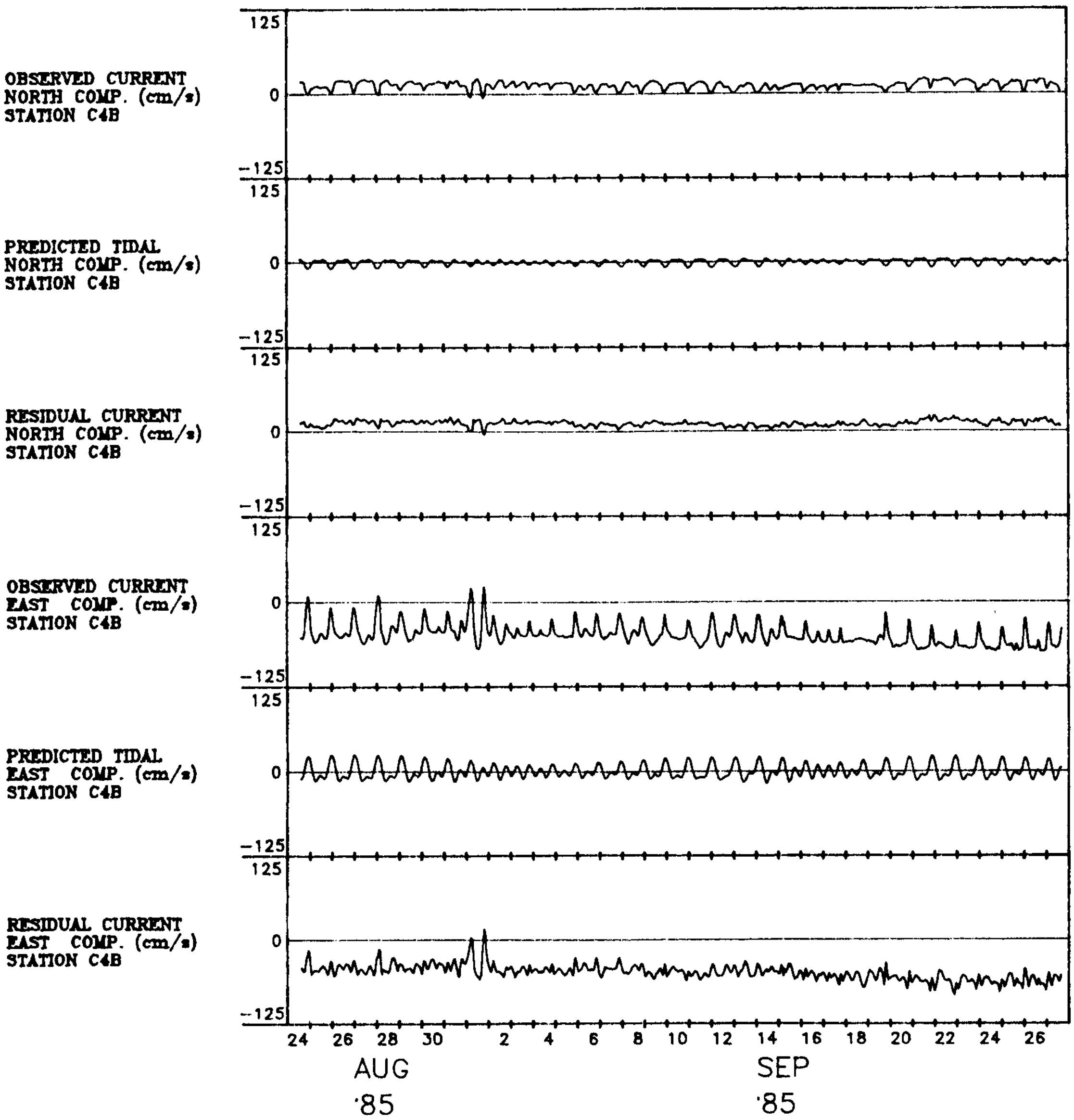


Figure 3-25. Tidal analysis of north and east current components obtained from mooring C-4B located within Middle Mouth during the period 24 August through 27 September 1985. The observed current, predicted tidal current, and residual (observed minus predicted) current are presented for each current component.

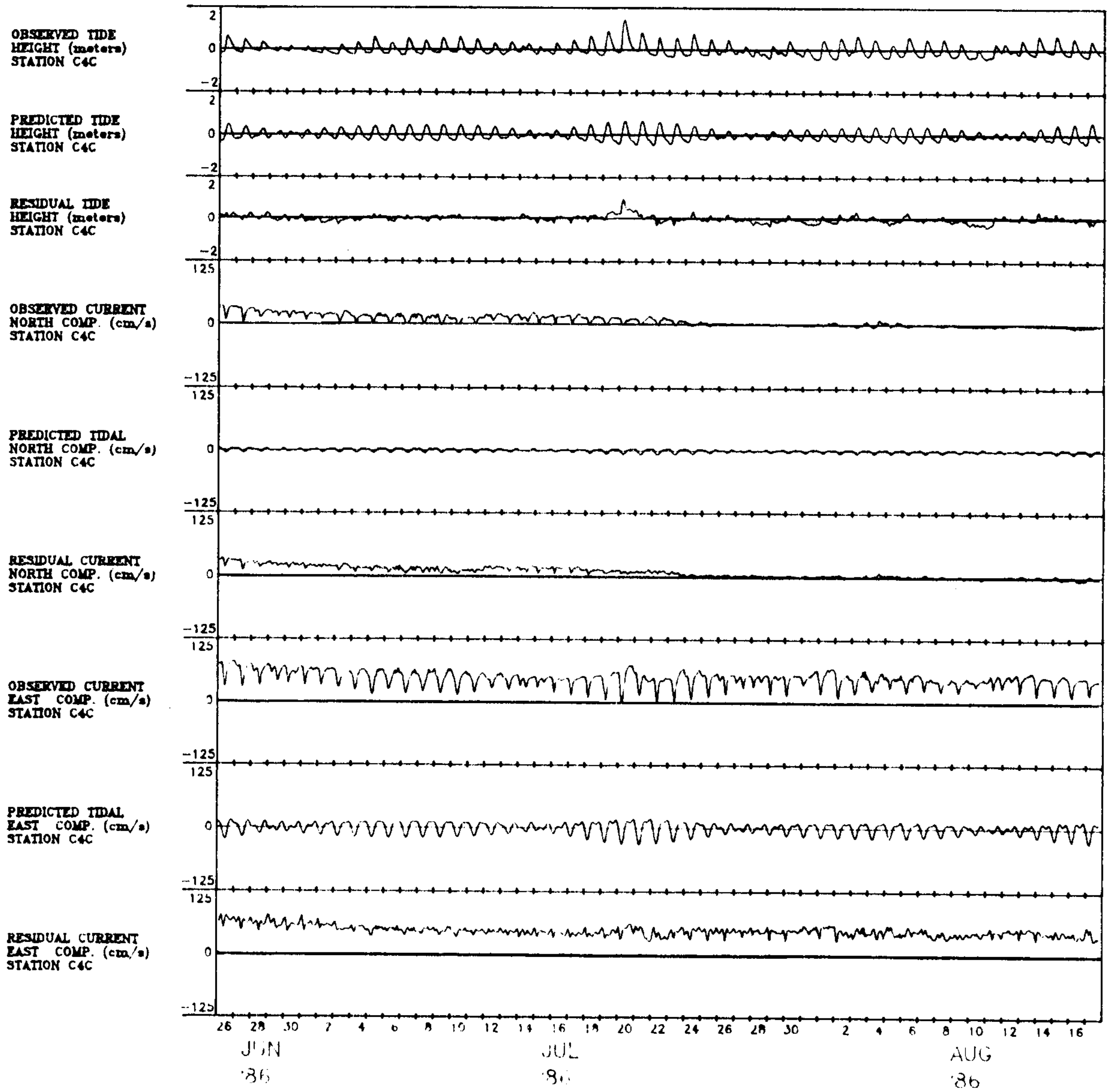


Figure 3-26. Tidal analysis of water-level and current data obtained from mooring C-4C located within North Mouth during the period 26 June through 17 August 1986. The upper three tiers present the observed water level (mean removed), predicted tide height, and the residual (observed minus predicted) water level. The lower six tiers present the tidal analysis for individual (north and east) current components.

Table 3-6. Principal harmonic tidal current constituents determined from moored current records within the three major Yukon River distributaries. Tidal phase is referred to Greenwich.

Constituent	Period (hrs)	Station C-2, South Mouth: Amplitude Major/Minor (cm/s)	Station C-2, South Mouth: Major Axis Orientation (^oT)	Station C-2, South Mouth: Major Axis Phase (deg)	Station C-4B, Middle Mouth: Amplitude Major/Minor (cm/s)	Station C-4B, Middle Mouth: Major Axis Orientation (^oT)	Station C-4B, Middle Mouth: Major Axis Phase (deg)	Station C-4C, North Mouth: Amplitude Major/Minor (cm/s)	Station C-4C, North Mouth: Major Axis Orientation (^oT)	Station C-4C, North Mouth: Major Axis Phase (deg)
Q_1	26.87	2.0/0.4	238	110	2.0/0.4	293	148	1.9/0.2	256	8
O_1	25.82	5.1/0.0	233	131	6.4/0.6	290	160	6.8/0.0	256	43
K_1	23.93	11.8/1.7	69	5	10.1/0.7	111	24	9.0/0.0	255	85
μ_2	12.87	2.1/0.7	58	31	1.2/0.1	107	87	0.6/0.3	295	93
N_2	12.66	2.6/0.1	250	118	1.6/0.3	280	158	2.5/0.1	262	107
M_2	12.42	15.2/0.6	68	17	9.6/0.6	109	48	7.4/0.2	254	139
S_2	12.00	5.3/1.2	79	104	3.7/0.3	110	138	2.2/0.5	262	10

for the water-level record, most of the tidal current fluctuations are contained in the M_2 and K_1 constituents, having amplitudes of 15.2 and 11.8 cm/sec, respectively. The direction orientation of the major axis is given for each constituent, and all agree with the general direction of the channel at that location (roughly 65/245°T).

Results of tidal current analyses for Middle Mouth during the 1985 measurement period are presented in Figure 3-25 and Table 3-6. (A water-level recorder was not deployed on mooring C-4B.) Tidal currents at this location were mixed, with near equipartition of energy between semidiurnal and diurnal constituents. The east component, which was nearly parallel with the channel axis (105/285°T), contained most of the current variability. Both the M_2 and K_1 constituents were oriented toward 110°T $\pm 1°$, with current amplitudes of 9.6 and 10.1 cm/sec, respectively. The nontidal current residual at Middle Mouth during 1 September 1985 reveals two major eastward flow periods that are associated with a meteorological storm. This surge event is described in subsection 3.6.

Tidal analysis of water-level and current records obtained from North Mouth during the summer of 1986 are presented in Figure 3-26. Here, the water level is primarily governed by a diurnal tide, and residuals are very small. The only significant residual (reaching approximately 1 m) is associated with a storm surge event on 20 July 1986. Amplitudes of the tide height constituents (Table 3-5) indicate that the K_1 and O_1 tides (19.3 and 16.3 cm, respectively) are both greater than the M_2 tide (12.6 cm).

The eastward current component at the mooring location in North Mouth also exhibits a predominantly diurnal tide, with high-frequency current fluctuations comprising the residual. (Note that at the site of the mooring, the river channel is oriented roughly 70/250^{o}T.) The tidal current constituent amplitudes, which are given in Table 3-6, confirm that the tidal current is predominantly diurnal at North Mouth.

The analyses presented above reveal several interesting features about the tides around the Yukon Delta. First, the ratio of diurnal to semidiurnal tidal amplitudes at the distributary mouths indicates a predominantly semidiurnal tide at South Mouth, while at Middle and North Mouths, the tide is predominantly diurnal. Second, the spring tide (sum of all constituent amplitudes) at North Mouth (roughly 60 cm) is significantly greater than the spring tide at South Mouth (43 cm). Third, based on the phase of the M_2 tidal current, there is a 2.8-hour lag in the maximum tidal current at North Mouth with respect to South Mouth, while Middle Mouth lags South Mouth by 1.1 hours.

As a final, qualitative note, close inspection of the residual water-level plots from each of the distributary mouths reveals a persistent high-frequency component with a significant rms amplitude. To an extent, this simply represents the effect of random turbulent fluctuations; however, there is also the hint of an underlying periodic signal which suggests the presence of higher harmonic constituents such as M_4, M_6, etc. These so-called "shallow-water tides" (Schureman, 1958) typically arise in coastal waters due to nonlinear modifications of the major diurnal and semidiurnal constituents. Further evidence of these effects is apparent in the asymmetry of the ebb and flood tides in the raw water-level and current velocity records. As a typical pattern, the water level is seen to rise more steeply on the flood and recede more gradually on the ebb. Consistent with this variation, the flood current is more sharply peaked and of shorter duration than the more sluggish ebb current. It should be emphasized that these comparisons of the tidal currents refer to fluctuations about a mean current. Note that in the Yukon during periods of strong discharge, the mean current is sufficiently large to maintain a seaward flow under all phases of the tide, so that there is typically no actual current reversal between the flood and ebb phases of the tidal cycle, at least at South Mouth.

The tidal asymmetry evident for each of the distributary mouths is similar to that reported for other tidal channels; e.g., for Nauset Inlet as observed by Aubrey and Speers (1983). Using a numerical model to simulate the nonlinear dynamics, they explain the behavior by the generation of the M_4 tide due to nonlinear bottom friction and the effect of changing water depth. In cases where tidal currents are predominant, the effect of higher velocity flood currents, as compared with ebb currents, has important consequences for the net transport of sediments through the system. For summer conditions in the Yukon distributaries, tidal velocities are small in comparison to the observed mean freshwater river discharge. The net transport remains seaward regardless of the nonlinear details of the tidal dynamics. Under conditions of reduced river discharge in late fall, it is possible that the tides may briefly assume a more dominant role within the distributary channels prior to winter freezeover. At this time, consideration of such effects as flood and ebb asymmetry may become a worthwhile object for analysis. The problem may be compounded by potential salinity intrusions at this time, as discussed in subsection 3.5.

3.3.2.3 Other Sources of Tide Data

In addition to the water-level measurements conducted by EG&G during the 1985 and 1986 field programs, two other sources of water-level data from the Yukon Delta have been identified: measurements obtained from within the three major distributary mouths during summer 1985 by NOAA RU 660 (Envirosphere, 1986), and measurements at sites along the Delta shoreline that were conducted in 1982 by ITEC and processed by EG&G under contract to

NOAA. These various water-level records have been archived and processed at EG&G to allow comparison with the recent water-level measurements conducted as part of this program.

Figure 3-27 indicates the locations of the nine water-level records that have been analyzed to resolve the tidal characteristics around the Yukon Delta. The EG&G water-level measurements were obtained from South Mouth, Apoon Pass (8 miles upstream from North Mouth), and an offshore site located 16 miles west of South Mouth. The water-level recorders deployed by RU 660 were located within South, Middle, and North Mouths at distances of a few miles upstream of the Delta shoreline. Bubbler tide gauges were installed by ITEC near the three distributary mouths: the first gauge was deployed on Blind Island, 4 miles west of the South Mouth; the second gauge was deployed at Middle Mouth on Nanuktuk Island; and the third gauge was deployed 3 miles east of Apoon Pass (North Mouth) at the entrance to the Pastoliak River.

Figure 3-28 presents a composite plot of observed, predicted, and residual water-level records that were obtained from analysis of the RU 660 measurements in the three distributary mouths. These records are very useful because they begin in mid-June 1985 (prior to the first EG&G deployment) and continue into mid-September, concurrent with the EG&G measurements.

In general, the predicted tide and residual water levels at North and South Mouths agree well with the characteristics of the EG&G water-level data from those sites. Characteristics are predominantly diurnal at North Mouth, and mixed, predominantly semidiurnal, at South Mouth. Residual water levels exhibit high-frequency fluctuations, and 1- to 3-day events related to meteorological forcing, but little energy at tidal frequencies, thus indicating that the tidal signal-to-noise ratio of the records is sufficient for accurate tidal analyses.

However, the tidal amplitude predicted from the water-level record at Middle Mouth seems to be erroneously small when

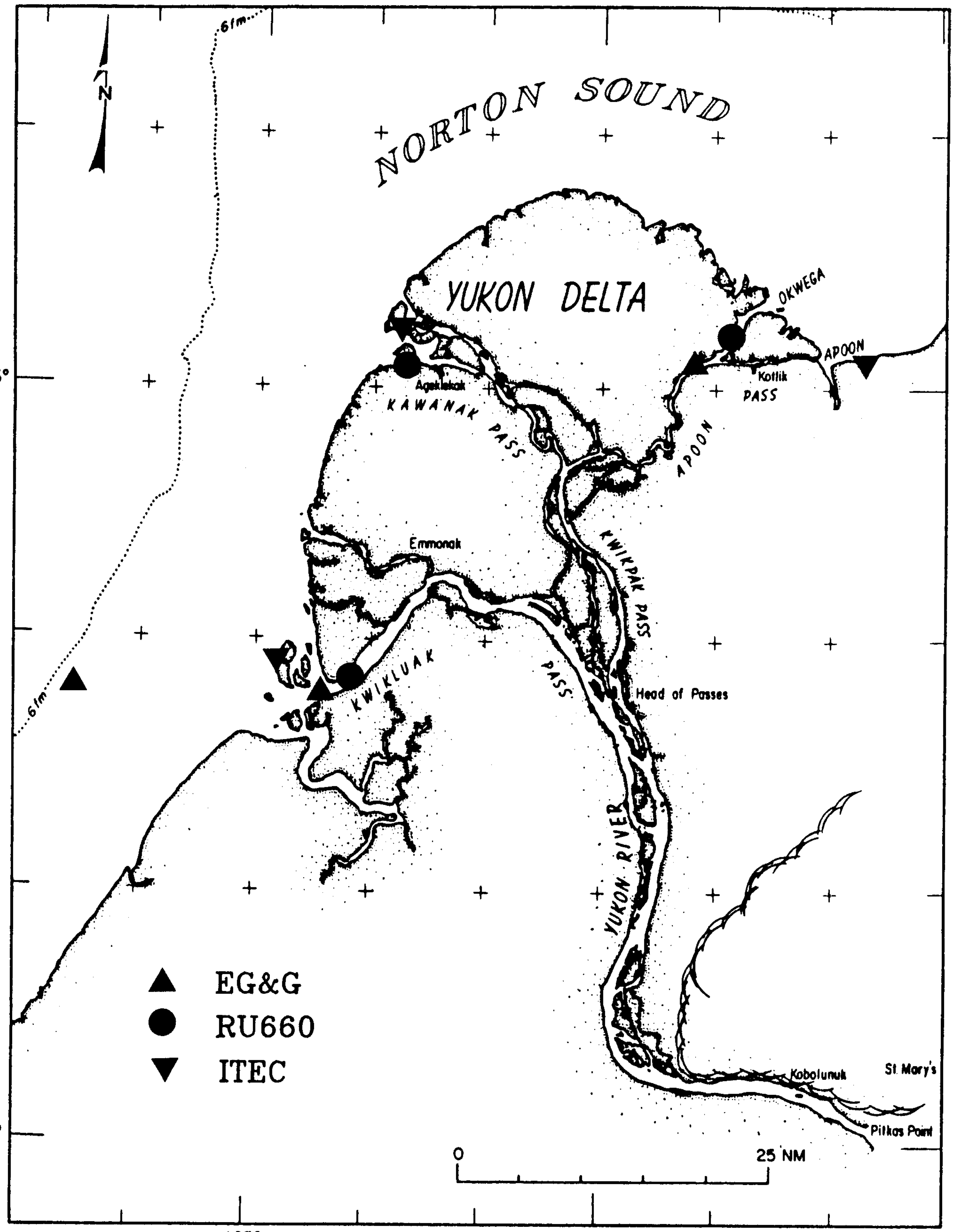
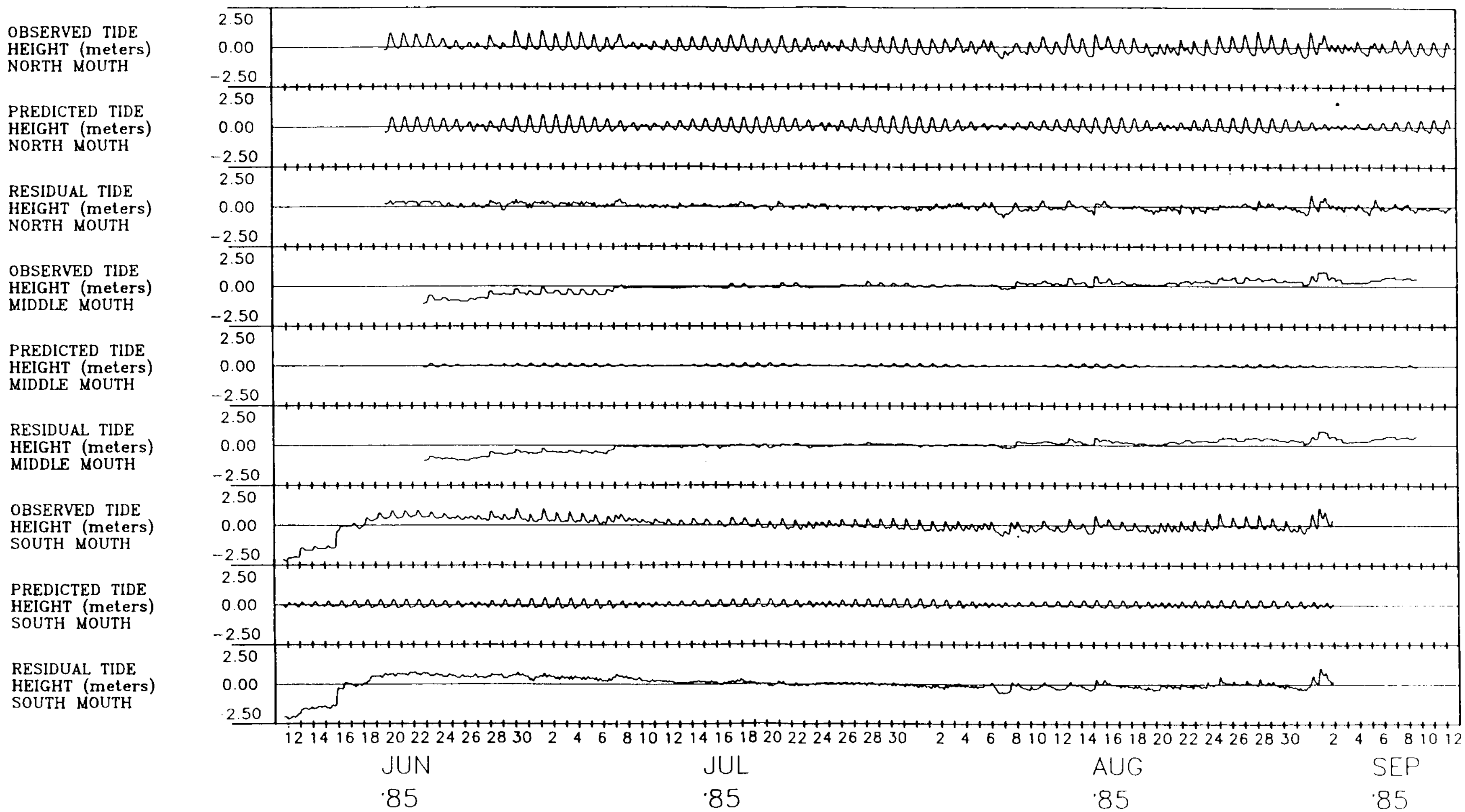


Figure 3-27. Locations of nine water-level records used in the analysis of tidal characteristics on the Yukon Delta. Measurements were made by EG&G (1985 and 1986), NOAA Research Unit 660 (1985), and ITEC (1982).



Tidal analyses of water-level data that were obtained from North, Middle, and South Mouths for the period mid-June through mid-September 1985 by NOAA Research Unit 660. The observed water level (mean removed), predicted tide height, and the residual (observed minus predicted) water level are presented for each of the measurement sites.

Figure 3-28.

compared with the tidal amplitudes at South and North Mouths. This discrepancy will become more evident upon analysis of the tide height constituents that are presented below.

Table 3-7 presents the amplitude and phase of the principal tide height constituents that were determined at South, Middle, and North Mouths from analysis of the RU 660 water-level measurements. Results from South and North Mouths agree with the tidal constituents derived from the EG&G measurements at these sites (Table 3-5). At Middle Mouth, however, tidal amplitudes for all constituents appear low, especially those for the M_2, K_1 and O_1 constituents. Comparison between these amplitudes and those obtained from nearby measurements is provided in the following subsection.

Tidal analyses of the water-level data collected by ITEC at three sites around the Yukon Delta are presented in Figure 3-29. The observed, predicted, and residual water levels are shown for Pastoliak (near North Mouth), Kawanak (Middle Mouth), and Kwikluak (South Mouth) for the period 20 July through 8 September 1982. Although both diurnal and semidiurnal components are present in all three records, the tides are predominantly semidiurnal near South Mouth and predominantly diurnal near North Mouth. These records also indicate that tidal ranges increase from South Mouth to North Mouth; the amplitude and phase of the principal tide height constituents (Table 3-8) indicate that maximum ranges for the sum of the seven constituents at South, Middle, and North Mouths are 62, 95 and 108 cm, respectively. These ranges are considerably larger than tide height ranges determined from the EG&G and RU 660 measurements due to the location of the measurements; the EG&G and RU 660 measurements were made upstream of the distributary mouths, while the ITEC measurements were made on the outer edge of the Delta. Further comparison between the individual tidal data sources is given below.

Table 3-7. Principal harmonic tide height constituents determined from analyses of water-level records within the three major Yukon River distributaries obtained in 1985 by NOAA Research Unit 660. Tidal phase is referred to Greenwich (GMT).

		South Mouth		Middle Mouth		North Mouth	
Constituents	Period (hrs)	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
Q_1	26.87	1.7	32	1.5	109	4.7	54
O_1	25.82	9.0	37	4.6	64	18.5	80
K_1	23.93	12.8	79	6.1	121	25.3	128
μ_2	12.87	1.3	119	0.4	270	0.8	226
N_2	12.66	4.6	82	1.1	130	4.8	171
M_2	12.42	13.8	145	3.6	189	14.9	210
S_2	12.00	5.2	269	1.3	290	4.1	2

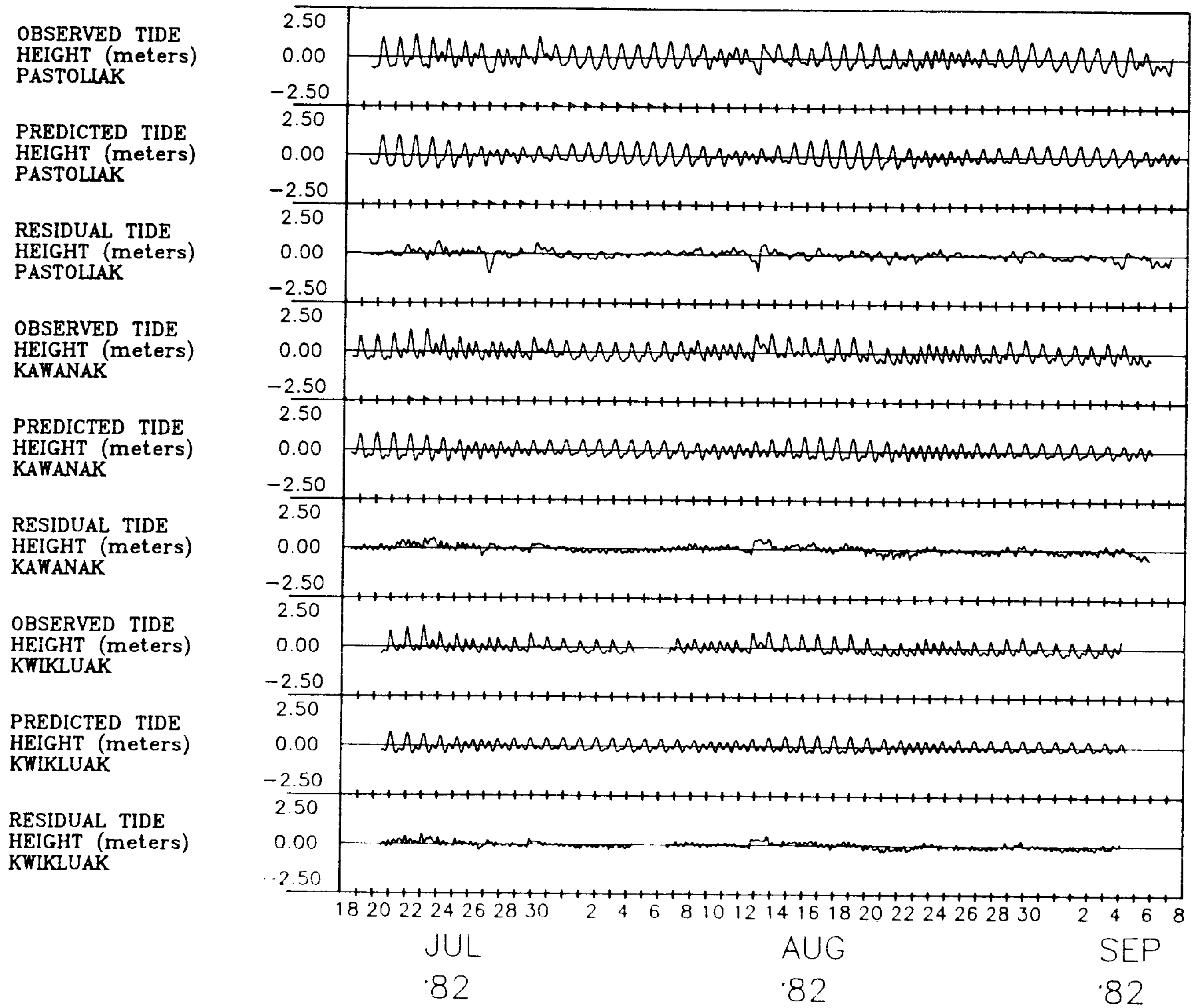


Figure 3-29. Tidal analyses of water-level data that were obtained from Pastoliak (near North Mouth), Middle Mouth (Kawanak), and South Mouth (Kwikluak) for the period mid-July to early September 1982 by ITEC. The observed water level (mean removed), predicted tide height, and the residual (observed minus predicted) water level are presented for each of the measurement sites.

Table 3-8. Principal harmonic tide height constituents determined from analyses of water-level records within the three major Yukon River distributaries obtained in 1982 by ITEC. Tidal phase is referred to Greenwich (GMT).

		South Mouth		Middle Mouth		North Mouth	
Constituents	Period (hrs)	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
Q_1	26.87	3.8	327	4.8	332	6.2	34
O_1	25.82	1.4	-9	17.8	-12	24.2	45
K_1	23.93	18.7	21	26.0	28	37.4	105
μ_2	12.87	1.4	281	1.3	267	1.6	7
N_2	12.66	5.8	10	7.0	19	4.7	143
M_2	12.42	21.8	47	25.5	58	21.8	184
S_2	12.00	9.1	206	12.7	213	12.1	334

3.3.2.4 Summary of Tidal Measurements

The results of the previous tidal analyses can be synthesized to obtain a meaningful picture of tidal characteristics around the Yukon Delta. To provide a framework from which to assess the various tidal characteristics, it is useful to first review the tidal regime of this region, with the purpose of identifying factors which may affect local tidal conditions.

Tides around the Yukon Delta are primarily influenced by the tidal dynamics of the eastern Bering Sea and Norton Sound. The tidal wave propagates counterclockwise from the western portion of Norton Sound (where water depths are 40 to 70 feet), across the shallow flats of the Delta platform (depths from 2 to 10 feet), and impinges on the Delta shoreline and into the river distributaries. Because the tide propagates with the phase velocity of a shallow water wave, its phase velocity is proportional to the square root of the depth. Since the shallow Delta platform is traversed by narrow subaqueous channels which originate at the mouths of the major distributaries, the tidal wave may propagate more rapidly within the channels than across the shallow coastal areas.

This complex coastal topography is conducive to a high degree of spatial variability in the amplitude and phase of the Yukon Delta tides. Tidal energy dissipation due to friction is also accentuated over the very shallow areas; this frictional effect reduces tidal amplitudes nearshore and decreases the phase velocity of the tide wave. In addition, within the major distributaries, the intense river flow opposes tidal propagation, reducing the phase velocity of the tide wave. Tidal propagation within Kwikluak, Kawanak, and Apoon Passes is also affected by the presence of numerous islands at the distributary mouths and complex bottom topography within the channels.

In order to evaluate the spatial variability of the Yukon Delta tidal characteristics, the amplitudes and phases of the

K_1 and M_2 tidal constituents have been plotted on separate maps of the Delta (Figures 3-30 and 3-31, respectively), with values indicated at the individual measurement locations. Both figures illustrate that phases increase from South Mouth to North Mouth, in agreement with the known counterclockwise tidal rotation in this region of the eastern Bering Sea.

These figures also indicate that the M_2 and K_1 tidal amplitudes at South Mouth are only 30% of their corresponding tidal amplitudes 16 miles offshore (station C-3). This 70% reduction in tidal amplitude indicates that the shallow topography surrounding the Delta acts as an efficient sink of tidal energy. Tidal amplitudes are further reduced upstream of the distributary mouths.

As previously mentioned, the tidal amplitudes obtained from the analysis of water-level data collected at Middle Mouth by RU 660 appear to be erroneously small. These amplitudes are roughly 80% less than tidal amplitudes determined from analysis of the ITEC data obtained at Middle Mouth, a distance of only 3 miles to the north of the RU 660 gauge. Considering this amplitude discrepancy and the extremely large (131^{o}) phase difference between the two records, we view the RU 660 water-level data from Middle Mouth as suspect.

In general, the phase of both the K_1 and M_2 tidal constituents increases rapidly with distance upstream in the major Yukon distributaries. This indicates that bottom friction and intense river flow within the distributaries contribute to a significant reduction of the phase velocity of the tidal wave. Although a limited number of water-level measurements is available from within the major distributaries, a rapid upstream decay in tidal amplitudes is evident in Figures 3-30 and 3-31. The extent of tidal influence upstream from the distributary mouths cannot, however, be determined from the available water-level measurements. The rate of tidal energy dissipation and the

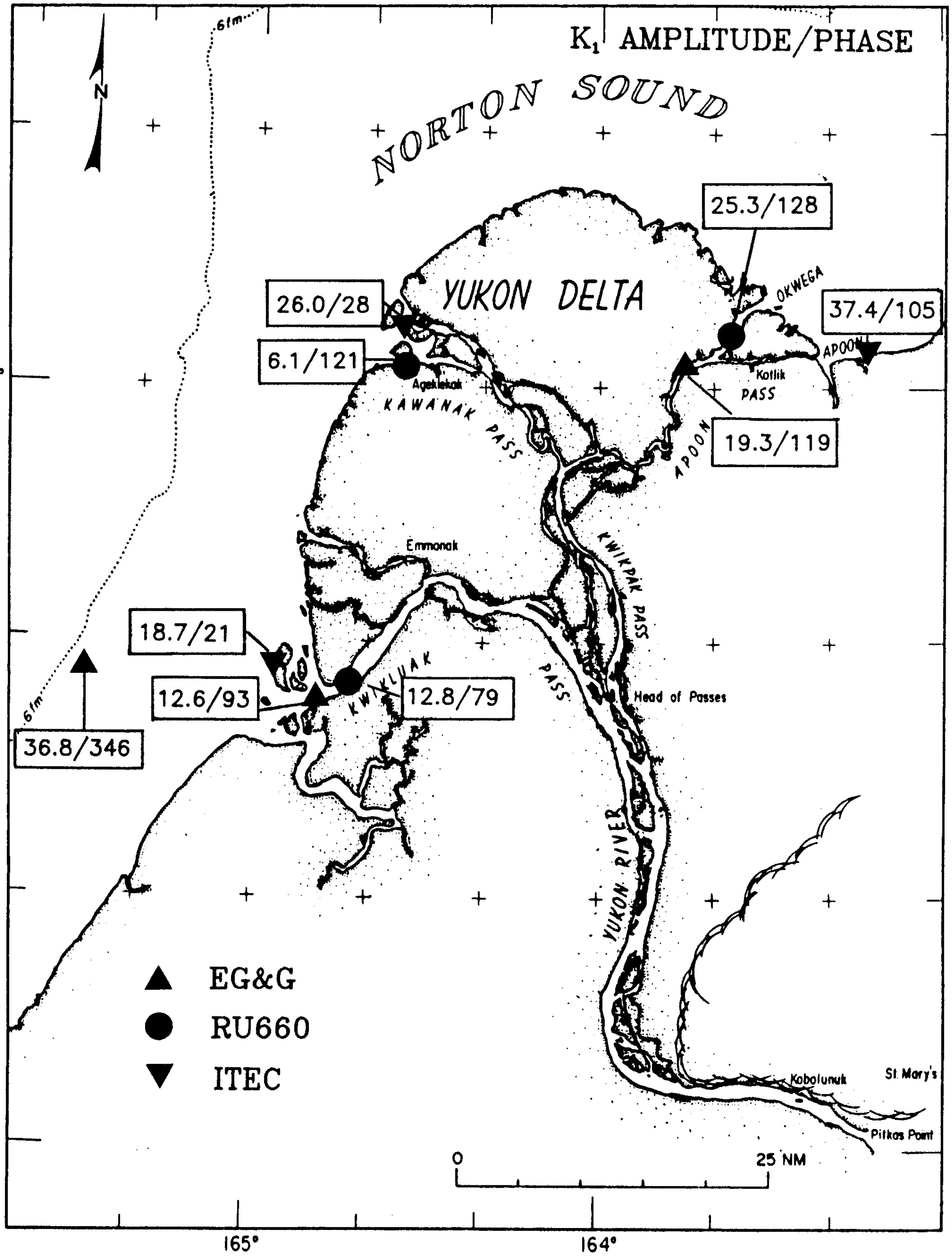


Figure 3-30. Spatial distribution of the amplitude (cm) and phase (degrees, referred to Greenwich) of the K_1 tidal constituent at measurement sites around the Yukon Delta.

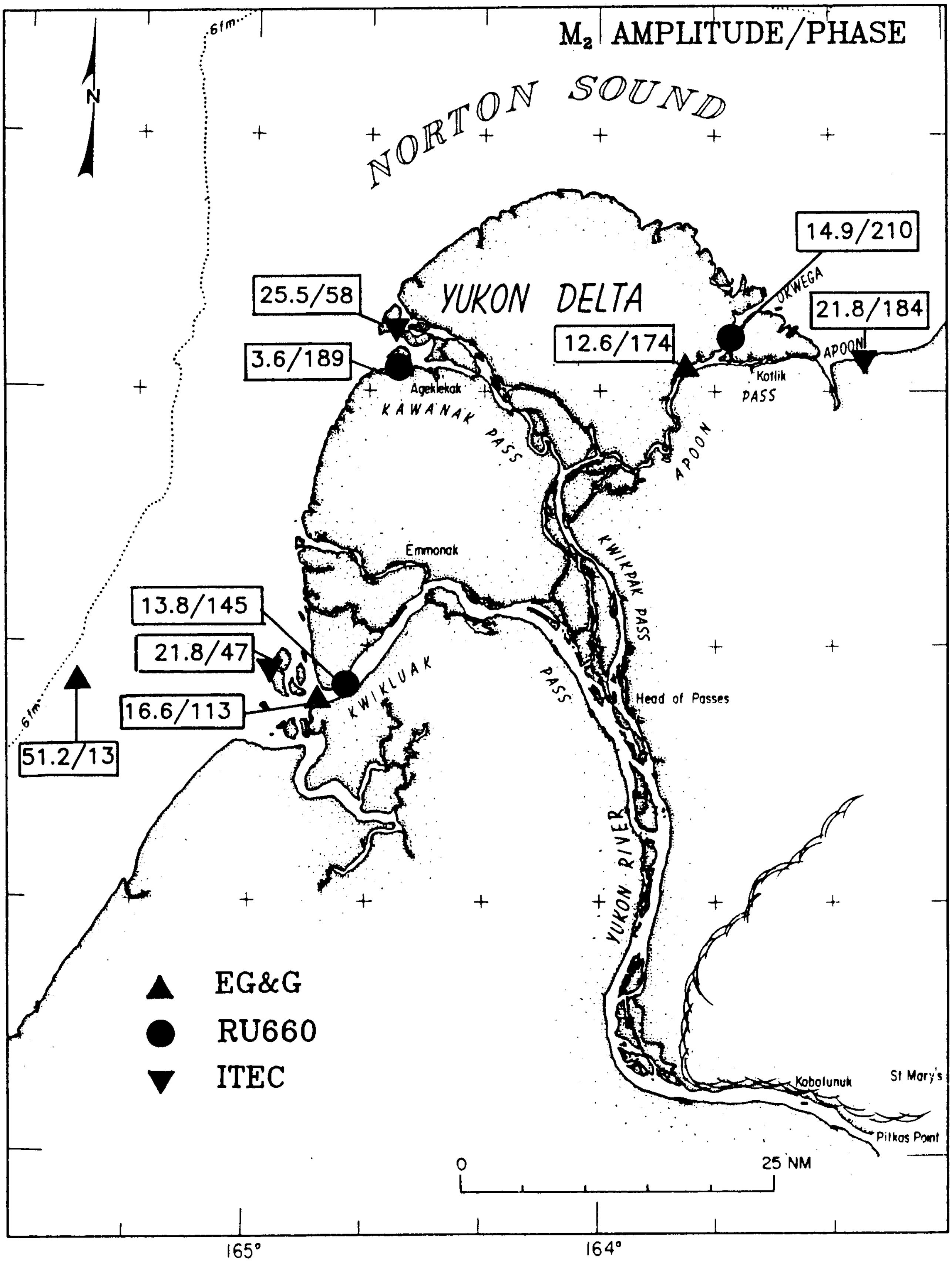


Figure 3-31. Spatial distribution of the amplitude (cm) and phase (degrees, referred to Greenwich) of the M_2 tidal constituent at measurement sites around the Yukon Delta.

extent of tide wave penetration within the distributaries can only be resolved with a closely spaced array of tide gauges within each of the distributaries, since the dissipation characteristics within South Mouth are certainly different from those in Middle and North Mouths.

In addition to the high degree of spatial variability in the amplitude and phase of the Yukon Delta tides, there is also significant spatial variability in the diurnal/semidiurnal tidal amplitude ratio along the Delta coastline. This tidal amplitude ratio, defined as $F = (K_1 + O_1)/(M_2 + N_2)$, has been introduced by Pearson et al. (1981) to characterize the tides in the eastern Bering Sea. As previously discussed, ratios ranging from 0.5 to 1.5 indicate predominantly semidiurnal tides, while ratios ranging from 1.5 to 3.0 indicate predominantly diurnal tides. Table 3-9 presents the values of F for the nine Yukon tide stations shown in Figure 3-27. With the exception of the RU 660 record from Middle Mouth, all other records from South and Middle Mouths indicate a mixed, predominantly semidiurnal tide. In contrast, all tide sources from North Mouth indicate a predominantly diurnal tide, with amplitude ratios over 2. The ratio of 2.28 for the RU 660 record at Middle Mouth is further evidence of measurement error in this water-level record.

Table 3-9. Diurnal/semidiurnal tidal amplitude ratios (F) determined from water-level records obtained at sites around the Yukon Delta. Measurements were made by EG&G (1985 and 1986), NOAA RU 660 (1985), and ITEC (1982) at sites shown in Figure 3-30. The RU 660 measurements from Middle Mouth appear erroneous.

Station Location	Source	Diurnal/Semidiurnal Amplitude Ratio (F)
Offshore South Mouth	EG&G	0.94
South Mouth	ITEC	0.73
	EG&G	0.88
	RU 660	1.18
Middle Mouth	ITEC	1.35
	RU 660	(2.28)
North Mouth	ITEC	2.32
	RU 660	2.22
	EG&G	2.15

$$F = \frac{K_1 + O_1}{M_2 + N_2}$$

3.4 RIVER DISCHARGE

Another primary objective of the Yukon measurement program was to quantify the volume transport or discharge at an upstream site (i.e., Kobolunuk), as well as within the major distributaries. The discharge from the various distributary mouths is of considerable importance because it effectively governs the dynamics of flow in the nearshore regions surrounding the Delta.

The basic method for determining discharge within a river is to monitor river height and use discrete current measurements to derive a transfer function between height and discharge. In the absence of any prior measurements of the flow in the lower Yukon and on the Delta, EG&G was concerned that the two-dimensional flow field may be complex and difficult to resolve with a single current meter moored on each of three or four river transects. For this reason, an extensive velocity profiling survey was conducted on four of the five field trips (two in 1985 and two in 1986) to resolve the cross-sectional flow field at various locations along the river. These data have proven to be extremely valuable in the present study in several respects. First, the velocity profiles clearly illustrate the large vertical and horizontal shear across each river transect, in addition to large temporal variations in the shear field between surveys. Second, the velocity transects can be used to accurately estimate the river discharge at specific transect locations. Estimates at various locations lead to a simple box model of flow throughout the major river distributaries, and its variability during the summer and early fall of 2 consecutive years. Third, the velocity profile data can be used to determine whether the moored current records from within the river are representative of the actual flow field and its variability. These issues are addressed in the following subsections.

3.4.1 Velocity Transects

Velocity profiles were conducted along numerous river transects during all but the first field trip; the four surveys were made in mid-August and late September of 1985, and mid-June and mid-August of 1986. This temporal sampling provided measurements in most summer months, as well as one interannual comparison during August. Although it was determined that the characteristics of the river flow field changed greatly on time scales much shorter than the survey interval, and, thus, the temporal evolution of the flow cannot be resolved, the velocity surveys do provide interesting snapshots that can be compared with the moored current measurements.

The spatial sampling scheme was based upon the need to quantify the Yukon flow at an upstream location, as well as at each major bifurcation on the Delta. For this reason, velocity transects were conducted at Kobolunuk during each survey. Transects were also repeated a short distance downstream of Head of Passes to quantify the flow within Kwikluak and Kwikpak Passes. On selected field trips, additional transects were occupied farther downstream to determine the flow within Kawanak, Apoon, and Kwiguk Passes. A limited number of transects were also made in South, Middle, and North Mouths, but these were difficult to interpret because of the significant tidal influence within the distributary mouths.

All of the velocity profiles have been used in conjunction with bathymetric profiles to construct cross-sections of the downstream flow field at each transect location. The procedure used to generate these velocity cross-sections is described in subsection 2.3. During the four surveys, a total of 36 velocity transects were occupied and analyzed, but only a small number of velocity cross-sections are presented here to illustrate the characteristics of the two-dimensional flow field and its temporal variability. Figure 3-32 presents the results of the

KOBOLUNUK TRANSECT

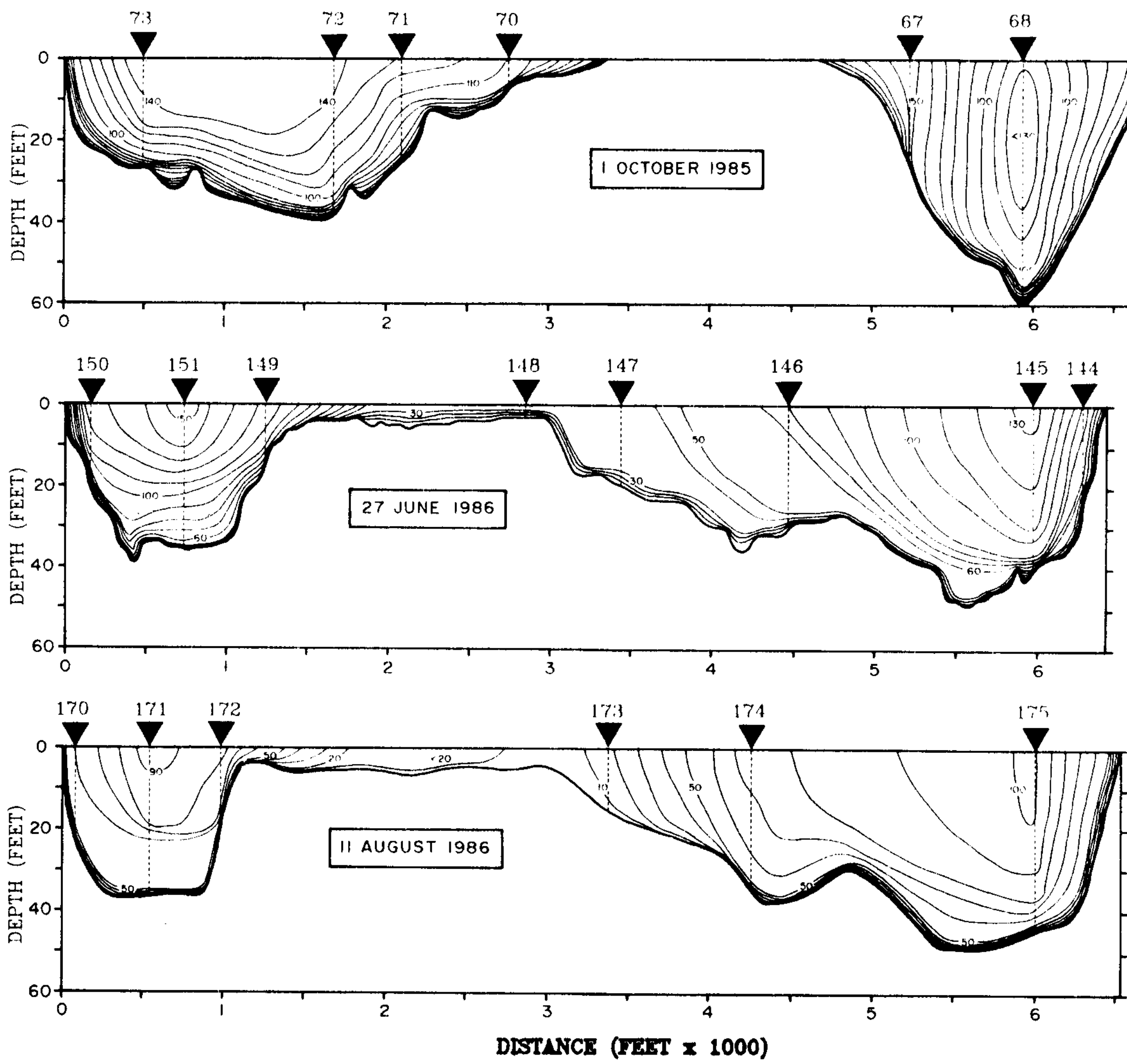


Figure 3-32. Yukon River transects at Kobolunuk illustrating the two-dimensional shear of downstream current speed during three profiling surveys: 1 October 1985, 27 June and 11 August 1986. Current data from individual profiling stations are given in Appendix B. Velocities are shown in units of cm/sec.

velocity profiling conducted near Kobolunuk on 1 October 1985, 27 June and 11 August 1986. At this location, there were two channels separated by a mid-river shoal. Differences in the bathymetric profiles between the three surveys were a result of the profiles being made at slightly different locations: the 1 October 1985 transect was located approximately 1/4-mile upstream of the two later transects. Only small bathymetric differences are noted between the two 1986 transects because they were made within 100 m of each other.

During 1 October 1985, the Kobolunuk velocity transect exhibited strong flow in both channels, with extensive current shear in the vertical and horizontal directions. This shear was clearly evident during the field measurements: the core of strongest flow could always be seen from the vessel; foam and floating debris were normally trapped at the surface within this high-velocity core; and surface waves were larger in the core than in the surrounding water when the wind was opposing the river flow.

In the northern channel at Kobolunuk (Figure 3-32), downstream currents exceeded 130 cm/sec within a relatively deep, but narrow core that was centered over the deepest part of the channel. Considerable horizontal shear was observed across the channel, while the vertical shear was small, except within the bottom boundary layer. Velocities of 100 cm/sec were observed within 10 feet of the bottom in the channel axis, and a thin bottom boundary layer, having velocities of 50 cm/sec within 3 feet of the bottom, existed at each profile station.

The broader, southern channel at this transect had a wide core with velocities exceeding 140 cm/sec (speeds may have been greater in the center of the core, but the profile spacing was not adequate to resolve the center of this feature). The bottom boundary layer was also very thin for all profiles. At this time, the southern channel at Kobolunuk conveyed considerably more flow than the northern channel (8,041 m^3/sec versus 5,094 m^3/sec, respectively).

The two 1986 Kobolunuk transects were made downstream of the sand bar where the 1985 transect was made. Consequently, the bathymetric profiles look totally different; the northern channel was roughly three times the width of the southern channel, but maximum depths were comparable. On 27 June 1986, the maximum downstream velocity of the transect (150 cm/sec) was measured at the surface within the axis of the narrow, southern channel. In the northern channel, maximum velocities of 130 cm/sec were observed slightly north of the deepest part of the channel.

The flow partition between the two Kobolunuk channels had apparently reversed by 11 August 1986, and the total river discharge decreased significantly since June. In the southern channel, the vertical shear had lessened and downstream velocities had decreased by roughly 30%; velocities in the northern channel decreased only slightly. The maximum velocity of the transect (100 cm/sec) was observed in the northern channel.

For comparison with the velocity transects from Kobolunuk, Figure 3-33 presents similar cross-sections for the same three time periods at a site in Kwikluak Pass near Lamont (10 miles downstream of Head of Passes). At this location, the navigable river is less than 1 mile wide, compared to the Kobolunuk sections, which ranged from 6,000 to 7,000 feet in width. The Lamont bathymetric profile is characterized by a deep channel adjacent to the northern bank, and a narrow, shallow channel at the southern bank. On 1 October 1985, strong flow was observed in both channels with maximum velocities in excess of 180 cm/sec in a core situated above the deepest part of the northern channel. Strong vertical and horizontal shear was present in both channels.

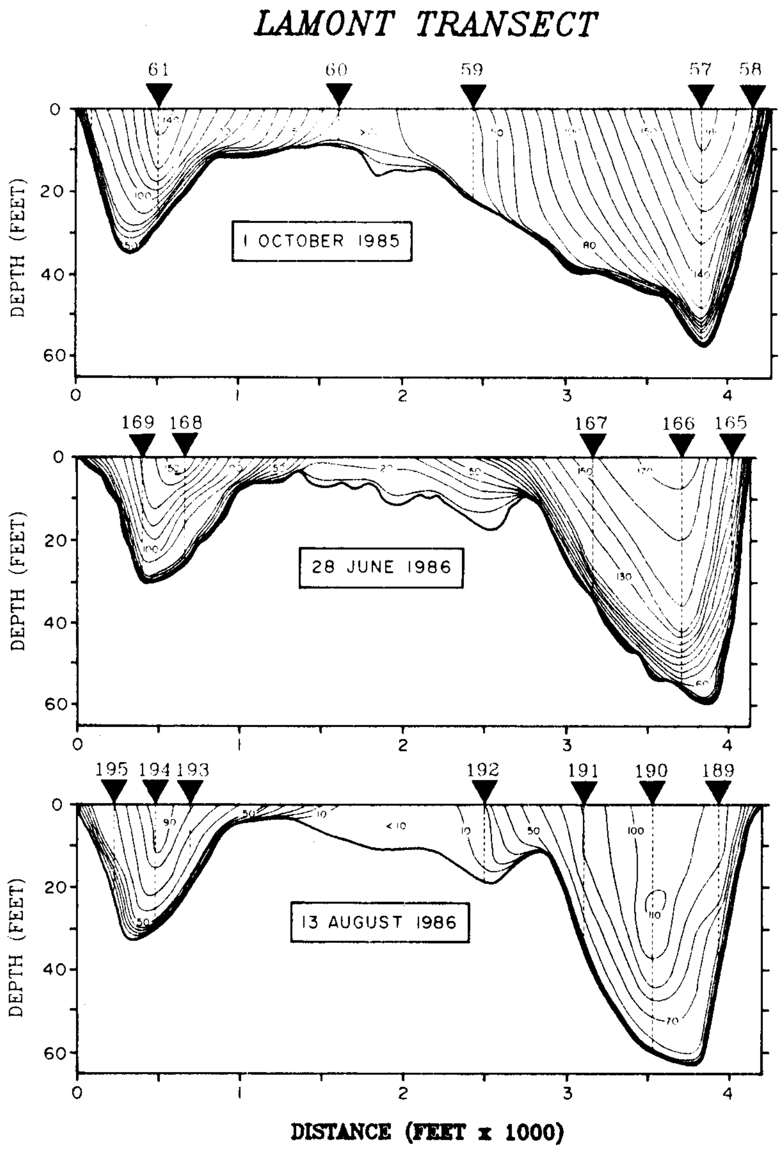


Figure 3-33. Yukon River transects in Kwikluak Pass near Lamont illustrating the two-dimensional shear of downstream current speed during three profiling surveys: 1 October 1985, 28 June and 13 August 1986. Current data from individual profiling stations are given in Appendix B. Velocities are shown in units of cm/sec.

The velocity cross-sections of October 1985 (Figures 3-32 and 3-33) illustrate that currents were stronger at Lamont than at Kobolunuk. It is shown in the following subsection that about two-thirds of the river discharge at Kobolunuk passes through the Lamont transect in Kwikluak Pass, but the restricted cross-sectional area at Lamont causes the local acceleration of the flow. In late June 1986, the river currents at Lamont were again significantly greater than speeds at Kobolunuk. During the survey of mid-August 1986, current speeds were comparable at the two transects, but the vertical and horizontal shear at Lamont was greater than at Kobolunuk.

These few velocity cross-sections clearly illustrate that the Yukon River and its distributaries are characterized by extensive current shear that varies greatly with time and location along the river. The velocity field at each river transect is complex, and point measurements of currents that are obtained from moored current meters cannot adequately represent the velocity field across a given transect. This is evident upon inspection of the current records presented in subsection 3.2. For instance, the current record from the north channel at Kobolunuk during summer 1985 exhibited very little variability, whereas the transport had increased by 42% from late August to early October.

As a final remark about the quality of the velocity profile results, excellent agreement was found when comparing the moored current measurements (at the time of the profiling survey) with the velocities interpolated from the profile measurements. On 1 October 1985, the current meter moored on the north slope of the northern channel at Kobolunuk measured 90.8 cm/sec, while the current, interpolated from the same relative position on the transect, was roughly 95 cm/sec according to the profile results. Comparisons at other times and at other locations in the river also gave equally favorable results.

3.4.2 Discharge Calculations

The Yukon velocity transects described in the previous subsection have been used to quantify the river discharge at each transect location. These results provide valuable information on the range of temporal variability during the summers of 1985 and 1986, and allow comparisons with hydrologic data from upstream monitoring stations. Each profiling survey also represents a "snapshot" of the Delta, which can be used to quantify the flow partition among the three major distributaries. The individual surveys are considered synoptic because, with the exception of periodic tidal oscillations, conditions varied minimally during the 3- to 5-day surveys.

Table 3-10 presents the discharge results for the four profiling surveys; transect numbers correspond with Figures 2-5 through 2-8. During each survey, transects were occupied at Kobolunuk, in the center of the Delta (Kwikpak and Aproka Passes), and at Lamont in Kwikluak Pass. Transects at South, Middle, and North Mouths were occupied less frequently, since the results were known to be affected by tidal processes.

Discharge at Kobolunuk

In 1985, the discharge at Kobolunuk increased from 9,200 m^3/sec in mid-August to 13,120 m^3/sec in late September, which represents a 43% increase during a period when the river is normally subsiding. This increase was also measured in Kwikluak Pass (a 37% increase from 7,160 to 9,780 m^3/sec), and further evidence is found in the water-level data (subsection 3.3) which documents a substantial rise in the river level during this period.

The first profiling survey of the 1986 field program was conducted in June in order to monitor the river during the period of intense runoff which follows ice breakup. During this survey, the discharge at Kobolunuk was measured twice, on 22 and 27 June,

Table 3-10. Yukon River discharge at various transect locations within the river and its major distributaries. Transect positions are shown in Figures 2-5 to 2-8. Discharge estimates obtained within regions of tidal influence are indicated by an asterisk.

	Survey #1 18-23 Aug 1985		Survey #2 26 Sept-1 Oct 1985		Survey #3 21-28 Jun 1986		Survey #4 12-14 Aug 1986	
	Transect No.	Transport m^3/sec	Transect No.	Transport m^3/sec	Transect No.	Transport m^3/sec	Transect No.	Transport m^3/sec
Upstream								
Kobolunuk	PA-1	9,200	PB-11	13,120	PC-6A	11,040	PD-1	8,950
					PC-6B	10,870		
Mountain Village					PC-5	10,300	PD-2	9,250
Central Delta								
Kwikpak Pass	PA-2	3,400	PB-4	3,540	PC-2A	4,370	PD-3	3,100
					PC-2B	3,850		
Aproka Pass	PA-3	220	PB-5	370	PC-4A	260	PD-4	220
					PC-4B	290		
South Branch								
Kwikluak Pass (Lamont)	PA-4	7,160	PB-8	9,780	PC-1A	8,530	PD-5	5,610
					PC-1B	8,460		
Kwiguk Pass			PB-10	850*				
South Mouth	PA-5	9,340*	PB-9	6,940*				
Middle Branch								
Kawanak Pass (Seagull Pt.)			PB-2	2,480*				
Middle Mouth (N)			PB-1	480*				
Middle Mouth (S)			PB-7	1,340*				
Kwikpakak Slough			PB-6	20*				
North Branch								
Apoon Pass (Hamilton)			PB-3	940	PC-3A	1,260	PD-6	710
					PC-3B	700		
Apoon Pass (Kakuktahuk)					PC-9	1,420*		
Apoon Pass (Kotlik)					PC-7	150*		
Okwega Pass					PC-8	540*		

at approximately 11,000 m^3/sec, with a difference of only ±1% between the two measurements. This consistency was surprising, since the estimates contain a finite measurement error, as well as actual variability in river flow.

To assess the accuracy of the computations, a control transect was occupied near Mountain Village (6 miles downstream of Kobolunuk) during the third and fourth profiling surveys. Since there are no significant tributaries or sloughs which intersect the Yukon between Kobolunuk and Mountain Village, the discharge through these two sections should be very similar at any given time. Comparison of the results for transects PC-6A and PC-5 (both conducted on 22 June 1986) reveals a 7% decrease at Mountain Village, which can be attributed to errors from inadequate resolution of the two-dimensional flow field with the limited number of profile stations, and positioning errors which affect the river cross-sectional area computed from the bathymetric data. Note, however, that this error estimate is actually a sum of errors on the two independent transects.

The two control transects were again occupied on 12 August 1986 (transects PD-1 and PD-2); the discharge at Mountain Village (9,250 m^3/sec) exceeded that of Kobolunuk (8,950 m^3/sec) by 3%. Additional control transects could not be occupied during the field program due to time limitations, but the two independent checks suggest that the transport estimates are accurate to roughly ±7%. These error estimates do not address bias errors that may be introduced, for example, by the calibration of the profiling current meter. However, there was good agreement between discrete profile measurements and simultaneous, nearby current measurements obtained from moored current meters.

Returning to the issue of discharge at Kobolunuk, a 19% decrease was found over the period late June 1986 to mid-August 1986, as would be expected for this time of year. Table 3-10 indicates that the discharge at Kobolunuk during mid-August 1985 (profiling survey 1) was not significantly different than that measured during mid-August of the following year (survey 4). Curiously, the discharge during late September 1985 was significantly greater than in June 1986. This result will be discussed later in this subsection, along with a presentation of hydrologic data from an upstream USGS monitoring station.

Distributary Discharges

The majority of the transects occupied during the profiling measurements were made downstream of Head of Passes in order to quantify the discharge within the major distributaries. Since the transects at Kwikluak, Aproka, and Kwikpak Passes were located roughly 70 miles downstream of Kobolunuk, it is likely that the lower Yukon gains a significant contribution of fresh water from the low hills and ponds which flank the river between these two sites. This downstream increase was evident during the first three profiling surveys: in August 1985, the sum of the Kwikluak, Aproka, and Kwikpak discharges (10,780 m^3/sec) exceeded that at Kobolunuk (9,200 m^3/sec) by 17%; similar downstream increases of 4% and 19% were measured in September 1985 and June 1986, respectively. During the fourth profiling survey, the discharge measured at Kobolunuk exceeded that derived from the sum of the three transects located downstream of Head of Passes by 0.2%, but this difference is not significant, considering an expected measurement error of roughly $\pm$7% at each transect.

Figure 3-34 presents the calculated budget for the three major Yukon distributaries, as determined from the estimates presented in Table 3-10. For this analysis, the sum for Kwikluak, Aproka, and Kwikpak Passes is considered to be the best estimate of total Yukon River discharge, T_h, at Head of Passes, because it is not affected by the runoff error described above. In Figure 3-34, percentages indicate the fraction of the total within the individual passes.

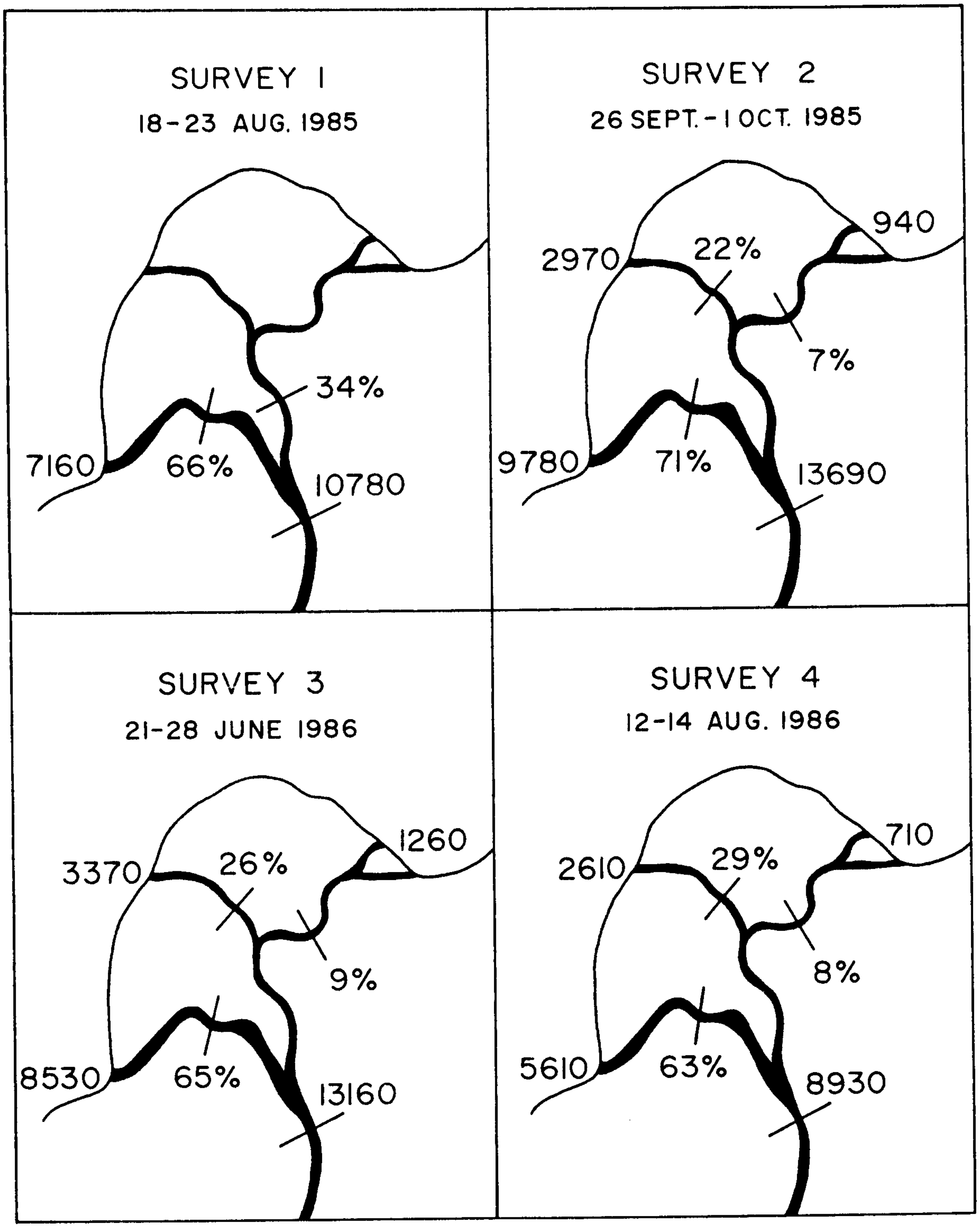


Figure 3-34. Percentage distribution of Yukon River discharge (m^3/sec) among the three major Delta distributaries as determined from profiling surveys. The total discharge at Head of Passes is based upon the sum of discharges within Kwikluak Pass (at Lamont) and Kwikpak Pass.

During the first profiling survey, 66% of the total discharge was conveyed through Kwikluak Pass at Lamont, while the remainder flowed toward the north through Kwikpak Pass. In the absence of profiling stations in Apoon or Kawanak Pass, the partitioning between Middle and North Mouths cannot be quantified.

In late September 1985 (when the Yukon discharge was relatively intense), Kwikluak Pass received 71% of the total discharge at Head of Passes. Of the 29% within Kwikpak Pass, 22% entered Kawanak Pass while only 7% eventually reached North Mouth via Apoon Pass. The results from the two 1986 surveys were remarkably similar, with only 9 and 8% of the discharge at Head of Passes reaching North Mouth in June and August, respectively.

It appears that the flow partition within the major Yukon distributaries is relatively independent of total river discharge, at least during the period from June through September when the river is relatively high. We suspect that the proportions may vary as the river level subsides, due to the complex system of erosional channels. In summary, our estimate of river discharge partitioning within the Delta is as follows:

66% ±5% through Kwikluak Pass (leading to South Mouth and Kwiguk Pass)

26% ±4% through Kawanak Pass (leading to Middle Mouth)

8% ±1% through Apoon Pass (leading to North Mouth)

Comparisons with USGS Data

Since 1974, Yukon River discharge measurements have been made by the U.S. Geological Survey at a hydrological station located near Pilot Station, roughly 19 miles upstream of Pitkas Point. These daily observations represent an interesting time series from which seasonal trends can be identified, and daily comparisons can be made with the measurements conducted during the present program.

The Yukon discharge is characterized by a consistent annual cycle with peak flow in May or June, followed by a gradual decrease until December or January when the river becomes ice covered. Subsequently, flow remains weak until ice breakup in May. For the period from October 1975 through September 1984, the average annual discharge was 6,258 m^3/sec, and the maximum daily discharge of 21,275 m^3/sec was recorded on 27 May 1982. During winter, discharge rates are generally between 1,000 and 2,000 m^3/sec.

Figure 3-35 presents monthly averages of Yukon discharge at Pilot Station for the period of February 1982 through September 1984. These 3 years are representative of the annual cycle in the lower Yukon; discharge increases rapidly from April to June, followed by a more gradual decrease through the summer and fall. By January, the discharge is normally about 7% of its maximum in June.

The Pilot Station data from 1982 through 1984 also illustrate a second, less intense peak in river discharge during the period from August to October. This peak is most pronounced in the maximum daily discharge rates (upper curve in Figure 3-35), but the peak is also evident in the monthly averages of 1983 and 1984. This secondary peak is a result of high precipitation across Alaska and the Canadian Yukon during the months of August and September. As discussed in subsection 1.3, climatological data from the Yukon Delta region exhibit maxima in precipitation and cloud cover during the month of August. This would not be contested by the EG&G field party which experienced many days of rain during August and September field trips to the Delta.

Figure 3-36 presents a time series of daily Yukon River discharge estimates at Pilot Station for the period late-May to 1 October 1986, as obtained from USGS records. These daily estimates reveal seasonal trends as well as short-term fluctuations which occur on time scales of a few days. This record

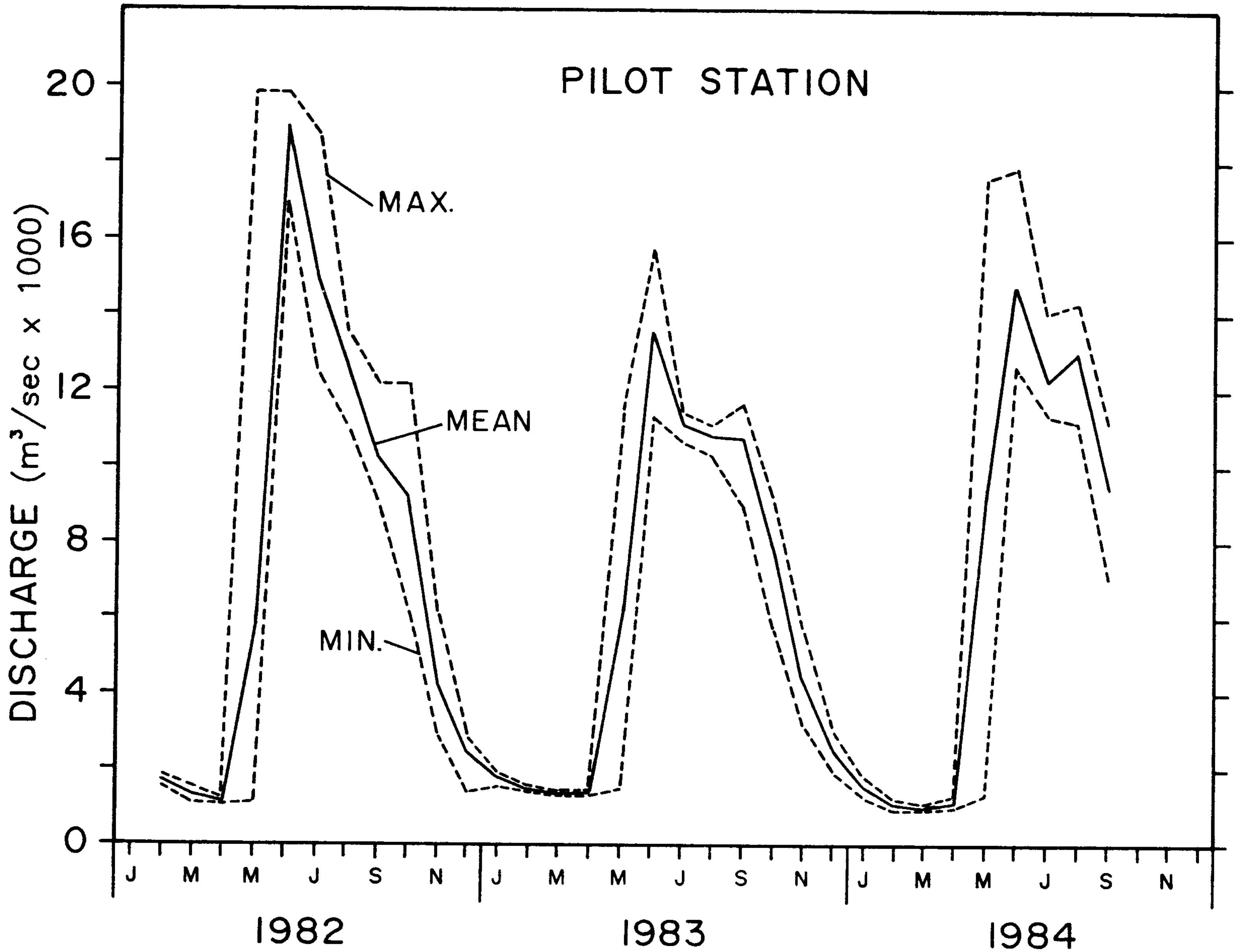


Figure 3-35. Time series of Yukon River discharge determined from USGS measurements at Pilot Station (located 19 miles upstream of Pitkas Point) during the period February 1982 through September 1984. Monthly mean values are represented by the solid line; the maximum and minimum 1-day discharge values for each month are represented by the broken line.

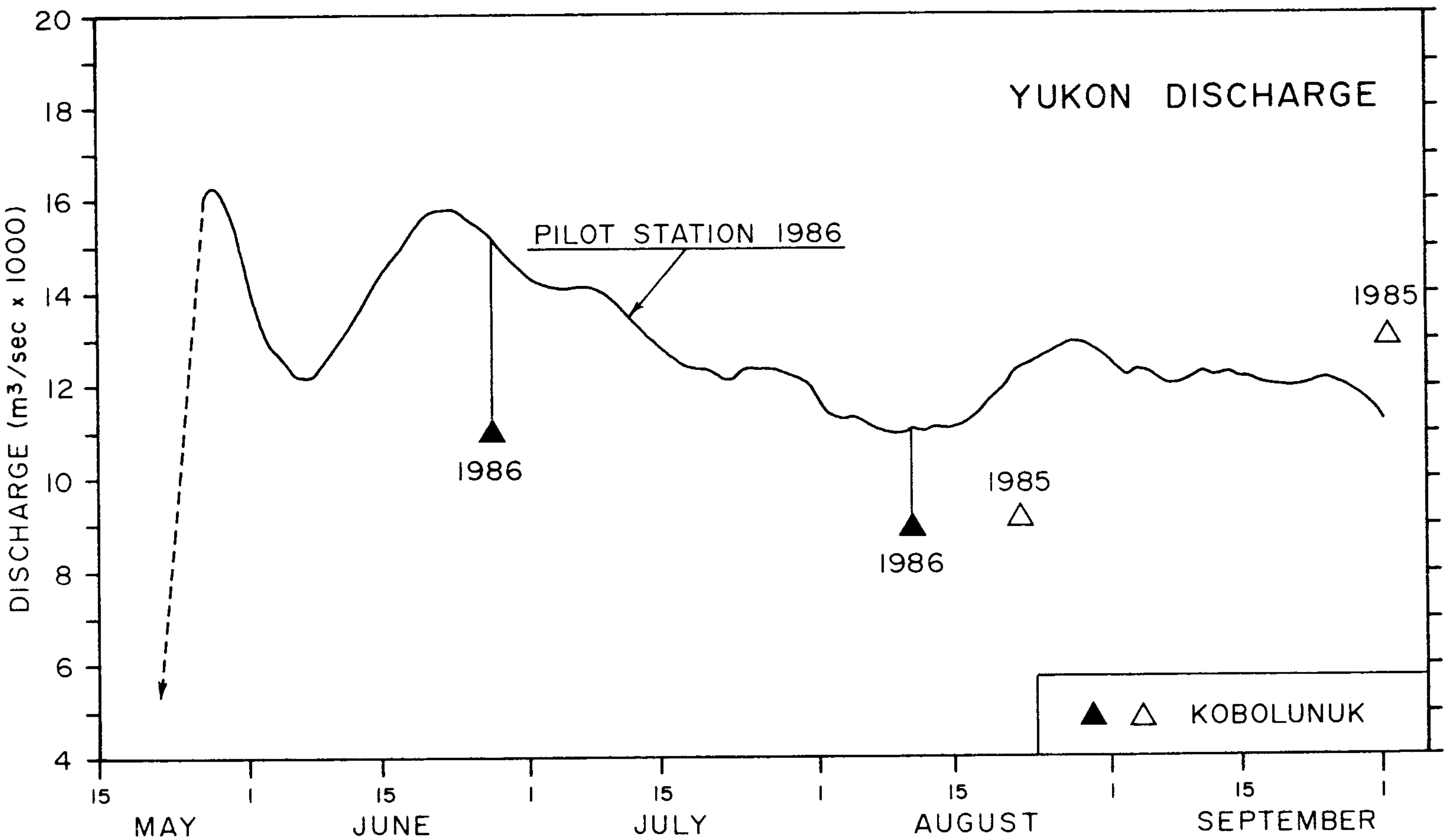


Figure 3-36. Time series of daily Yukon River discharge estimates from Pilot Station (USGS data) for the period mid-May through September 1986. Discharge estimates from Kobolunuk on 27 June and 11 August 1986 (solid triangles), which were derived from profiling surveys, are shown for comparison with the Pilot Station results. Kobolunuk discharge estimates from 22 August and 1 October 1985 are represented by open triangles.

indicates that 1986 was an abnormal year, whereby nearly equivalent discharge peaks were observed in late-May and mid-June. The June maximum was followed by a gradual decrease until a summer minimum was achieved in early August. The relatively common, autumn discharge maximum was observed in late August.

These Pilot Station data are expected to be of high quality, since direct current measurements were used to derive an accurate transfer function from the water-level data (the basic hydrologic measurement) to the discharge values. Note, however, that Pilot Station data from summer 1985 are not available from USGS due to uncertainties in calibration.

Also presented in Figure 3-36 are Yukon River discharge estimates for Kobolunuk which were derived from two profiling surveys in 1985 (open triangles) and two surveys in 1986 (solid triangles).

From August to October 1985, the EG&G data from Kobolunuk exhibited a 43% increase. Discharge estimates of 13,000 m^3/sec for October are not uncommon at Pilot Station during this time of the year.

The EG&G measurements from June and August 1986 exhibited a 19% decrease over this time period, in agreement with the mean monthly values from Pilot Station. The EG&G values from Kobolunuk are, however, significantly less than the mean monthly and daily discharge values from Pilot Station. For instance, on 27 June 1986, the measurement at Pilot Station (15,200 m^3/sec) exceeded that at Kobolunuk (11,000 m^3/sec) by roughly 38%. Similarly, the measurement at Pilot Station exceeded that at Kobolunuk by 25% on 11 August 1986. If there were an actual difference in the river discharge between these two sites, we would expect that at Kobolunuk to be somewhat larger than at Pilot Station, due to the addition of the Andreafsky River. Since the intercomparison suggested a downstream decrease, we suspect much of the discrepancy lies with a bias error in one or both of the measurements. The source of this error was being investigated while this report was in final preparation.

Regardless of the absolute offset between the EG&G and USGS discharge estimates, both data sets illustrate a significant decrease from June through August 1986. The EG&G measurements in summer 1986 were apparently made prior to the autumn rise in Yukon discharge. The mean monthly values from Pilot Station exhibited an increase from August to September 1986, but the EG&G field program had terminated earlier. We strongly recommend that the questions raised here over the accuracy of river discharge measurements be further investigated in future studies.

3.5 WATER PROPERTIES

3.5.1 CTD Measurements

The measurement of physical water properties, mainly temperature and salinity, forms an important element of the field program because it provides a direct indication of the manner in which the river outflow is mixed with the receiving ocean waters of the Bering Sea on the west and Norton Sound on the north. In turn, this provides an indirect indication of the possible manner in which pollutants, mainly hydrocarbons, might be transported and distributed within the Delta region.

Since the most likely sources of hydrocarbon contamination are offshore spills, emphasis is placed on transport processes which affect the seaward boundary of the study area. Although the precise processes involved are speculative, the most obvious candidates include onshore, storm-driven surface currents and estuarine-type circulation mechanisms driving upstream, near-bottom currents within the distributary channels. This second mechanism has aroused the most interest, due to various accounts of salinity intrusions within the distributary channels at significant distances upriver from the mouths. One account describes the presence of brackish water at a point 160 km upstream (Zimmerman, 1982); more commonly, observations and empirical calculations suggest that traces of salt (salinity of 0.4 ppt) may be found at distances of about 50 km from the distributary mouths (LGL, 1984). Consequently, one of the main objectives of the hydrographic surveys was to obtain thorough coverage of the major distributary channels to detect and map the extent of any near-bottom salinity intrusion.

As described in subsection 3.4, about 66% of the total Yukon River discharge flows through Kwikluak Pass, which is the Yukon Delta major distributary. After leaving the mouth of Kwikluak Pass (South Mouth), a minor portion of the Yukon River outflow is dispersed laterally over the shallow offshore platform of the Delta. The majority continues flowing offshore through a network of five subaqueous channels which cut the platform to depths of 4 to 9 m. These channels, namely the Acharon, Taku, Kutmuknuk, Kwikluak, and Nurukomarot Channels (NOAA Chart No. 16240), are very narrow (less than 100 m wide in some places) and meandering. River water flowing through the mouth of Kawanak Pass (Middle Mouth), which carries about 26% of the total Yukon River discharge, flows seaward through a single subaqeous channel, the Kawanak Channel. There does not appear to be any discernible offshore channel at Apoon Pass (North Mouth).

Two series of hydrographic stations were obtained near the mouths of the Kwikluak and Kawanak distributaries and offshore within the subaqueous channels during the field trips in August and September 1985.

Figures 3-37 and 3-38 illustrate the CTD station locations occupied during these field trips. Nine stations (A-1 to A-9) were made in August 1985, and 13 (B-1 to B-13) were made in September. Table 3-11 presents a summary of the data from all stations, including water depth and observed temperature and salinity at the top and bottom of each profile.

Several CTD stations in Table 3-11 are listed as having "no salt." This classification is used to indicate that the entire profile contained "pure" Yukon River water. At the present time, the chemical composition of Yukon River water has not been sampled extensively. However, Livingstone (1963) has estimated that average river water has a total concentration of dissolved solids of about 100 mg/l (or 0.1 ppt). Equating salinity as measured with the CTD to total dissolved solids concentrations, it is assumed that salinities above 0.1 ppt indicate the presence of a seawater fraction. This threshold salinity corresponds to a conductivity range of between 0.31 and 0.43 mmho/cm for the observed temperature range. A salinity of 0.1 ppt is considered

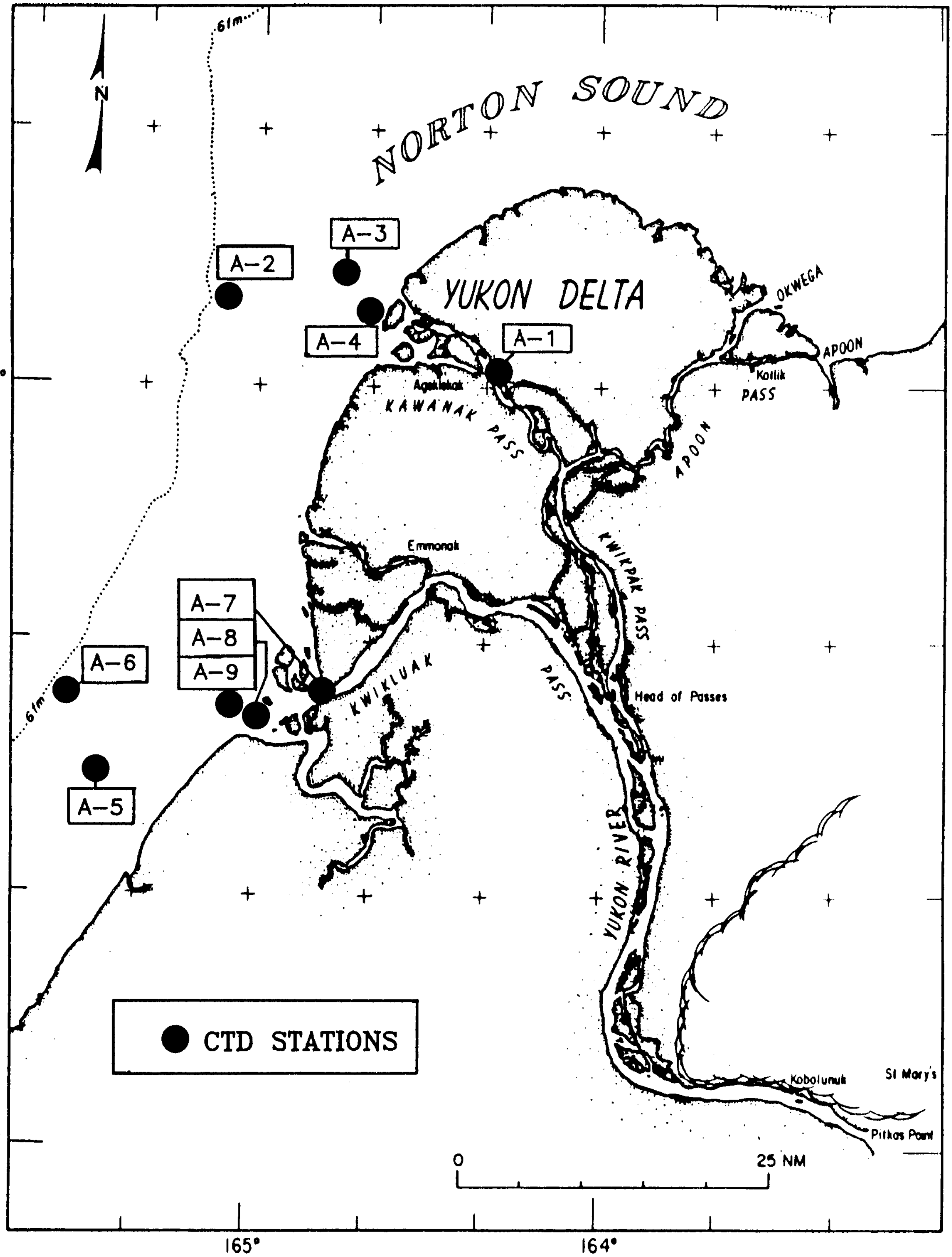


Figure 3-37. Locations of CTD stations A-1 through A-9 occupied in August 1985.

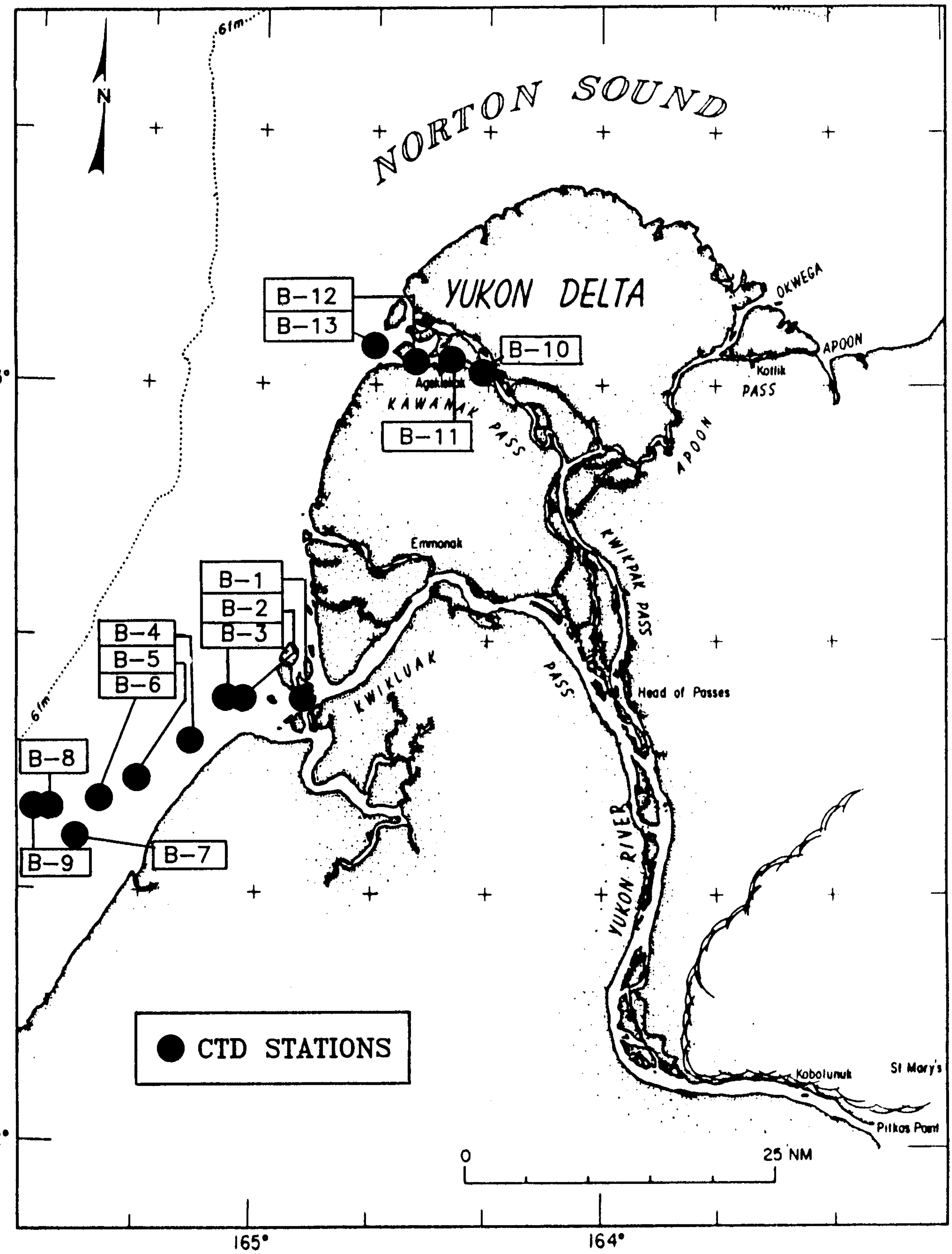


Figure 3-38. Locations of CTD stations B-1 through B-13 occupied in September 1985.

Table 3-11. Summary of CTD results from the second and third field trips to the Yukon Delta in summer 1985. Station positions are shown on Figures 3-37 and 3-38.

SECOND FIELD TRIP

CTD Station	Date	Water Depth (m)	Profile Depth (m)	Temperature Top/Bottom (°C)	Salinity Top/Bottom (ppt)
A-1	08/24/85	15.2	13.7	12.48/12.45	No Salt
A-2	08/25/85	7.6	5.5	10.59/10.59	14.28/14.74
A-3	08/25/85	7.3	6.6	11.90/11.98	No Salt
A-4	08/25/85	18.0	17.0	12.07/12.09	No Salt
A-5	08/26/85	4.3	4.3	10.77/10.77	26.83/26.85
A-6	08/26/85	9.8	8.0	10.81/10.80	27.24/27.26
A-7	08/28/85	18.3	16.5	11.67/11.67	No Salt
A-8	08/28/85	6.1	4.4	11.64/11.66	No Salt
A-9	08/28/85	6.1	5.2	11.59/11.63	No Salt

THIRD FIELD TRIP

CTD Station	Date	Water Depth (m)	Profile Depth (m)	Temperature Top/Bottom (°C)	Salinity Top/Bottom (ppt)
B-1	09/24/85	18.3	16.5	6.67/6.65	No Salt
B-2	09/24/85	8.2	6.7	6.51/6.52	No Salt
B-3	09/24/85	20.4	18.8	6.51/6.52	No Salt
B-4	09/24/85	7.9	6.6	6.49/6.36	No Salt
B-5	09/24/85	10.1	8.7	6.37/6.23	No Salt
B-6	09/24/85	6.7	6.1	5.91/5.85	No Salt
B-7	09/24/85	2.4	1.7	6.04/6.16	0.94/ 5.42
B-8	09/24/85	4.0	3.4	6.57/6.81	8.29/17.04
B-9	09/24/85	7.1	6.2	7.04/7.37	20.02/24.82
B-10	09/25/85	14.3	13.3	6.26/6.21	No Salt
B-11	09/25/85	9.1	7.3	6.26/6.27	No Salt
B-12	09/25/85	15.2	11.6	6.26/6.26	No Salt
B-13	09/25/85	12.8	10.9	6.29/6.29	No salt

as quite a low threshold, and the natural range of dissolved solids concentrations in the river probably intermittently exceeds this level independent of any mixing with seawater.

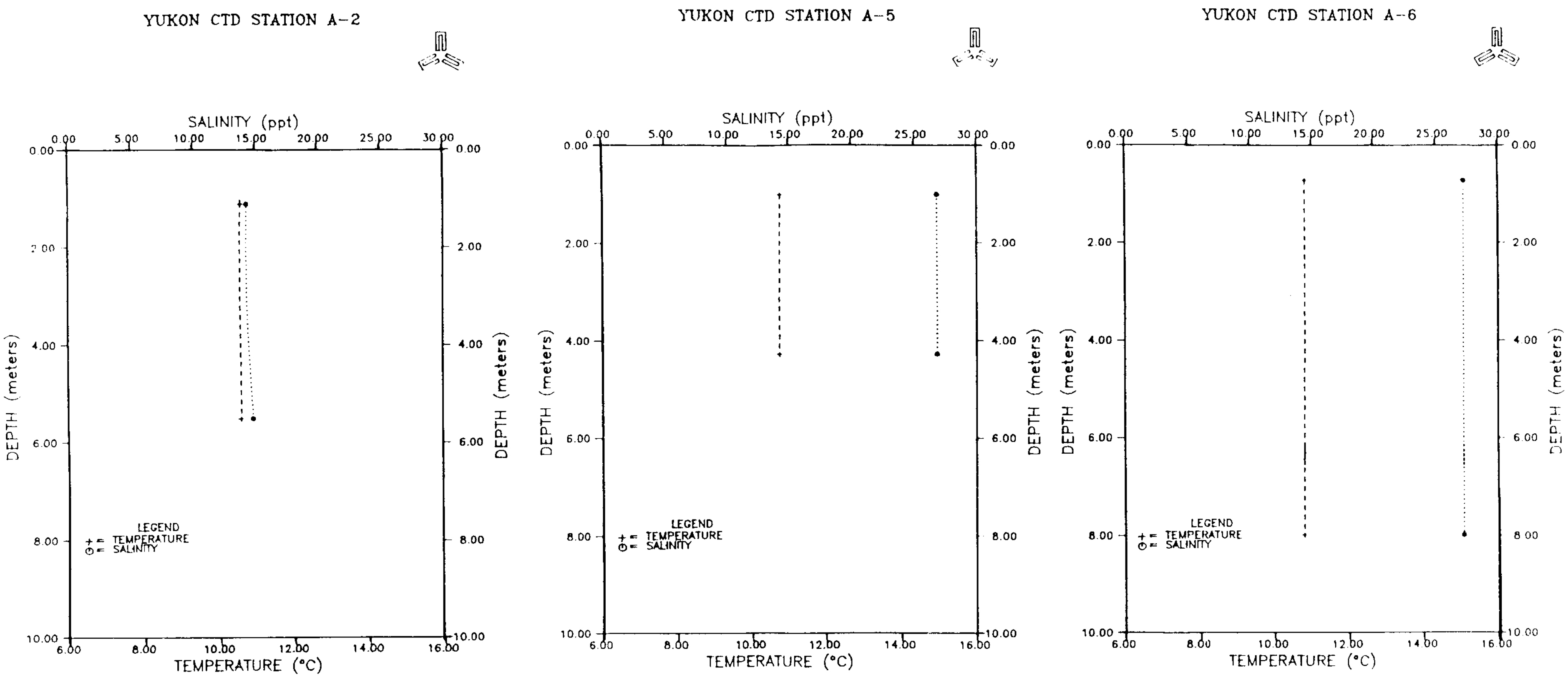
As is evident from inspection of Table 3-11, the data fail to reveal any trace of salinity intrusion into the distributary system. Significant salinity levels were encountered only near the seaward edge of the Delta platform, at distances well off-shore of the channel mouths. Accordingly, during the subsequent surveys scheduled for the summer of 1986, it was decided that there was no need to conduct additional CTD surveys within the major distributaries because salt could not penetrate upstream during this season of high discharge. To further support this claim, a limited CTD survey was conducted at North Mouth during August 1986 using a portable Beckman RS5-3 salinometer. This instrument has a conductivity range of 0 to 60 mmho/cm and an accuracy of $\pm$0.5 mmho/cm. Although much less accurate than the NBIS CTD used in the 1985 field work, the Beckman salinometer is still capable of detecting seawater fractions at quite high dilutions. Stations were occupied along Apoon Pass near Kotlik and to a distance of 2 miles offshore of the North Mouth. Again, these data indicated no seawater fraction was present in the Apoon Pass during August 1986.

In support of the CTD measurements, Aanderaa RCM current meters equipped with conductivity sensors were deployed in Kwikluak Mouth and Kawanak Mouth. The sensors were moored near the bottom at location C-2 during both deployments in 1985, and at C-4B during the second deployment in 1985. Neither record contained any significant conductivity above the noise level of the instrument (0.2 mmho/cm).

Significant fractions of seawater were found only at the most distant offshore hydrographic stations of the two 1985 surveys. These stations lie 25 km or more offshore of the Kwikluak and Kawanak Mouths, either at the seaward edge of the

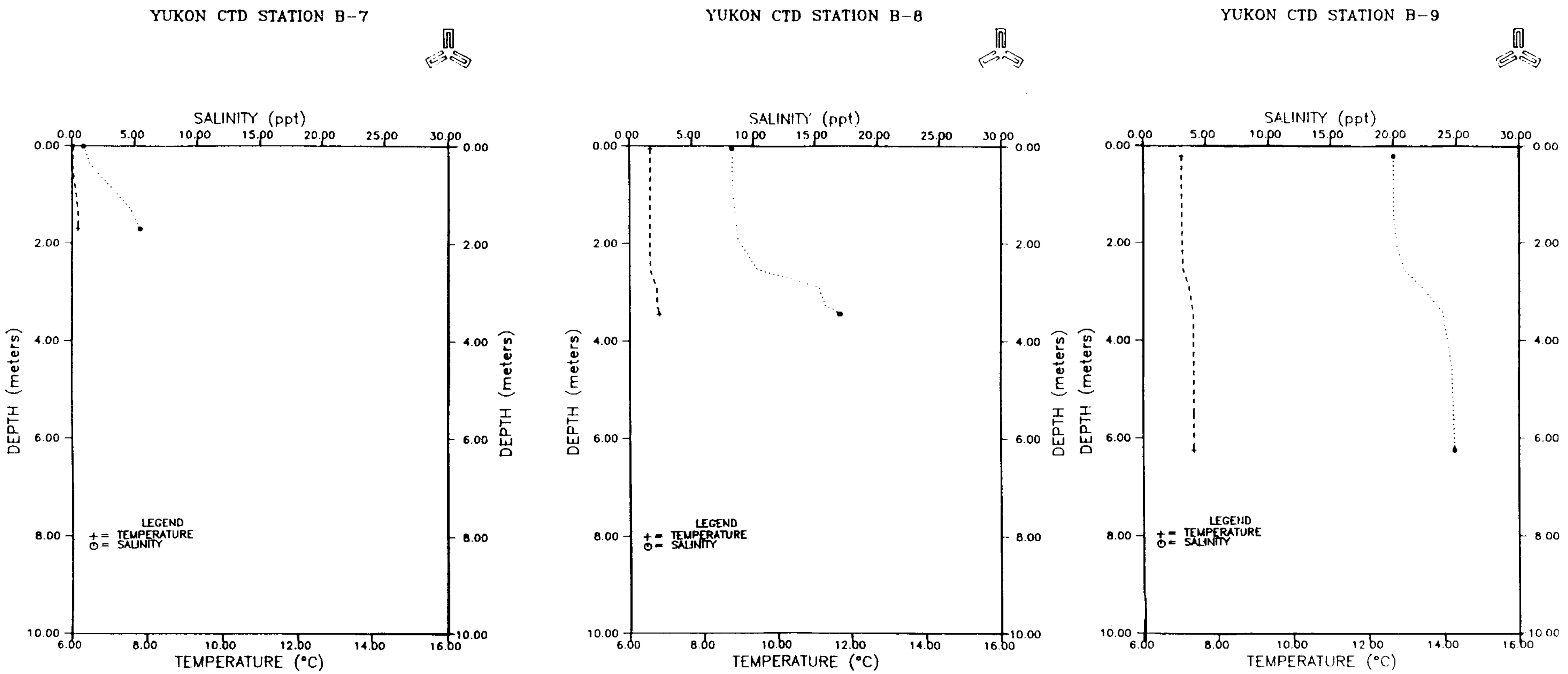
Delta platform or farther offshore over the steeply sloping face of the Delta front. The vertical profiles of temperature and salinity for selected stations from the August and September surveys are shown in Figures 3-39 and 3-40, respectively. It is immediately noticeable that the two sets of profiles differ fundamentally in terms of the degree of salinity stratification. The stations from the August survey provide coverage of the areas offshore of both the Kwikluak and Kawanak Mouths and are vertically homogeneous in all cases. The stations from the September survey are confined to the Acharon Channel leading offshore to the southwest from Kwikluak Mouth. These stations are in the same general vicinity as stations A-5 and A-6 from the second survey, but by the time of the third survey, the water column had become strongly stratified with respect to salinity. Unfortunately, profiles from stations farther north could not be obtained during the September 1985 survey; thus, it is uncertain how far the stratified front extends to the north. It may be that the stratified portion of the front is limited to the leading southerly edge of the plume off Kwikluak Mouth. Note that this southerly area lies in the vicinity of mooring C-3. Data from this mooring yielded evidence of sustained stratified conditions, as discussed in subsection 3.2.

Vertical temperature variability among the profiles is much less distinct, with a contrast of less than 0.5°C from top to bottom. A comparison of the profiles shown in Table 3-11 indicates that in mid-August, Yukon River temperatures ranged from 11.6 to 12.5°C, while the offshore temperatures ranged from 10.6 to 10.8°C. During late September, river and ocean water temperatures were similar, ranging from 5.9 to 7.4°C, with the ocean water slightly warmer than the river. Thus, the contrast between the two water masses is slight in relation to the variability among the profiles, and, consequently, temperature is not a very sensitive water mass indicator for these two data sets.



Vertical profiles of temperature and salinity obtained from three CTD stations located on the Yukon Delta front during August 1985 (see Table 3-11 for station dates and water depths). Station positions are illustrated in Figure 3-37.

Figure 3-39.



Vertical profiles of temperature and salinity obtained from three CTD stations located offshore South Mouth during September 1985 (see Table 3-11 for station dates and water depths). Station positions are illustrated in Figure 3-38.

Figure 3-40.

As discussed in subsection 3.2, wider temperature contrasts exist both earlier and later in the season, so that profiles at these times would be expected to show well-defined temperature, as well as salinity stratification.

3.5.2 Likelihood of Salt-Wedge Intrusion

The field data demonstrate that salinity intrusions upstream of the mouths of the major distributaries did not occur during the two summers of 1985 and 1986. Moreover, the available data indicate that the shoreward limit of seawater mixing lies approximately near the seaward end of the subaqueous channels where water depths shoal to 2 m or less on the Delta platform. This point presumably marks the seaward extent where the along-channel velocity of the river outflow is finally dissipated and the bed-load is deposited. At this point, the river outflow has lost its cross-shore momentum and other jet-like characteristics and drifts freely with the ambient current as a buoyant plume.

The shoal area of the platform lies roughly 10 km from the coast and appears to be a rather broad structure with a width of several kilometers. Farther offshore, to a distance of roughly 25 km, the platform slopes gently downward to a depth of, roughly, 10 m where the platform break marks the beginning of the steeply sloping Delta front. The hydrographic data indicate that this is the general vicinity where mixing occurs between the river plume and Bering Sea water during summer and early fall. Apparently, the mixing zone may occur either as a sharp front or as a broad, vertically homogeneous zone characterized by strictly horizontal gradients.

Under stratified conditions, the surface layer of the plume appears to have a maximum depth of roughly 2.5 m. At station B-7, the total water depth is only 3.0 m and relatively low salinity is distinguishable at the bottom. It appears reasonable to infer that the toe of the frontal interface intersects the bottom at approximately this depth. The shoals at the head of the subaqueous channels thus form a bar crest that blocks the shoreward flow of saline bottom water into the deeper reaches of the subaqueous channels further inshore. In the case of a vertically well-mixed plume, it appears that the shoreward limit of seawater mixing is again over the crest of the distributary bar. However, in this case, such a boundary is more apt to arise because of the low diffusive flux of salt shoreward, permitted by the shallow water column and the low horizontal salinity gradient produced by intense mixing.

The evidence available from these two surveys does not provide any assurance that seawater intrusion is limited to the bar crest during other seasonal periods or under different conditions during the same months in other years. The dynamic balance of forces which determines the cross-shore movement of the salinity front presumably involves the magnitude of the river discharge as a primary factor. Both surveys represent periods when the river discharge was at relatively high levels (e.g., between roughly 10,000 and 14,000 m^3/sec. As shown in subsection 3.4, the annual hydrograph recedes precipitously into the fall months immediately prior to freeze-up in late November or early December. Throughout the winter months, river discharge beneath the shorefast ice cover is typically in the range of 1,000 to 2,000 m^3/sec, an order of magnitude less than during the two hydrographic surveys. Salinity intrusion past the bar crest, into the subaqueous channels, and possibly past the river mouths, could occur during quiescent conditions in late fall, or under the ice during the early winter months. Intrusion during the late winter is seen as unlikely, due to the depth of shorefast ice which would block flow over the bar crest.

The length to which seawater could penetrate into the distributary channels under these conditions is critically dependent upon the dynamic balance of forces governing the flow regime. A number of quantitative models have been proposed to characterize this balance in estuarine systems. The most straightforward approach is based on the use of non-dimensional combinations of readily determined physical variables. One of the early formulations is the Estuary Number, as proposed by Harleman and Abraham (1966), i.e.,

$$E = P_t F_o{}^2 / Q_f T$$

where P_t is the tidal prism,

F_o is the estuarine (densimetric) Froude Number defined in terms of the mean depth and peak flood-tide velocity,

Q_f is the volume rate of river discharge, and

T is the tidal period.

This formulation is essentially based on the volume ratio of tidal flow to river discharge over a full tidal cycle. In the simple case of a standing wave within a relatively small (in comparsion to the wavelength) embayment with well-defined boundaries, this represents a convenient formulation where all of the variables are easily defined and measured. In the case of the Yukon Delta, it is not clear how well a simple standing wave pattern represents the actual tidal dynamics. In turn, it is not straightforward to compute the volume of the tidal prism. An alternate formulation proposed by Fischer (1976), termed the Estuarine Richardson Number, appears to be more directly applicable:

$$R = g' Q_f / bU^3$$

where g' is the reduced gravitational acceleration,

b is the mean width, and

U is the rms tidal velcity.

This formulation eliminates both the tidal prism and the need for assigning a "mean" depth to the river. The widths of the Yukon distributary channels, at least when measured bank to bank, are relatively constant and easily determined from the existing topographic maps. The most uncertain aspect regards the rms tidal velocity. While this has been measured quite accurately at discrete points, the above formulation implies some integration of the spatial variation in the tidal velocity field over a significant reach of the river. It is not clear how effective the mooring locations might be in representing such an integrated measure of the velocity field.

Fischer (1976) cites the range from $0.80>R>0.08$ as marking the transition from a well-stratified to a well-mixed condition. Using the following estimates appropriate for South Mouth, R is found to vary from roughly 5 to 65:

$U = 0.25$ m/sec

$b = 2{,}000$ m

$g' = 0.15$ m/sec^2

$Q_f = 1{,}000\text{–}13{,}000$ m^3/sec.

This is obviously well above the transitional range and indicates that if salinity intrusion were to occur, it would appear as a highly stratified intrusion of seawater along the bottom, presumably as a classical saline wedge.

The distance to which the wedge might penetrate upstream is given by Keulegan (1966) as:

$$L/H = 6.0\ (Re)^{1/4}(2C'/V_f)^{-5/2}$$

where L is the length of the intrusion measured from the channel mouth,

H is the mean channel depth,

Re is the estuarine Reynolds Number based on the internal wave speed, $C'(g'H)^{1/2}$, as the velocity scale, and the mean depth, H, as the length scale, and

V_f is the freshwater flow velocity.

With Re assumed equal to $5\cdot10^6$, H equal to 5.0 m, C' equal to 1.0 m/sec, and V_f equal to 0.20 m/sec (Q_f=1,000 m^3/sec), the length of salinity intrusion is predicted to be 14 km. In view of the uncertainty involved with these parameters, it is more realistic to conclude that the predicted length is simply of the order of 10 km. This is somewhat less that the 50 km intrusions reported by others (LGL, 1984), but still a substantial effect with the potential to act as a mechanism for significant pollutant impacts.

In this analysis, a point of ambiguity exists which should be emphasized; mainly, the assumption that the predicted length of the intrusion should be measured from the channel mouth. This assumption is valid if the densimetric Froude Number is critical (equal to unity) at this section of the channel. This has been found to be an accurate assumption in hydraulic model tests and for prototype conditions, such as at the mouths of the South and Southwest Passes of the Mississippi River (Wright, 1971). However, hydraulic conditions in these cases are highly artificial, consisting of jettied entrances and dredged navigational channels. The configuration of the Yukon distributary mouths is much different, and it is not clear that critical two-layer flow must occur directly at the mouths. The appropriate assumption in these cases needs to be resolved by direct measurement under suitable river discharge conditions.

3.6 METEOROLOGY

3.6.1 Large-Scale Meteorological Characteristics

Background

The climate of Norton Sound, including the Yukon Delta, is primarily influenced by arctic and continental air from the north and east in the winter, and by maritime air from the Pacific Ocean in the summer (Overland, 1981). During the period September to May, the atmospheric pressure regime from the northern Pacific Ocean to the Arctic Ocean is most frequently characterized by low-pressure systems lying over the southern part of the sound and high-pressure systems in the northern part (Barry, 1979). The low-pressure systems generally move to the east along trajectories in the vicinity of the Aleutian Archipelago; however, these weather systems occasionally travel northeast through the Bering Sea. Although the high-pressure systems tend to be stationary, when they do move, these systems are often displaced to the south or southwest.

The atmospheric pressure regime is more variable during the summer than it is during the winter. Low-pressure systems are usually found overlying the area extending from the northeastern Bering Sea to the eastern Beaufort Sea. Along the coast of the northeastern Bering Sea and Norton Sound, surface winds are more frequent from the northeast from September through May; however, the eastern part of Norton Sound is characterized by frequent easterly winds (Brower et al., 1977). Southwesterly to southeasterly winds are more frequent during the summer (June through August). Wintertime wind speeds generally range from 4 to 11 m/sec (8 to 21 knots), while summertime wind speeds range from 4 to 9 m/sec (8 to 18 knots). Wind speeds of more than 21 m/sec (41 knots) occur less than 10% of the time.

Analysis of Yukon Delta Data

Data processing and analyses of meteorological data from six coastal stations were originally planned for this study. Figure 3-41 illustrates the locations of the meteorological stations. Data from Cape Romanzof, St. Marys, Emmonak, and Unalakleet were obtained from NWS for June through September 1985. In addition, EG&G deployed an automated station on Nokogamiut Island (in Middle Mouth) during the 1985 field program, and two additional stations during the 1986 field program, one at Emmonak and one at Kotlik.

Due to equipment failure at the Nokogamiat Island station, a minimum amount of data was obtained at that site during 1985. The station provided only 2 weeks of data: 1 week in August and 1 week in September. These very short records are of very limited statistical value and, therefore, were not included in this report. However, good data were obtained from the two stations deployed during the 1986 field program.

As discussed in subsection 2.3, the meteorological data obtained from the NWS stations in 1985 contain daily gaps of approximately 12 hours. This is due to the fact that the weather observers were only at the stations from early morning to early evening. As explained in subsection 2.3, a cubic spline algorithm was used to fill in data gaps of less than 3 hours for the wind, less than 12 hours for the air temperature, and less than 24 hours for the barometric pressure.

Data from Emmonak and St. Marys are more complete than the data obtained from Cape Romanzof and Unalakleet. While observations at Emmonak and St. Marys were made almost every day, the observations at Cape Romanzof and Unalakleet contain numerous gaps of 3 to 5 days. For this reason, only Emmonak and St. Marys data are suitable for statistical analysis.

Composite time series plots of barometric pressure, air temperature, and wind vectors at Emmonak and St. Marys for the

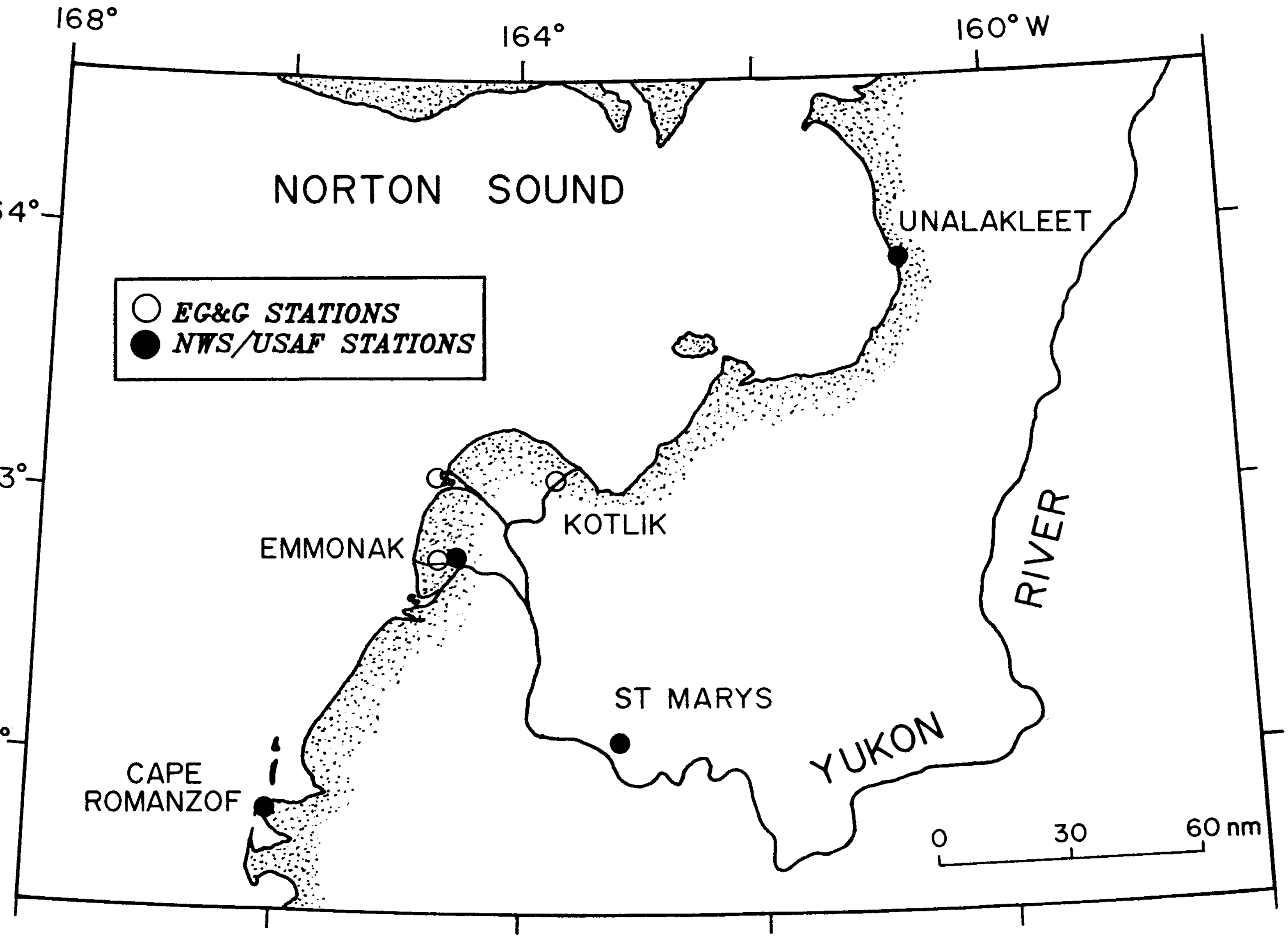


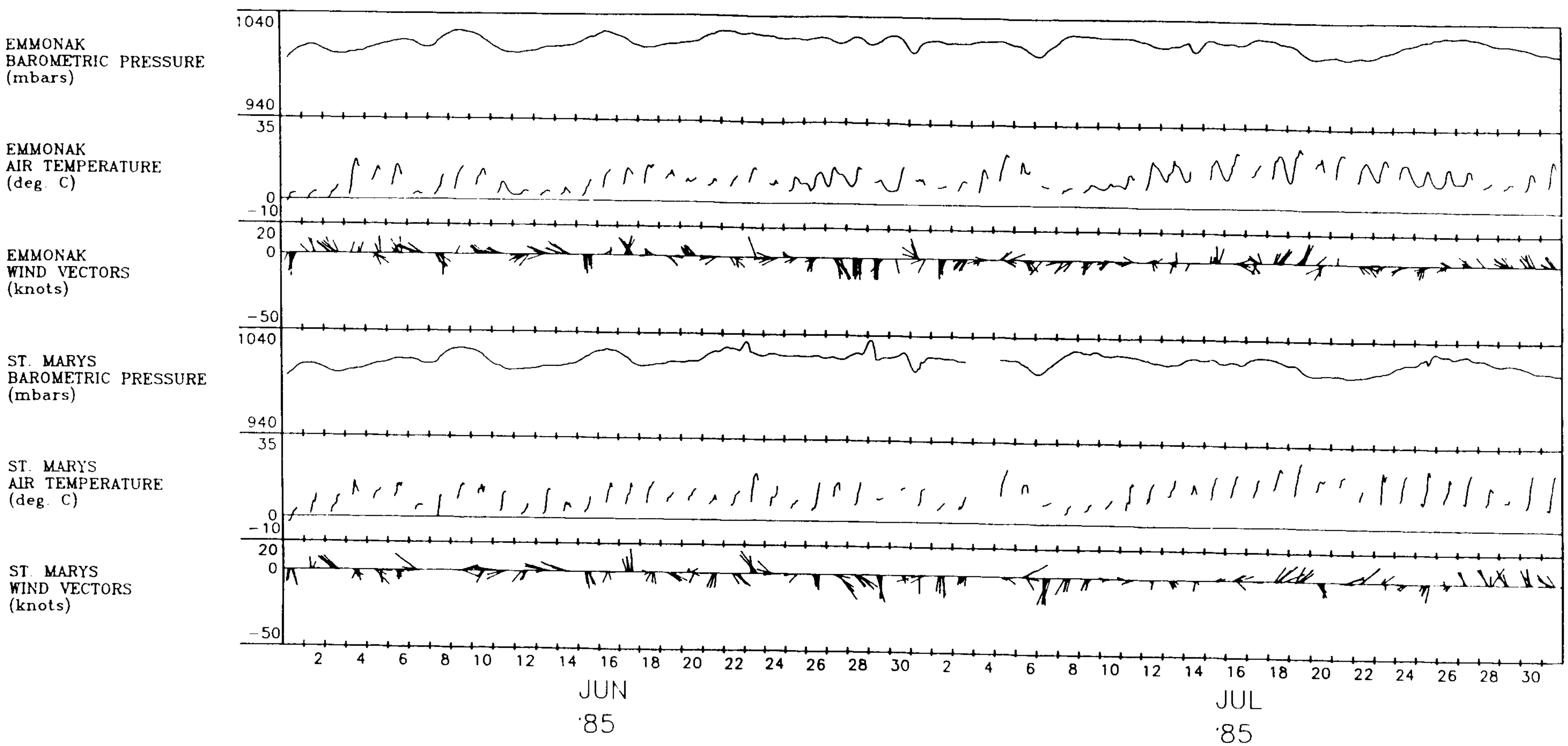
Figure 3-41. Locations of EG&G and government-operated weather stations in the vicinity of the Yukon Delta. Observations from NWS facilities at Emmonak, St. Marys, and Unalakleet, and a U.S. Air Force facility at Cape Romanzof have been used in the analysis of regional weather conditions.

period June through September 1985 are shown in Figures 3-42 and 3-43. The barometric pressure records at these two stations are very similar, reflecting the large-scale nature of the atmospheric pressure regime. In addition, large diurnal oscillations in air temperature, as a result of the daily solar radiation cycle, appear on both records from early June through early August.

A statistical comparison between the wind data from Emmonak with the wind data from St. Marys may be derived from the bivariate distributions of wind speed versus wind direction provided in Figures 3-44 and 3-45. The statistical results in these figures are based on data covering the period 1 June through 30 September 1985. The Emmonak statistical results (Figure 3-44) indicate a mean wind speed of 9.5 knots, a maximum wind speed of 24.0 knots, most frequent wind speeds ranging from 7.5 to 9.0 knots, and most frequent wind directions out of the southeast. In contrast, statistical results from St. Marys (Figure 3-45) reveal a mean wind speed of 10.0 knots, a maximum wind speed of 31.8 knots, most frequent wind speeds ranging from 9.0 to 10.5 knots, and predominant wind directions out of the south.

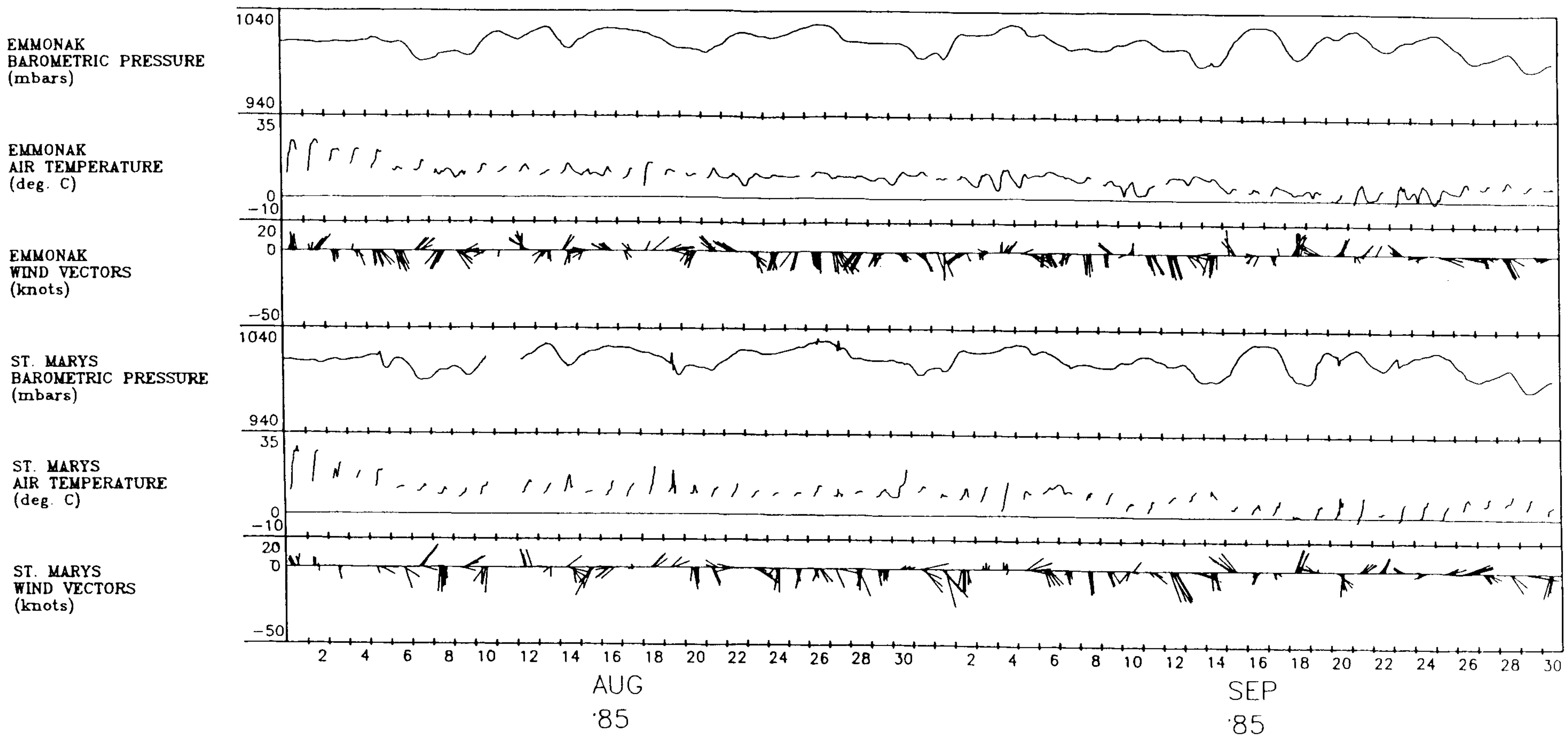
The above results are in good agreement with previous accounts of the regional large-scale atmospheric circulation. However, the data also indicate that wind speeds at St. Marys are consistently higher than the wind speeds at Emmonak. This wind speed intensification may be a result of topographic effects caused by the presence of mountains in the vicinity of St. Marys. In addition, the fact that St. Marys lies on top of a plateau, at an elevation of 364 feet above sea level, may also have an influence on the higher wind speeds observed at that site.

Directional distributions of 1985 wind data from Emmonak and St. Marys are presented in Figure 3-46. The predominant southwesterly to southeasterly summertime wind directions are clearly



Composite time series plot of barometric pressure, air temperature, and wind vectors from NWS observations at Emmonak and St. Marys for the period 1 June through 31 July 1985. Wind vectors are plotted according to the meteorological convention.

Figure 3-42.



Composite time series plot of barometric pressure, air temperature, and wind vectors from NWS observations at Emmonak and St. Marys for the period 1 August through 30 September 1985. Wind vectors are plotted according to the meteorological convention.

Figure 3-43.

DISTRIBUTION FREQUENCY
0.3 HOUR AVERAGES STATION EMMONAK WIND SPANNING 85/ 6/ 1 TO 85/ 9/30

DIRECTION DEGREES TRUE																					SUM	PERCENT
0- 15		2	9	26	9	12	10	6	2	5	13		1								95	2.5
15- 30	1	2	9	12	20	10	11	15	13	18	9										120	3.1
30- 45		2	10	19	28	31	33	25	14	9	7	3									181	4.7
45- 60	1		6	8	20	14	12	2	5	9											77	2.0
60- 75		2	4	15	9	8	18	3	6	1											66	1.7
75- 90		2	3	10	8	4	13	9	14	13	1										77	2.0
90-105		2	4	12	17	14	15	20	12	14	9										119	3.1
105-120		3	5	15	20	9	17	14	5	16	9										113	2.9
120-135			9	15	16	12	21	20	26	3	6	2	2								132	3.4
135-150		1	5	18	30	11	19	14	17	18	23	5	3								164	4.2
150-165	1		16	23	42	28	37	17	43	50	30	11	6								304	7.9
165-180			10	30	31	46	35	17	28	36	21	2									256	6.6
180-195	1	2	16	24	19	62	43	44	35	44	6	3									299	7.7
195-210		1	12	26	22	46	36	19	23	21	1	1		1		1					210	5.4
210-225		3	8	27	39	59	28	25	28	10	5				1	1	1				235	6.1
225-240		2	11	10	23	20	20	12	9	3	1	1	1								113	2.9
240-255		3	7	5	26	51	36	7	16	4											155	4.0
255-270		7	10	15	30	39	34	18	24	3											180	4.6
270-285		2	8	9	19	39	17	21	18	4											137	3.5
285-300	1	3	8	16	28	29	39	23	20	24	9										200	5.2
300-315			10	10	39	58	48	34	59	17	8										283	7.3
315-330	1	3	7	9	19	34	32	23	11	19	1										159	4.1
330-345			5	6	9	17	14	15	17	16	3										102	2.6
345-360		1	6	15	8	15	16	11	9	10		2	2								95	2.5
																					3872	
SPEED KNOTS	0.0 ! 1.5	1.5 ! 3.0	3.0 ! 4.5	4.5 ! 6.0	6.0 ! 7.5	7.5 ! 9.0	9.0 ! 10.5	10.5 ! 12.0	12.0 ! 13.5	13.5 ! 15.0	15.0 ! 16.5	16.5 ! 18.0	18.0 ! 19.5	19.5 ! 21.0	21.0 ! 22.5	22.5 ! 24.0	24.0 ! 25.5	25.5 ! 27.0	27.0 ! 28.5	28.5 ! 30.0		
SUM	6	43	198	375	531	668	604	414	454	367	162	30	15	1	1	2	1	0	0	0	3872	
PERCENT	0.2	1.1	5.1	9.7	13.7	17.3	15.6	10.7	11.7	9.5	4.2	0.8	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.0		

SUMMARY STATISTICS

MEAN SPEED = 9.54 KNOTS STANDARD DEVIATION = 3.43 KNOTS
MAXIMUM = 24.00 KNOTS MINIMUM = 0.71 KNOTS RANGE = 23.29 KNOTS

IN A COORDINATE SYSTEM WHOSE Y AXIS IS POSITIONED 0.0 DEGREES COUNTER-CLOCKWISE FROM TRUE NORTH,
MEAN X COMPONENT = -0.88 KNOTS STANDARD DEVIATION = 6.54 KNOTS
MEAN Y COMPONENT = -1.67 KNOTS STANDARD DEVIATION = 7.52 KNOTS
MAJOR PRINCIPAL AXES ORIENTATION, DEGREES TRUE = 335

Figure 3-44. Statistical plot of bivariate distribution of wind speed versus wind direction at Emmonak for the period 1 June through 30 September 1985.

DISTRIBUTION FREQUENCY
0.3 HOUR AVERAGES STATION ST MARYS WIND SPANNING 85/ 6/ 1 TO 85/ 9/30

DIRECTION DEGREES TRUE	0.0-1.5	1.5-3.0	3.0-4.5	4.5-6.0	6.0-7.5	7.5-9.0	9.0-10.5	10.5-12.0	12.0-13.5	13.5-15.0	15.0-16.5	16.5-18.0	18.0-19.5	19.5-21.0	21.0-22.5	22.5-24.0	24.0-25.5	25.5-27.0	27.0-28.5	28.5-30.0	SUM	PERCENT
0- 15	3	3	8	10	4	5	7	5			1										46	1.5
15- 30	4	2	8	1		2	2	17	3	7	10	3									59	1.9
30- 45	6	2	9	6	1	7	10	12	15	10	4	2	3	1	2		2				92	3.0
45- 60	3	2	7	9	6	10	18	20	9	10	15	10	1	1							121	4.0
60- 75	4	4	8	8	12	5	23	20	27	17	12	7	9	4				2			162	5.3
75- 90	1	5	5	10	4	5	16	15	3	7	3	6	3	4							87	2.8
90-105	1	2	3	6	5	9	21	11	10	10	5	8	7	7	4		1				110	3.6
105-120	4	3	9	10	11	15	10	11	11	8	3	2	2	6	1						106	3.5
120-135	6	4	13	14	18	13	25	14	12	24	15	5	3	4							170	5.6
135-150	1	6	7	22	16	21	32	15	15	20	6	7	6	7	4	7	3		1	2	198	6.5
150-165	3	6	17	24	20	22	43	18	25	5	6	7	2	4	6	9	1		1		219	7.2
165-180	3	5	14	22	28	52	36	39	30	15	14	15	4	6		1	6				290	9.5
180-195	2	5	17	33	39	31	34	39	26	21	21	15	4	2	1						290	9.5
195-210	6	8	17	17	21	23	15	15	14	10	5	6	5	3		1					166	5.4
210-225	6	3	7	24	19	24	15	5	9		1	1	2				1	2		1	120	3.9
225-240	2	3	10	9	7	9	12	5	5	1	1	1		1							66	2.2
240-255	6	7	8	10	10	12	8	1	5	4	2										73	2.4
255-270	2	6	9	8	6	14	16	9	4	5	1	3	2								85	2.8
270-285	1	5	9	22	13	12	15	16	9	8	1	2	2	3	3						121	4.0
285-300	4	3	8	10	14	11	9	15	19	9	7	5	1	4		2					121	4.0
300-315		5	3	14	12	9	22	11	8	17	3	4	3	1	2	1					115	3.8
315-330	2	5	5	4	2	6	9	7	13	6	7	4	3	4							77	2.5
330-345	4	3	2	10	3	12	21	10	8	3	2			2							80	2.6
345-360	2	5	5	12	8	13	14	9	12	6		2									88	2.9
																					3062	

SPEED KNOTS	0.0-1.5	1.5-3.0	3.0-4.5	4.5-6.0	6.0-7.5	7.5-9.0	9.0-10.5	10.5-12.0	12.0-13.5	13.5-15.0	15.0-16.5	16.5-18.0	18.0-19.5	19.5-21.0	21.0-22.5	22.5-24.0	24.0-25.5	25.5-27.0	27.0-28.5	28.5-30.0	
SUM	76	102	208	315	279	342	433	339	292	223	145	115	62	64	23	21	14	4	2	3	3062
PERCENT	2.5	3.3	6.8	10.3	9.1	11.2	14.1	11.1	9.5	7.3	4.7	3.8	2.0	2.1	0.8	0.7	0.5	0.1	0.1	0.1	

SUMMARY STATISTICS

MEAN SPEED = 10.01 KNOTS STANDARD DEVIATION = 4.90 KNOTS
MAXIMUM = 31.77 KNOTS MINIMUM = 0.03 KNOTS RANGE = 31.74 KNOTS

IN A COORDINATE SYSTEM WHOSE Y AXIS IS POSITIONED 0.0 DEGREES COUNTER-CLOCKWISE FROM TRUE NORTH,
MEAN X COMPONENT = 1.19 KNOTS STANDARD DEVIATION = 7.41 KNOTS
MEAN Y COMPONENT = -2.44 KNOTS STANDARD DEVIATION = 7.86 KNOTS
MAJOR PRINCIPAL AXES ORIENTATION, DEGREES TRUE = 331

Figure 3-45. Statistical plot of bivariate distribution of wind speed versus wind direction at St. Marys for the period 1 June through 30 September 1985.

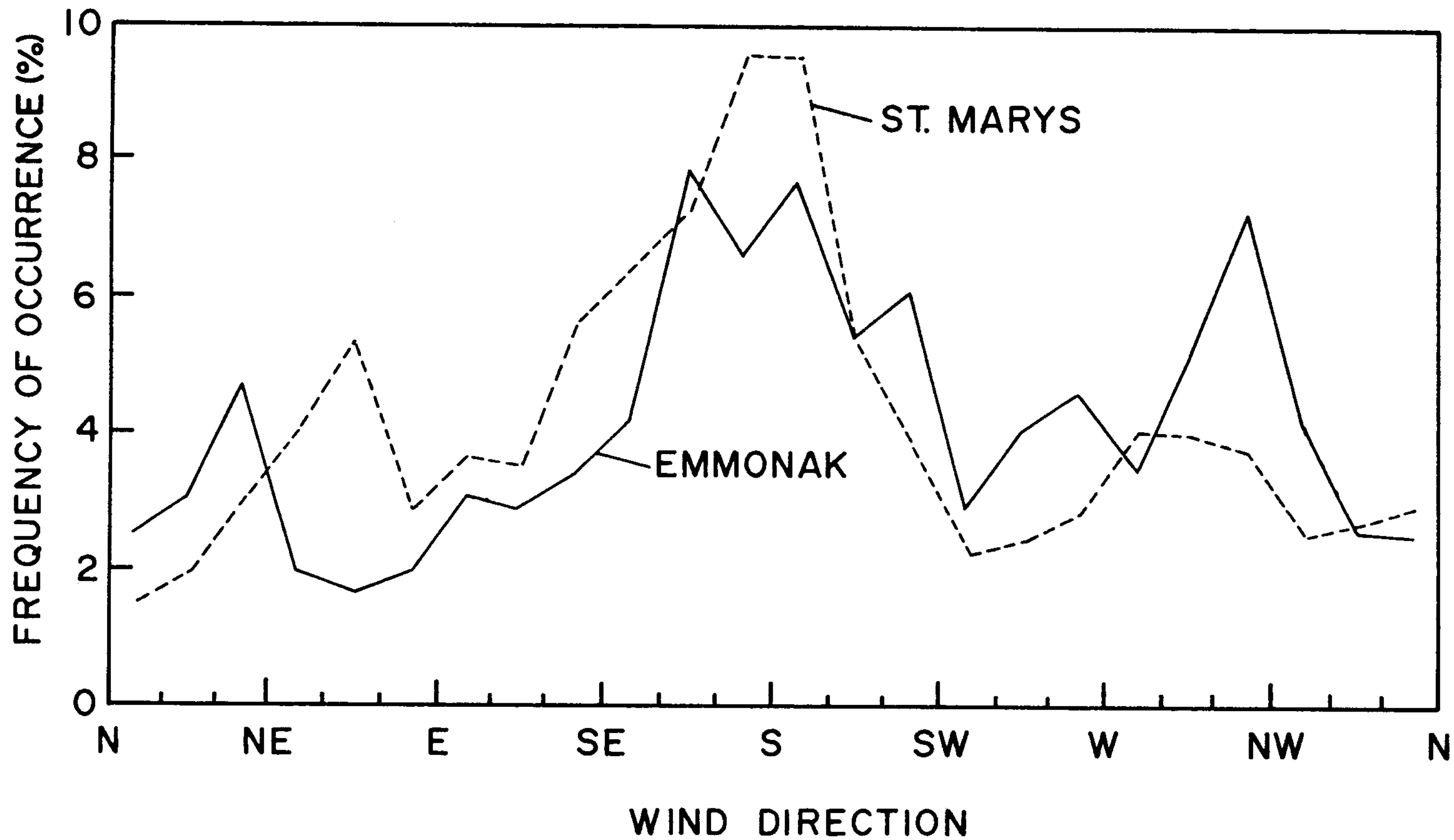


Figure 3-46. Directional distributions (percent frequency of occurrence) of wind records from Emmonak and St. Marys for the period 1 June through 30 September 1985.

shown at both stations. Secondary peaks also appear at both stations within the north-to-east quadrant; however, the data from St. Marys indicate a clockwise rotation in the direction of the secondary peak with respect to Emmonak. This is probably an orographic effect on the wind circulation at St. Marys due to the surrounding topography. On the other hand, the Emmonak directional distribution also exhibits a significant northwesterly peak which is not present at St. Marys. This wind direction, being onshore and perpendicular to the coast at Emmonak, may indicate the presence of a sea breeze at that station. A detailed analysis of the sea breeze regime, utilizing more complete meteorological data obtained during the 1986 field program, is offered in the next subsection.

3.6.2 Sea Breeze Processes

Background

Zimmerman (1982) indicated that summer mesoscale winds, in particular sea breezes, can dominate the local meteorology 25% of the time, and reach speeds up to 15 m/sec (29 knots). Kozo (1982) has shown evidence of the existence of sea breezes along the Beaufort coast of Alaska (70^{o}N latitude) with a horizontal extent including at least a 20-km zone centered on the coastline. Typical values of arctic land-sea temperature differences which generate sea breezes are on the order of 20^{o}C. Moritz (1977) points out that in coastal locations of the Alaskan arctic coast (such as at Barrow), the summer tundra-ocean thermal contrast remains positive (land always warmer than water) despite 15^{o}C drops in land temperature over the short arctic summer nights.

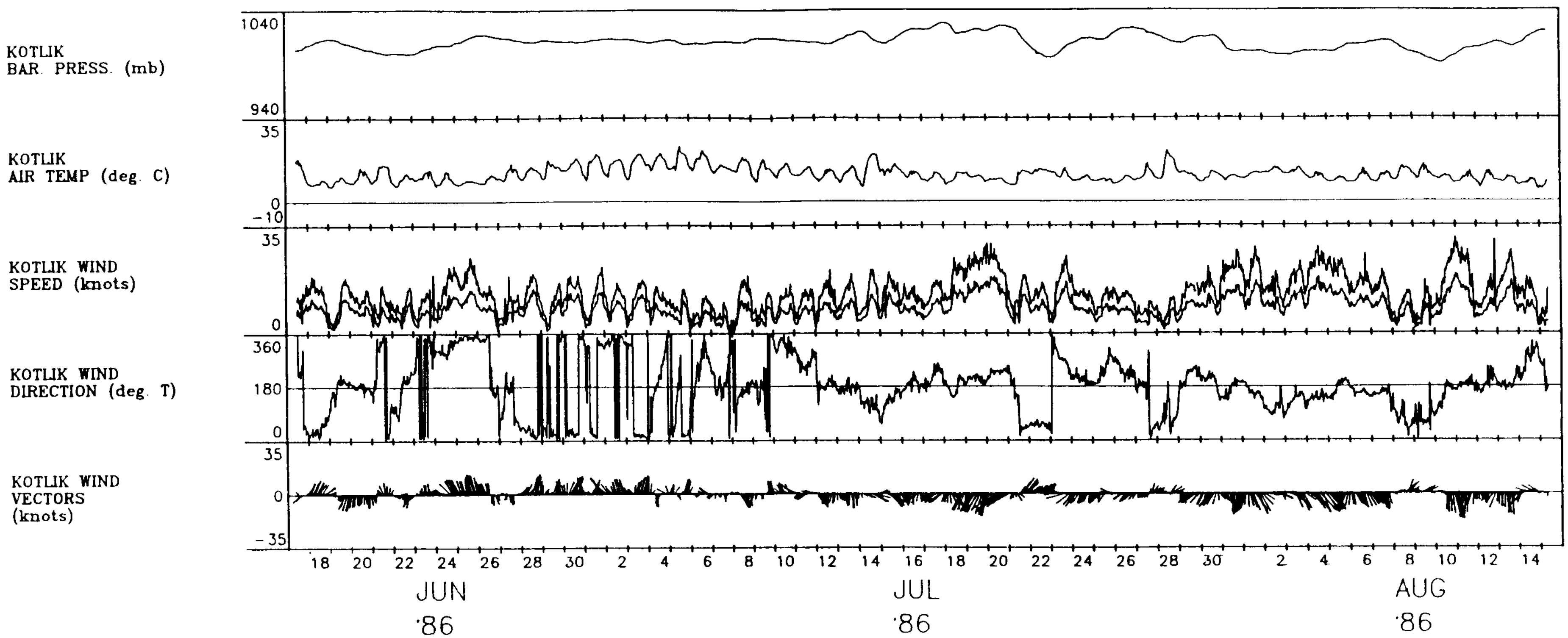
Kozo (1984) used 3-hourly surface winds from coastal stations at Northeast Cape, Unalakleet, and Nome to study the mesoscale meteorology of the Norton Sound region. The wind time series were tested for the appearance of a significant peak on the clockwise (CW) component of rotary spectra corresponding to a 1-day (diurnal) period characteristic of sea breezes. However, both CW and counterclockwise (CCW) peaks appear on the Nome and Unalakleet spectra for the month of July. Kozo (1984) points out that the significant CCW diurnal peaks seen in the rotary spectra have not appeared on previous data analyses of other Alaskan Arctic coastal sites (e.g., Beaufort sea coast).

Also, according to the above study, the highest sea breeze winds measured (1964 through 1968) during low-speed synoptic wind periods were 10.8 m/sec (21 knots) at both Nome and Unalakleet. This value seems to indicate that the 15 m/sec (29 knots) reported by Zimmerman (1982) is an overestimate of the sea breeze speeds; Kozo (1984) speculates that the synoptic winds were probably onshore at the time and the observers assumed that they were sea breezes.

Data from the Norton Sound mesoscale study also reveal that the major directions of onshore winds due to sea breeze influence are south-southwesterly at Nome and westerly at Unalakleet. Since these directions are perpendicular to the coast at Nome and Unalakleet, by analogy, the convex shape of the Yukon Delta would be conducive to sea breezes with directions ranging from northwest to northeast.

Analysis of Yukon Delta Data

Meteorological data obtained from the two EG&G stations deployed during the 1986 field program were analyzed to identify major characteristics of the Yukon Delta sea breeze. Figures 3-47 and 3-48 illustrate composite time series plots of barometric pressure, air temperature, average and gust wind speeds, average wind direction, and wind vectors at Kotlik and Emmonak, respectively. The meteorological convention (direction from which the wind is blowing) has been adopted for the wind directions displayed on these plots. The Kotlik station was deployed 8 km upstream from North Mouth on Okwega Pass, while the Emmonak



Composite time series plots of barometric pressure, air temperature, wind speed (hourly averages and maximum gust), wind direction, and wind vectors from the Kotlik meteorological station for the period 17 June through 15 August 1986. Wind vectors are plotted according to the meteorological convention.

Figure 3-47.

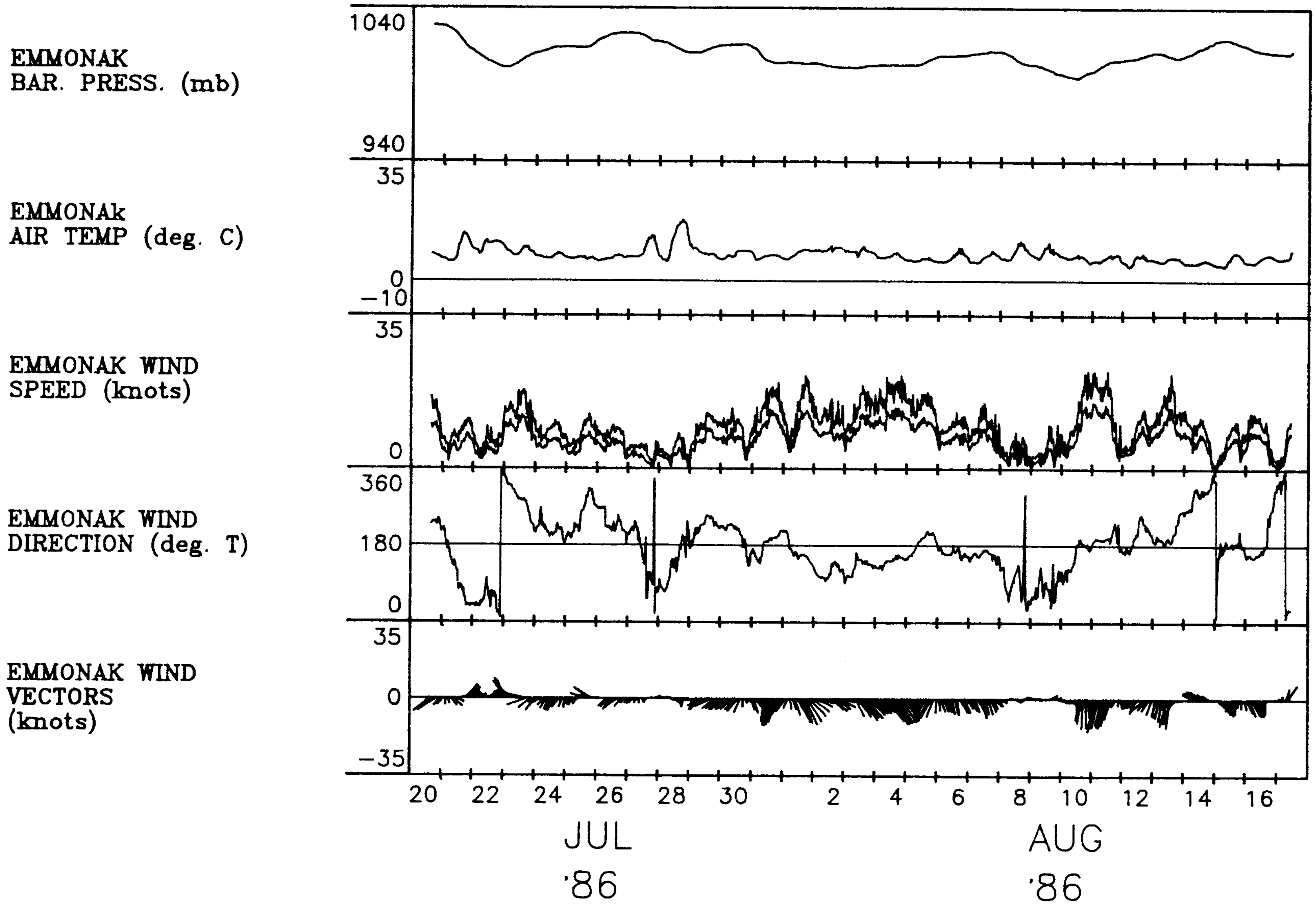


Figure 3-48. Composite time series plots of barometric pressure, air temperature, wind speed (hourly averages and maximum gust), wind direction, and wind vectors from the Emmonak meteorological station for the period 20 July through 17 August 1986. Wind vectors are plotted according to the meteorological convention.

station was deployed 14 km upstream from the coast on Kwiguk Pass near South Mouth. Both stations lie within the expected influence of the sea breeze regime. The Kotlik meteorological data range from 17 June through 15 August 1986, whereas the Emmonak data cover a shorter time period ranging from 20 July through 17 August 1986, as a result of equipment failure.

As observed in meteorological records from summer 1985 (subsection 3.6), large, diurnal air temperature oscillations occurred during periods of high atmospheric pressure (clear skies) in summer 1986. The data were dominated by synoptic offshore winds, except for the period of 28 June through 14 July (at Kotlik) when onshore winds were dominant and characterized by coherent, diurnal wind speed and air temperature oscillations. Although there were no offshore water temperature measurements made during the 1986 field program to identify land-ocean thermal contrasts, the diurnal variability of the wind speed and the concurrent onshore wind direction seem to indicate that the sea breeze regime was dominant during that time period. Additional characteristics of the Delta wind field can be derived from wind rose plots and bivariate wind speed/direction tabulations of the wind records from Emmonak and Kotlik. Wind rose plots (Figures 3-49 to 3-51) and bivariate statistics (Figures 3-52 to 3-54) have been generated from three time series, respectively: the Emmonak record (20 July through 17 August); the Kotlik record for the complete deployment (17 June through 15 August); and the portion of the Kotlik record concurrent with the Emmonak measurements (20 July through 15 August).

A comparison between the wind statistics at Emmonak and Kotlik, for the period 20 July through 15 August, reveals that wind speeds were generally higher at Kotlik than they were at Emmonak. Wind statistics from Emmonak (Figure 3-52) indicate that the mean wind speed was 6.5 knots, maximum wind speed was 15.1 knots, most frequent wind speeds were between 6 and 7 knots,

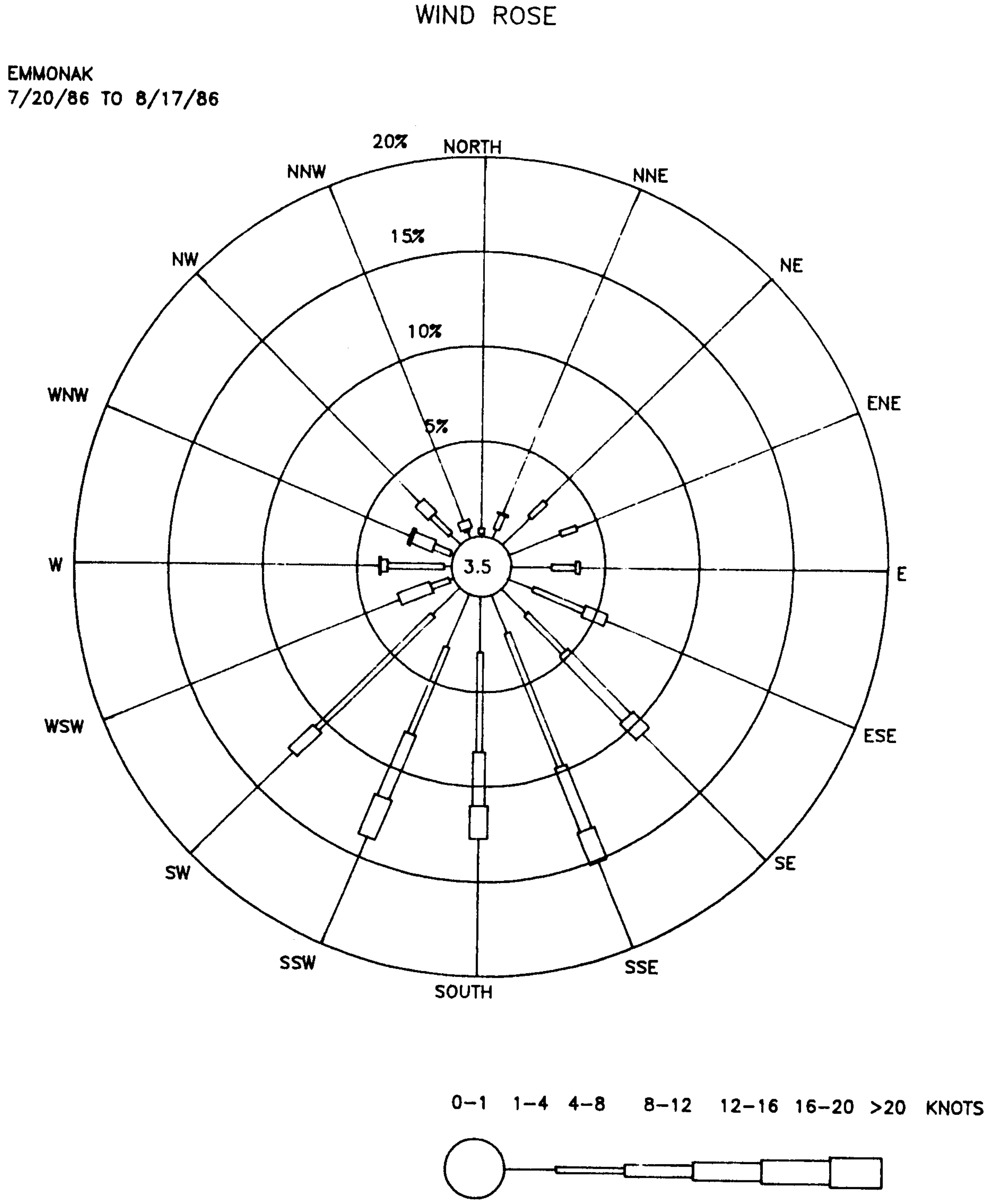


Figure 3-49. Wind rose plot of speed versus direction derived from Emmonak measurements for the period 20 July through 17 August 1986.

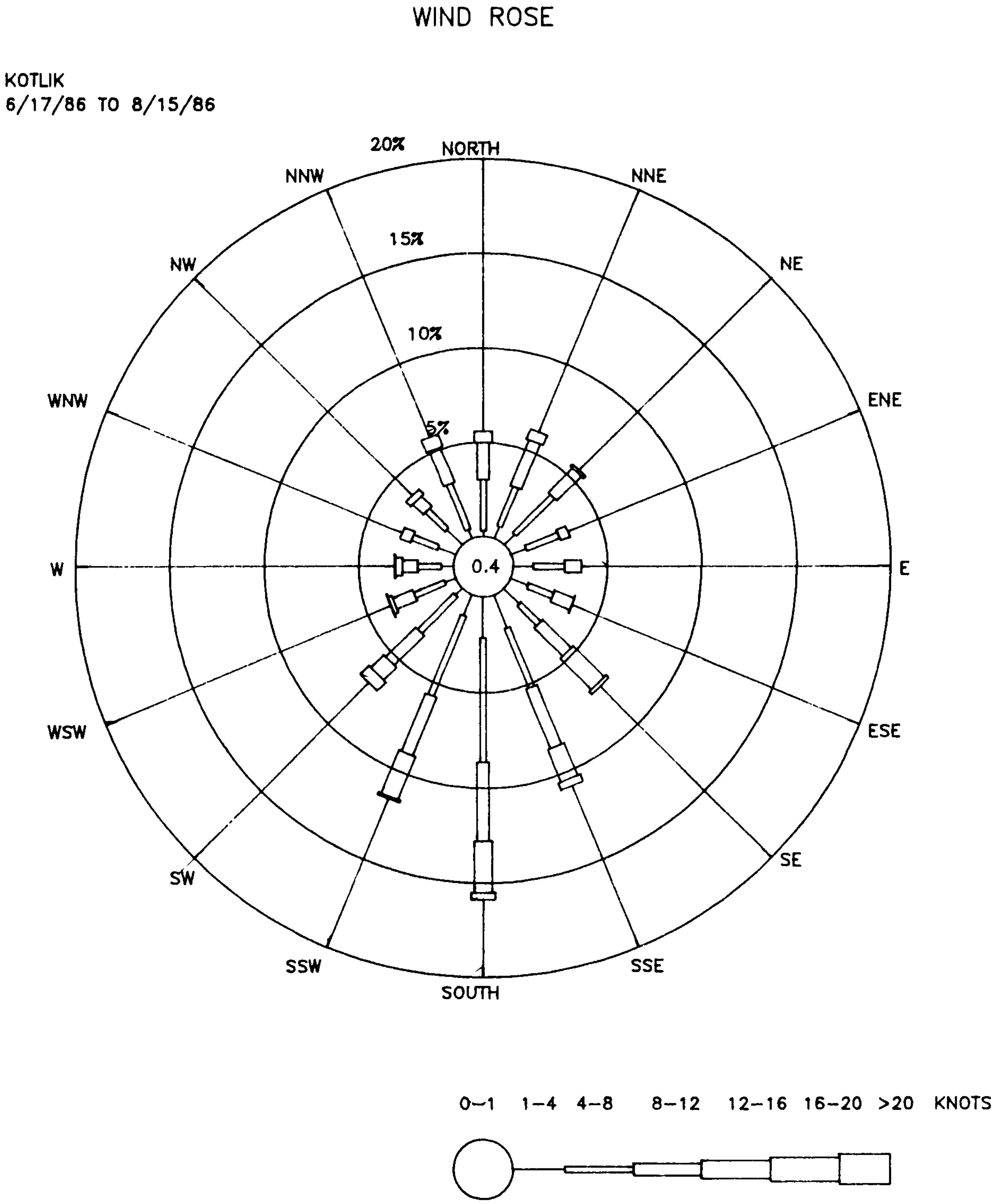


Figure 3-50. Wind rose plot of speed versus direction derived from Kotlik measurements for the period 17 June through 15 August 1986.

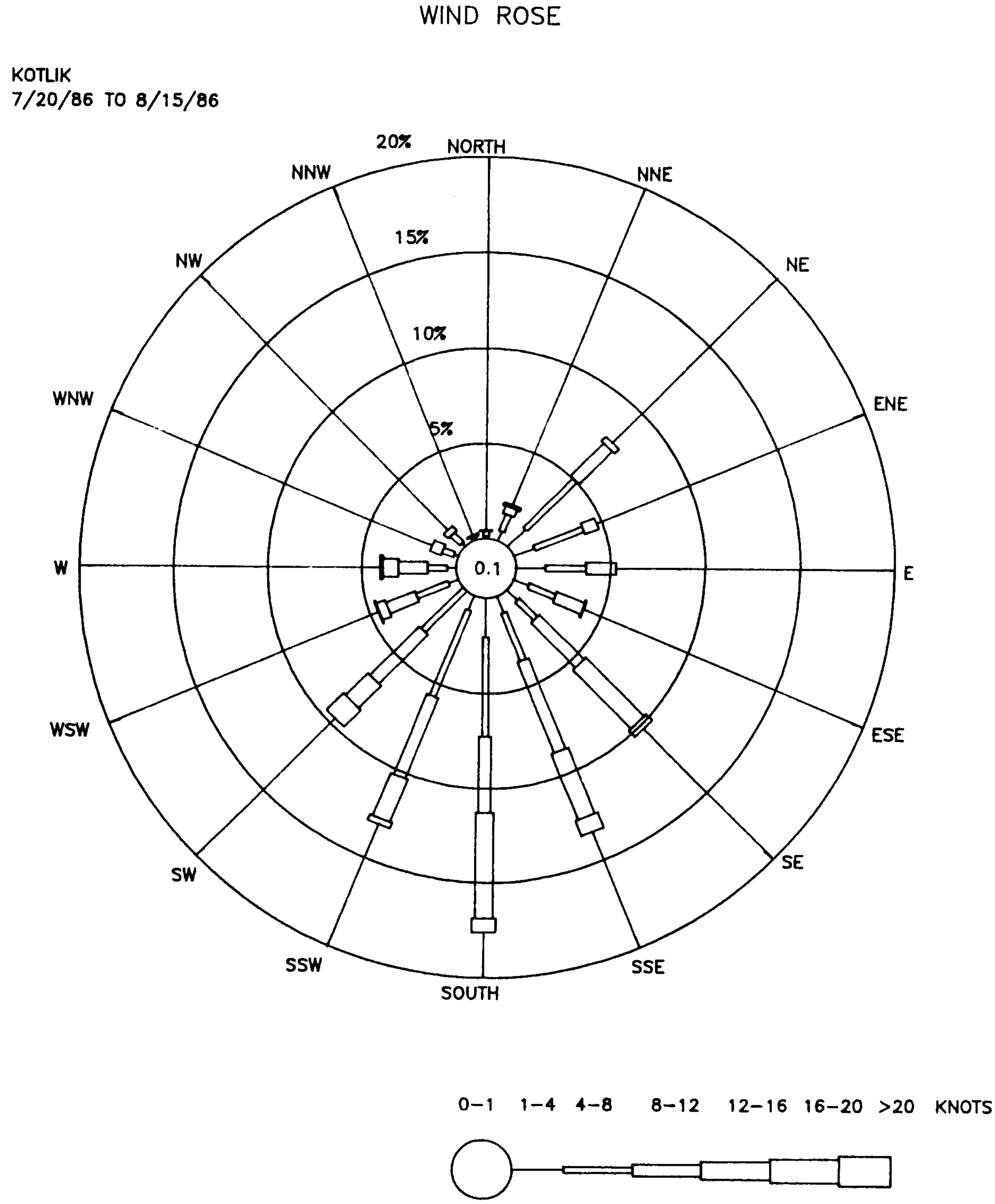


Figure 3-51. Wind rose plot of speed versus direction derived from Kotlik measurements for the period 20 July through 15 August 1986.

DISTRIBUTION FREQUENCY
0.5 HOUR AVERAGES STATION EMMONAK WIND SPANNING 86/ 7/20 TO 86/ 8/17

DIRECTION DEGREES TRUE	0.0-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	15.0-16.0	16.0-17.0	17.0-18.0	18.0-19.0	19.0-20.0	SUM	PERCENT
0- 15	9				1	1															11	0.8
15- 30	2	1		1	1	3	1	1	1												11	0.8
30- 45		6	5	7	3	2	4	8													35	2.6
45- 60	4	11	9	6	3		3														36	2.7
60- 75	4	6	9	6	3		1														29	2.2
75- 90	1	6	7	9	10	4	1														38	2.8
90-105	4	6	6	4	4	2	3	6	6												41	3.1
105-120	5	3	6	1	4	4	4	10	7	2	1										47	3.5
120-135	2	4	4	15	11	4	5	6	4	10	14	4	1								84	6.3
135-150	1	2	7	5	8	8	5	6	11	4	7	16	13	5							98	7.3
150-165		3	3	6	9	18	31	18	16	9	5	9	12	6	1						146	10.9
165-180		4	9	21	11	12	17	11	8	4	2	3	3	2	1						108	8.1
180-195		5	8	9	9	6	15	11	4	8	14	11	13	11	4	2					130	9.7
195-210		4	8	14	8	7	19	11	3	6	15	8	11	4	4						122	9.1
210-225		1	10	15	19	26	26	15	2	6	4										124	9.3
225-240	1	2	5	4	3	13	21	15	10	8	2										84	6.3
240-255				2	2	1	1	2	13	6	1	1									29	2.2
255-270		1	2	2	7	9	6	13	2	1		1									44	3.3
270-285	2			1		3	3	2	2	2		2	3								20	1.5
285-300		1		1		1	4	5	5		3	4									24	1.8
300-315	3	2		4	3	4	8	4	4	3											35	2.6
315-330	3	2	2	1		1				6	1	1									17	1.3
330-345	5	3					2		1		3										14	1.0
345-360	1	1	1	1	1	1				1											7	0.5
																					1334	
SUM	47	74	101	135	120	130	180	144	99	76	72	60	56	28	10	2	0	0	0	0	1334	
PERCENT	3.5	5.5	7.6	10.1	9.0	9.7	13.5	10.8	7.4	5.7	5.4	4.5	4.2	2.1	0.7	0.1	0.0	0.0	0.0	0.0		

(SPEED KNOTS)

SUMMARY STATISTICS

MEAN SPEED = 6.45 KNOTS STANDARD DEVIATION = 3.34 KNOTS
MAXIMUM = 15.07 KNOTS MINIMUM = 0.00 KNOTS RANGE = 15.07 KNOTS

IN A COORDINATE SYSTEM WHOSE Y AXIS IS POSITIONED 0.0 DEGREES COUNTER-CLOCKWISE FROM TRUE NORTH,
MEAN X COMPONENT = -0.07 KNOTS STANDARD DEVIATION = 4.26 KNOTS
MEAN Y COMPONENT = -3.82 KNOTS STANDARD DEVIATION = 4.47 KNOTS
MAJOR PRINCIPAL AXES ORIENTATION, DEGREES TRUE = 325

Figure 3-52. Statistical plot of bivariate distribution of wind speed versus wind direction from Emmonak measurements for the period 20 July through 17 August 1986.

DISTRIBUTION FREQUENCY
0.5 HOUR AVERAGES   STATION KOTLIK WIND   SPANNING 86/ 6/17 TO 86/ 8/15

DIRECTION DEGREES TRUE	0.0–1.0	1.0–2.0	2.0–3.0	3.0–4.0	4.0–5.0	5.0–6.0	6.0–7.0	7.0–8.0	8.0–9.0	9.0–10.0	10.0–11.0	11.0–12.0	12.0–13.0	13.0–14.0	14.0–15.0	15.0–16.0	16.0–17.0	17.0–18.0	18.0–19.0	19.0–20.0	SUM	PERCENT
0- 15		3	3	3	4	10	11	19	9	7	11	5	7	5							97	3.4
15- 30		2	3	8	4	8	15	15	21	13	8	14	9	1	2						123	4.4
30- 45		1	2	10	9	18	8	10	11	14	5	3	6								97	3.4
45- 60	3	5	9	4	11	10	17	23	15	11	4	1	1								114	4.0
60- 75		3	5	9	13	7	6	9	7	2	1										62	2.2
75- 90		5	7	7	6	11	3	9	4	2											54	1.9
90-105	1	3	3	15	7	11	5	8	11	6	5	1									76	2.7
105-120		5	7	4	7	10	2	6	8	4	5	4									62	2.2
120-135	2	3	11	10	13	13	3	4	6	12	7	6	5	6	4			1			106	3.7
135-150		6	10	10		6	9	12	10	17	9	9	23	17	14	3	5		1		161	5.7
150-165	1	5	9	12	11	27	13	17	19	22	13	11	16	6	9	9	5	1	2		208	7.4
165-180		4	7	26	16	21	21	40	29	30	16	5	10	13	12	5	3	4	2		264	9.3
180-195		3	2	42	15	39	33	34	25	23	11	12	20	15	11	10	3				298	10.5
195-210		3	5	12	14	14	22	43	17	18	13	12	18	9	9	8	3		1		221	7.8
210-225		2	1	7	7	9	7	30	17	22	8	4	6	4	8	5	4	1	1		143	5.1
225-240		1	1	7	2	12	10	20	11	19	9	2	9	3	3	2	4	5	3		123	4.4
240-255		1	4	8	5	9	7	14	10	7	2	1	1		2		1				72	2.5
255-270		5	4	4		4	7	13	3	5	3	3	4	1	2	1	2				61	2.2
270-285		2	6	2	2	3	5	13	6	7	1		1		2						50	1.8
285-300	1	5	5	10	5	7	9	7	5	9											63	2.2
300-315		2	11	11	7	5	5	9	5	3	3	1	3								65	2.3
315-330		2	3	13	11	12	3	8	8	3	2	5	7	3							80	2.8
330-345	2	3		5	4	6	6	31	13	9	6	9	8	1	1						104	3.7
345-360	2	1	1	2	4	21	10	21	13	19	9	6	6	6	2						123	4.4
																					2827	
SUM	12	75	119	241	177	293	237	415	283	284	151	114	160	90	81	43	30	12	10	0	2827	
PERCENT	0.4	2.7	4.2	8.5	6.3	10.4	8.4	14.7	10.0	10.0	5.3	4.0	5.7	3.2	2.9	1.5	1.1	0.4	0.4	0.0		

SPEED KNOTS (column heads above: lower bound ¦ upper bound)

SUMMARY STATISTICS

MEAN SPEED = 7.89 KNOTS   STANDARD DEVIATION = 3.57 KNOTS
MAXIMUM = 18.98 KNOTS   MINIMUM = 0.14 KNOTS   RANGE = 18.84 KNOTS

IN A COORDINATE SYSTEM WHOSE Y AXIS IS POSITIONED 0.0 DEGREES COUNTER-CLOCKWISE FROM TRUE NORTH,
MEAN X COMPONENT = 0.03 KNOTS   STANDARD DEVIATION = 4.76 KNOTS
MEAN Y COMPONENT = -2.29 KNOTS   STANDARD DEVIATION = 6.87 KNOTS
MAJOR PRINCIPAL AXES ORIENTATION, DEGREES TRUE = 1

Figure 3-53. Statistical plot of bivariate distribution of wind speed versus wind direction from Kotlik measurements for the period 17 June through 15 August 1986.

DISTRIBUTION FREQUENCY
0.5 HOUR AVERAGES STATION KOTLIK WIND SPANNING 86/ 7/20 TO 86/ 8/15

DIRECTION DEGREES TRUE	0.0-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	15.0-16.0	16.0-17.0	17.0-18.0	18.0-19.0	19.0-20.0	SUM	PERCENT
0- 15		1				2	1			1											5	0.4
15- 30		1		5	1		4	2	2												15	1.2
30- 45			1	4	4	7	5	6	7	8	1	2	5								50	3.9
45- 60	1	4	9	3	5	5	13	15	10	7	1	1	1								75	5.9
60- 75		3	3	4	9	5	3	6	6		1										40	3.2
75- 90		3	6	5	3	5		5	4	1											32	2.5
90-105		2	2	6	5	6	5	6	9	6	2										49	3.9
105-120		1	4		1	7	1	4	7	4	2	2									33	2.6
120-135		1	5	5	3	7	1	1	5	8	4	4	5	6	4			1			60	4.7
135-150			3	3		2	4	8	6	13	5	8	16	14	14	2	5		1		104	8.2
150-165		1	1	3	4	15	1	4	11	14	10	11	13	6	9	9	5	1	2		120	9.5
165-180		1		13	5	12	5	8	12	11	12	5	10	12	11	5	3	4	2		131	10.3
180-195				19	8	12	12	14	8	8	4	5	20	13	10	7	2				142	11.2
195-210		1	1	5	5	6	6	27	15	12	6	9	10	1	7	2	3		1		117	9.2
210-225					1	4	6	18	14	14	6	3	3		1	2	2	1	1		76	6.0
225-240					1	5	7	10	8	12	7	1	9	3	3	2	4	5	3		80	6.3
240-255			2	4	3	2	3	9	8	3	2	1	1		2		1				41	3.2
255-270		3		2		2	2	7	3	4	2	2	4	1	2	1	2				37	2.9
270-285		1	1	1				7	4	6	1		1		2						24	1.9
285-300							2	2	2	5											11	0.9
300-315			3		2		2	5	2	1	1										16	1.3
315-330				2	1		1	1													5	0.4
330-345				2							1										3	0.2
345-360				1	1																2	0.2
																					1268	

SPEED KNOTS	0.0 : 1.0	1.0 : 2.0	2.0 : 3.0	3.0 : 4.0	4.0 : 5.0	5.0 : 6.0	6.0 : 7.0	7.0 : 8.0	8.0 : 9.0	9.0 : 10.0	10.0 : 11.0	11.0 : 12.0	12.0 : 13.0	13.0 : 14.0	14.0 : 15.0	15.0 : 16.0	16.0 : 17.0	17.0 : 18.0	18.0 : 19.0	19.0 : 20.0	
SUM	1	23	41	87	62	104	84	165	143	138	68	54	98	56	65	30	27	12	10	0	1268
PERCENT	0.1	1.8	3.2	6.9	4.9	8.2	6.6	13.0	11.3	10.9	5.4	4.3	7.7	4.4	5.1	2.4	2.1	0.9	0.8	0.0	

SUMMARY STATISTICS

MEAN SPEED = 8.82 KNOTS STANDARD DEVIATION = 3.82 KNOTS
MAXIMUM = 18.98 KNOTS MINIMUM = 0.72 KNOTS RANGE = 18.26 KNOTS

IN A COORDINATE SYSTEM WHOSE Y AXIS IS POSITIONED 0.0 DEGREES COUNTER-CLOCKWISE FROM TRUE NORTH,
MEAN X COMPONENT = 0.54 KNOTS STANDARD DEVIATION = 5.62 KNOTS
MEAN Y COMPONENT = -5.06 KNOTS STANDARD DEVIATION = 5.91 KNOTS
MAJOR PRINCIPAL AXES ORIENTATION, DEGREES TRUE = 31

Figure 3-54. Statistical plot of bivariate distribution of wind speed versus wind direction from Kotlik measurements for the period 20 July through 15 August 1986.

most frequent wind direction was from south-southeast with maximum wind speeds ranging between 12 and 16 knots. By comparison, wind statistics from Kotlik (Figure 3-54) reveal that the mean wind speed was 8.8 knots, maximum wind speed was 18.9 knots, most frequent wind speeds were between 7 and 8 knots, and most frequent wind direction was from the south with maximum speeds ranging between 16 and 20 knots.

The intensification of the wind speeds at Kotlik may have been a result of topographic effects caused by the presence of mountains 20 miles east of Kotlik. Kozo (1984) points out that topographic effects in Norton Sound redirect winds and may act to intensify the wind field depending on the large-scale wind direction and orographic obstacle orientation.

A significant change in the Kotlik wind direction distribution occurs when wind data for the entire deployment (17 June through 15 August 1986) are included in the statistics. This change is clearly shown by comparing the Kotlik wind rose for the period 20 July through 15 August (Figure 3-51) with the Kotlik wind rose for the entire deployment (Figure 3-50). Bivariate wind statistics for the full deployment period are presented in Figure 3-53. The wind rose including data from the entire deployment (Figure 3-50) indicates the presence of onshore winds with directions ranging from north-northwesterly to north-northeasterly, resulting from the addition of data from the time period dominated by the sea breeze (28 June through 14 July). These onshore winds occurred during a time period equivalent to 28% of the deployment period (mid-June through mid-August) with maximum speeds ranging from 14 to 15 knots. This result seems in agreement with the previously discussed characteristics of the Arctic sea breeze. Unfortunately, the lack of meteorological data from Emmonak during the sea breeze-dominated period precludes an evaluation of the spatial variability of the Yukon Delta sea breeze.

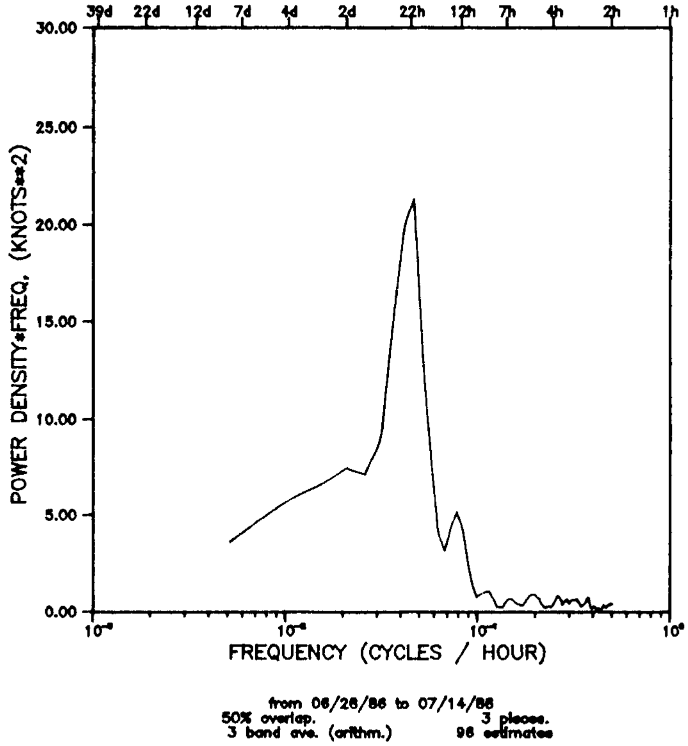
In order to evaluate the periodicity and sense of rotation of the sea breeze, spectra of the north and east wind velocity components, as well as rotary wind spectra, were computed for the time period of sea breeze influence. Spectra were computed on three 8-day long time series with a 50% overlap; ensemble and frequency averages (three-band average) were performed on the spectral estimates to increase the statistical confidence.

The north and east wind component spectra, and the wind rotary spectra of Kotlik wind data, for the period 28 June through 14 July, are illustrated in Figures 3-55 and 3-56, respectively. The wind component spectra (Figures 3-55) indicate significant diurnal peaks, with the north component peak being four times more energetic than the east component peak.

The rotary spectra (Figure 3-56) indicate significant peaks in both clockwise (CW) and counterclockwise (CCW) diurnal components. Previous investigations of the Alaskan Arctic sea breeze have shown that the wind vector rotation is predominantly CW. However, coastal regions of Norton Sound seem to be an exception, since Kozo (1984) has also observed CCW diurnal peaks in rotary spectra of Unalakleet and Nome wind data. We point out that a purely rectilinear oscillation exhibits equal CW and CCW energy from rotary spectra analysis. Additional data would be needed to resolve the rotational characteristics (or linear behavior) of the sea breeze on the Yukon Delta.

In summary, the analysis of Kotlik wind data has shown that the Yukon Delta coastal wind circulation during the period 28 June through 14 July 1986 was predominantly controlled by the sea breeze. During this time period, which corresponds to 28% of the entire deployment period (17 June through 15 August 1986), north-northwesterly to north-northeasterly onshore winds with maximum speeds of 14 to 15 knots were predominant. Unlike coastal areas of the Beaufort Sea, where the sea breeze has predominantly CW rotations, the Yukon Delta sea breeze contains

KOTLIK WIND, NORTH COMPONENT



KOTLIK WIND, EAST COMPONENT

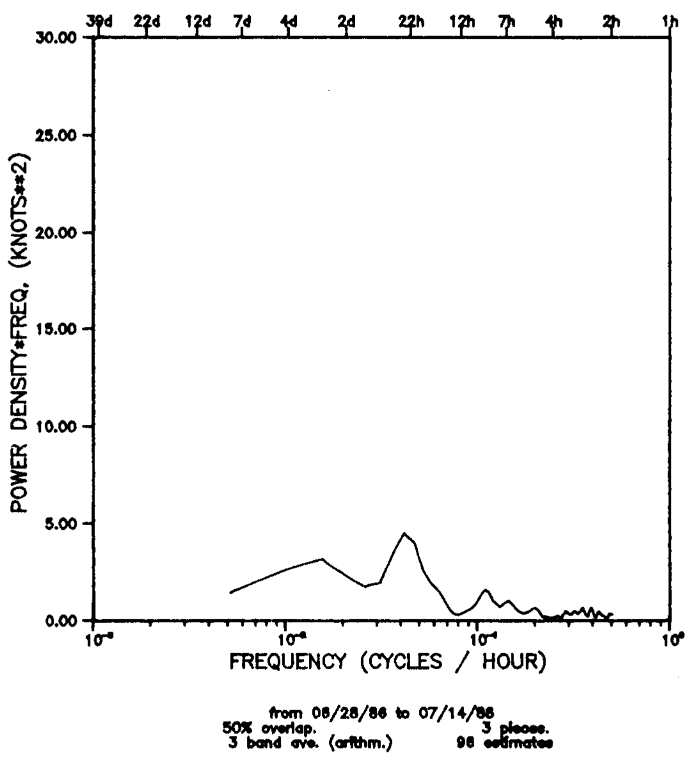


Figure 3-55. Variance conserving autospectra of north (upper) and east (lower) wind components based upon observations at Kotlik for the period 28 June through 14 July 1986.

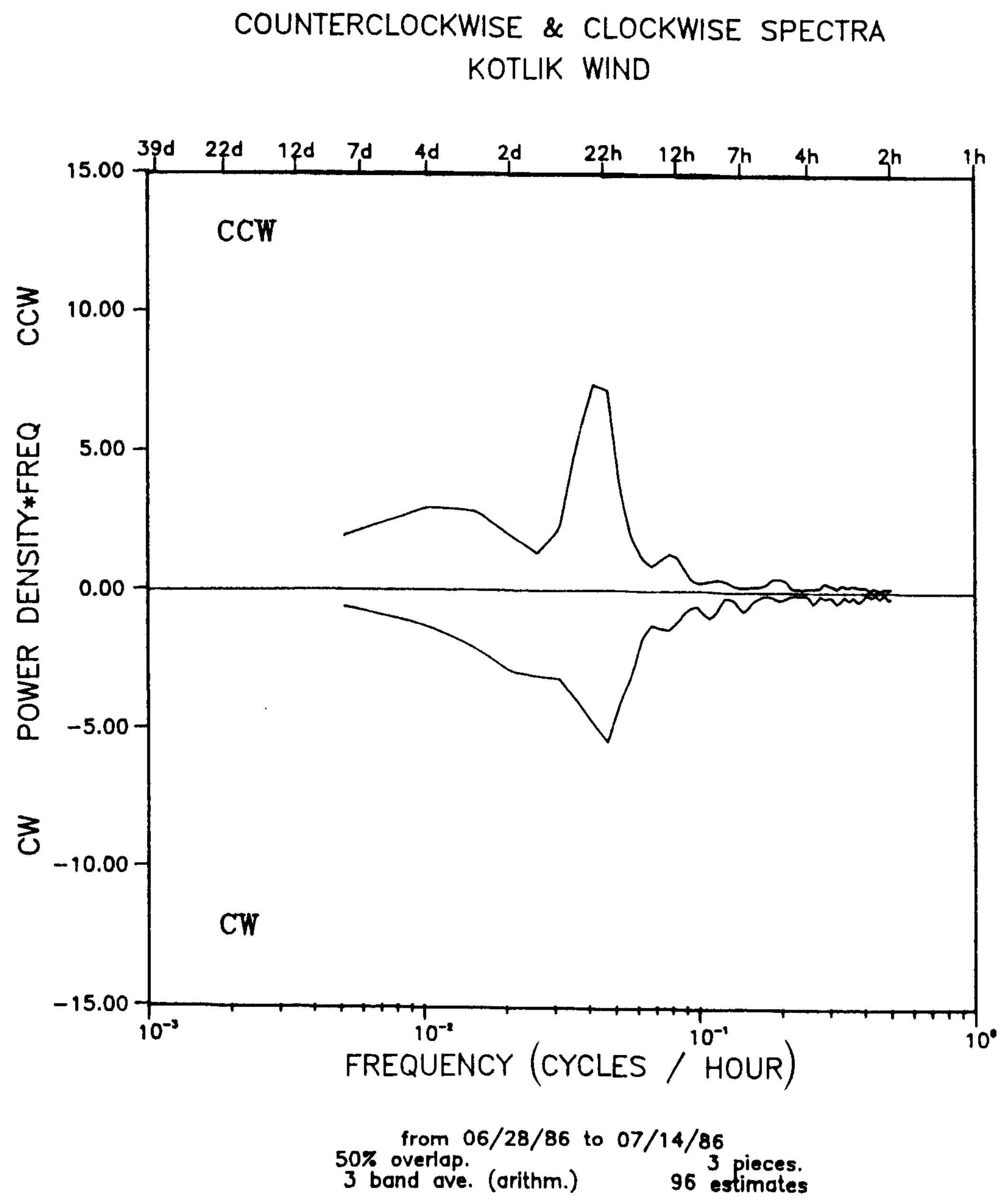


Figure 3-56. Variance conserving rotary spectra of wind records from Kotlik for the period 28 June through 14 July 1986. Counterclockwise spectra are given in the upper frame; clockwise in the lower frame.

significant diurnal variance in both CW and CCW components of the rotary spectra. These results seem to be in agreement with previous studies of the sea breeze in coastal areas of Norton Sound (Kozo, 1984).

3.6.3 Storm Surge

During the open-water season, roughly mid-June to mid-November, the Delta is subject to coastal flooding from storm-driven waves and surges. Along this section of the Alaskan coast, storms typically approach from the southwest quadrant, generating strong southerly winds. According to Ekman dynamics, this should favor onshore transport and elevated water levels against the open coastal boundary of the Bering Sea, which is approximately aligned north-south. Conversely, northerly winds should favor offshore transport and a drop in water level at the coast. As shown in earlier subsections, the moored data collected off South and Middle Mouths generally confirm this expected behavior.

Along the northern margin of the Delta, within the partially enclosed waters of Norton Sound, the surge dynamics may be quite different than along the open coast. Because the natural period of oscillation in the Sound is approximately 24 hours, appropriate storm events can drive a seiching action, which quickly becomes resonantly amplified. The most extreme example of storm surge within Norton Sound occurred during the "Great Bering Sea Storm" of 11 through 13 November 1974. Winds of 50 to 75 knots occurred within 12 hours of frontal passage and were sustained for several days. A total water-level rise, including the astronomical tide, estimated at 7.6 m, occurred in Unalakleet at the extreme northeastern end of the Sound (NOAA, 1977). Johnson and Kowalik (1986) used a hydrodynamic storm surge model to simulate this event and estimated the storm-surge contribution to the rise at Unalakleet at 5 m, and within the vicinity of the Yukon Delta at 1.6 to 2.0 m. Other estimates (LGL, 1984) of extreme surge heights in excess of 2.0 m along the northern coast of the Delta appear reasonable in view of the model results.

There were no severe storms during the periods of observation in the present study which generated extreme surge levels such as occurred in 1974. However, more moderate surge events were recorded which are still useful in analyzing the dynamic processes involved. For example, the data collected with the offshore moorings at stations C-3 and C-4A, in conjunction with the wind data from Emmonak, provide a revealing description of surge events along the western coastal margin of the Delta. Figure 3-57 presents these data from August 1985, together with a water-level record (NOAA RU 660) from South Mouth. These records have been described previously in subsection 3.3. The "surge height" plots represent detided versions of the raw water-level records, uncorrected for variations in atmospheric pressure. Similarly, the tides have been removed from the current data by means of a low-pass filter with a cutoff point at 33 hours. The wind vectors have been plotted according to the oceanographic convention; i.e., pointing in the direction toward which the wind is blowing, consistent with the current vectors.

Due to the relatively short record length and the presence of shallow-water constituents, removal of the tidal variance from the water-level records is not complete. This results in a rather noisy appearance and exaggerates the variability due to meteorological forcing. Nevertheless, the major variations representing storm surge effects are readily seen, especially from 5 through 16 August. There are two distinct storm events of major interest during this time period: the first occurs from 5 through 8 August, and the second from 14 through 16 August. These events are somewhat obscured in the wind vector plot due to their moderate intensity and the large daily gaps in the data. However, the water-level variations are quite apparent.

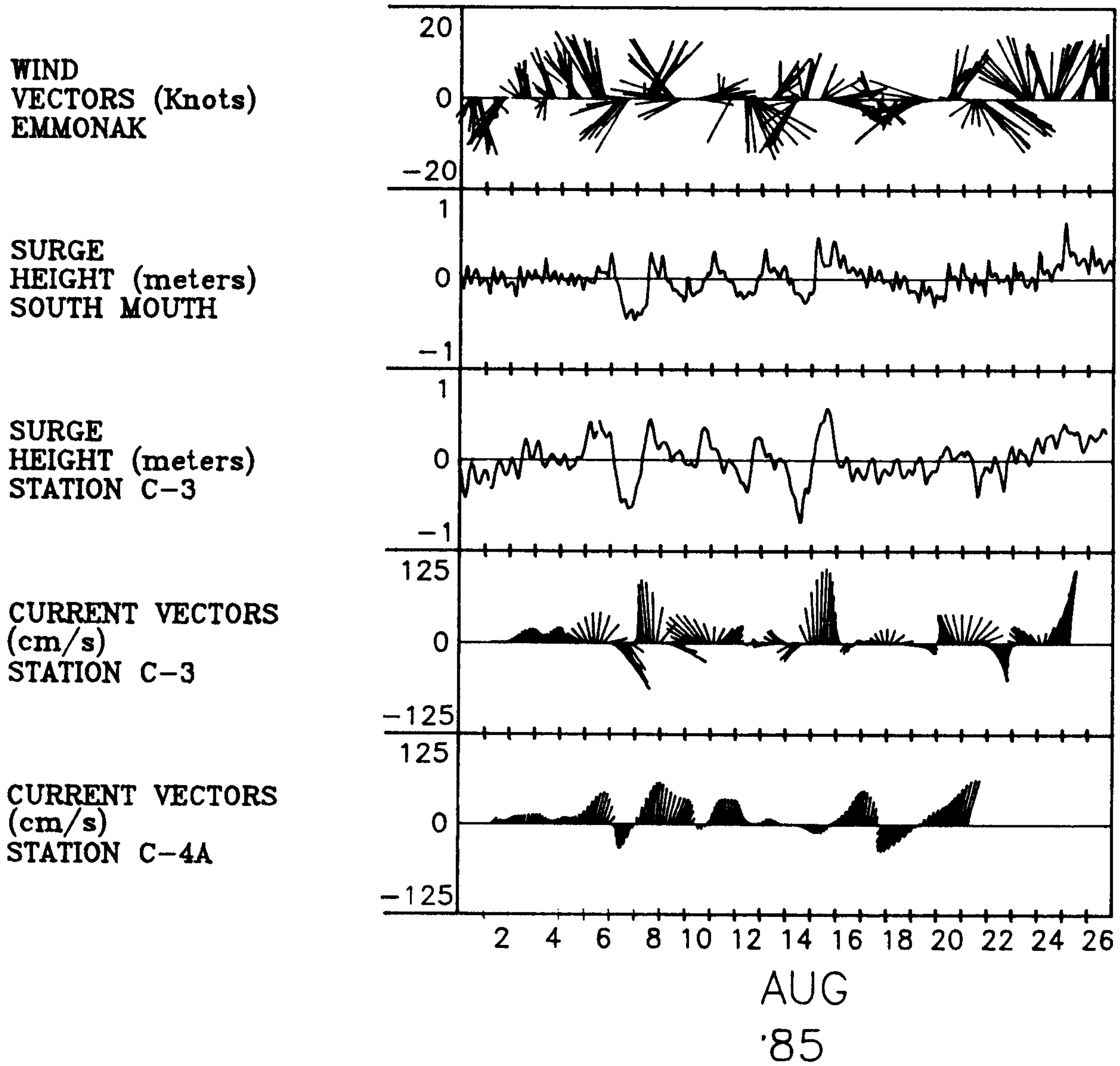


Figure 3-57. Composite time series plot of Emmonak wind vectors (plotted as direction toward which wind is blowing), water levels at South Mouth and offshore mooring C-3, and low-pass filtered currents from offshore moorings C-3 and C-4A. Surge height represents the residual water level after the predicted tide height has been removed from the observed water-level record.

In order to provide a detailed description of the evolution of one of these storm surge events, an analysis of NWS surface weather charts (obtained from the University of Alaska) has been made for the period 5 August at 2100 AKST through 8 August at 2100 AKST. During this interval, there were actually two successive storms which caused positive and negative surges of about 0.5 m at the location of station C-3. A map of the Bering Sea, containing the low-pressure center trajectories for the two storms, is presented in Figure 3-58.

The following is a 6-hourly interpretation of the surface weather charts and of how the storm parameters relate to the storm surge evolution:

- 5 August at 2100 AKST - Storm center 'A' (986 mb) lies in the central Bering Sea, 510 nm southwest of the Yukon Delta. At a distance of about 80 nm from the storm's center, wind speeds range between 32 and 37 knots. Winds are from the south-southeast at 9 to 4 knots near the Delta. Water level at C-3 begins to rise (0.1 m above MSL).
- 6 August at 0300 AKST - Storm A's low-pressure center (LPC) intensifies to 984 mb and advances 30 nm northward. In the vicinity of the Yukon Delta, approximately 480 nm northeast of the storm's center, winds are still from the south-southeast with speeds ranging from 9 to 14 knots. Water level at C-3 rises to 0.3 m above MSL.
- 6 August at 0900 AKST - LPC in the Bering Sea intensifies to 982 mb and is now located 60 nm northward of previous position. Yukon Delta winds are still from the south-southeast, but wind speeds are now 15 to 20 knots. Water level at station C-3 reaches 0.4 m above MSL.

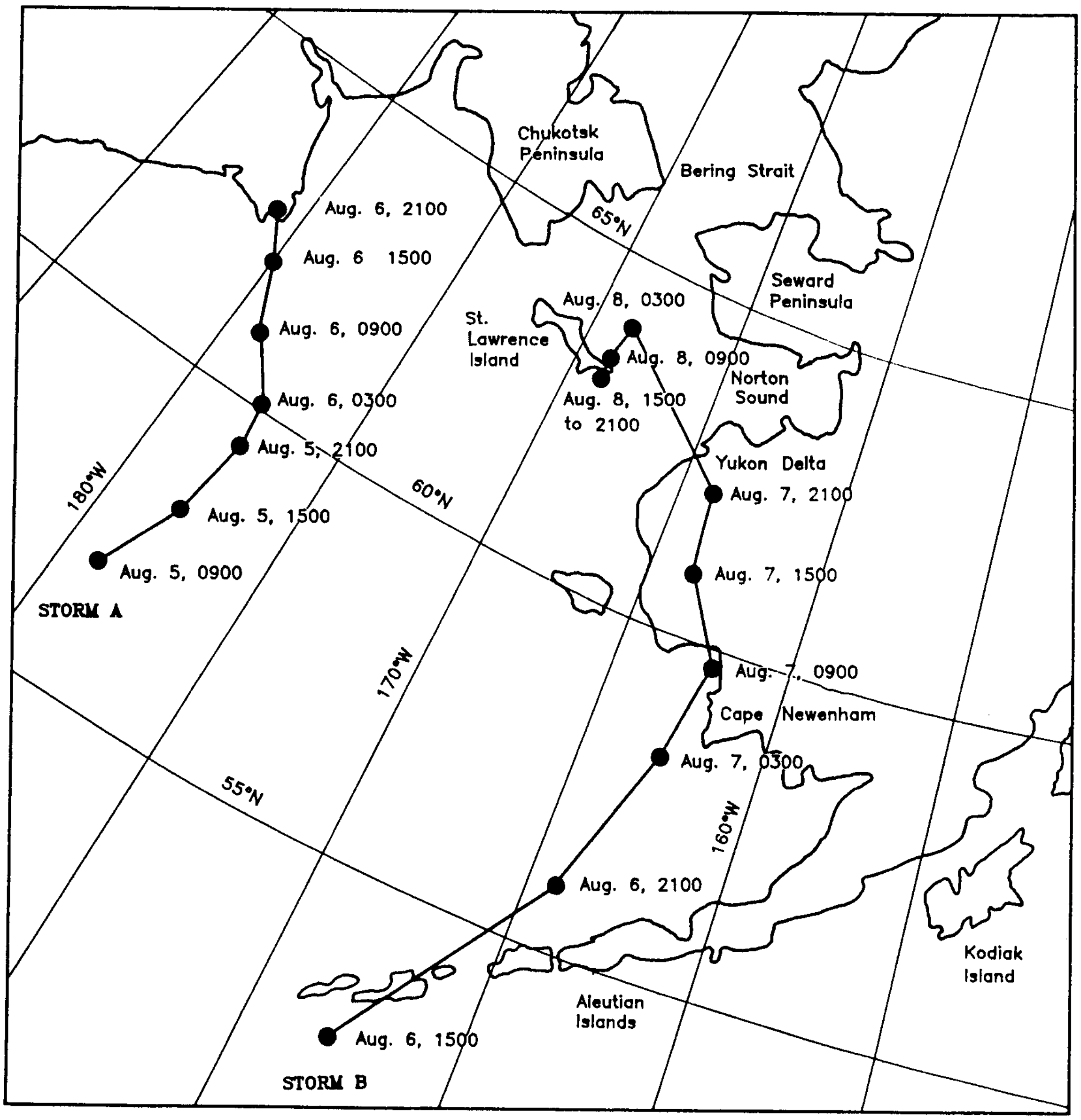


Figure 3-58. Map of the Bering Sea region illustrating the tracks of two extra-tropical, low-pressure storms which caused measurable storm surge at the Yukon Delta during the period 5-8 August 1985.

- 6 August at 1500 AKST - LPC advances 60 nm northwestward and the central pressure increases to 988 mb. Yukon Delta wind speeds range between 15 and 20 knots from the south-southeast direction. A second storm, B, with its LPC (1,000 mb) located on the Fox Islands in the Aleutian archipelago, begins to intensity. The water level at station C-3 remains at 0.4 m above MSL.
- 6 August at 2100 AKST - The LPC of storm A, with a northward track nearly parallel to the 180^{o}W meridian, reaches the Russian coast west of the Chukotsk Peninsula. At this time, the wind speed at the Yukon Delta decreases to the range of 9 to 14 knots from south-southeast. The water level at C-3 subsides to 0.2 m above MSL. The second storm, originating in the Aleutian Islands, continues to intensify with the LPC reaching 996 mb. This storm moves much faster than the previous one; at this time the LPC has traveled 240 nm northeastward in the past 6 hours.
- 7 August at 0300 AKST - LPC of storm B advances 150 nm to the northeast, and its central pressure, now located 30 nm southwest of Cape Newenham, intensifies to 992 mb. The Yukon Delta is now under the influence of storm B, with winds from the northeast at 10 knots. The water level at C-3 drops to 0.05 m below MSL.
- 7 August at 0900 AKST - LPC of storm B is near the coast, 60 nm north of Cape Newenham, with a central pressure of 984 mb. Although at this time, northwesterly storm winds over the southeastern portion of the Bering Sea intensify to about 50 knots, northeasterly winds in the Yukon Delta are much weaker with speeds near 10 knots. This is due to the fact that Yukon winds, at this stage of the storm, are the result of the eastern portion of the storm's circulation which is much weaker because of frictional

effects imposed by the Alaskan land mass. The water level at C-3 is now 0.35 m below MSL due to the offshore transport caused by the northeasterly winds.

- 7 August at 1500 AKST - At this time, the LPC lies 120 nm south of the Delta and the central pressure has increased to 987 mb. However, due to the LPC's proximity to the Delta, wind speeds increase to 15 to 20 knots, and the wind direction shifts from northeast to east. The more intense easterly winds cause the water level at C-3 to drop to 0.5 m below MSL. The minimum water level of 0.52 m below MSL occurs later at 1700 AKST.
- 7 August at 2100 AKST - Storm B's LPC is now close to the Yukon Delta (60 nm to the south) and the central pressure has risen to 992 mb. Wind speeds near station C-3 drop below 10 knots and the water level rises to 0.45 m below MSL.
- 8 August at 0300 AKST - LPC advances 165 nm northwestward and is now over the Bering Sea, 45 nm north of St. Lawrence Island. The central pressure is still 992 mb, but, due to the storm's new location, winds near the Delta shift to southwesterly, with speeds under 10 knots. The water level at C-3 rises to 0.2 m below MSL.
- 8 August at 0900 AKST - LPC moves 30 nm to the south, in a portion closer to St. Lawrence Island. Central pressure drops to 990 mb, southwesterly winds increase to 15 knots, and the water level at C-3 rises to 0.1 m above MSL.
- 8 August at 1500 AKST - LPC advances only 20 nm southward, the central pressure increases to 993 mb, and winds are still from the southwest at 10 to 15 knots. The water level at C-3 continues to rise and is now at 0.3 m above MSL.

- 8 August at 2100 AKST - LPC remains stationary and central pressure increases to 994 mb. Wind conditions and water level at C-3 do not change considerably. However, after this time, the storm begins to weaken, winds become more variable, and the water level at C-3 finally subsides to normal MSL conditions (zero surge height) at 1800 AKST on 9 August.

It is important to note that this storm event marks the time of transition between two distinctive offshore current regimes, as described in detail in subsection 3.2. In that earlier description, it was concluded that the river plume was advected a substantial distance offshore by the effect of this storm event. Such an effect is quite reasonable in view of the sustained period of strong northeasterly winds which accompanied the early stages of the second storm throughout the day on 7 August.

The second storm event from 14 through 16 August appears to follow a similar pattern. The wind is initially directed toward the southwest at roughly 20 to 25 knots, causing a rapid decline in water level to 0.7 m below MSL. The wind then reverses toward the northeast, as before, accompanied by a rapid rise in water level to a peak of 0.6 m above MSL. The northward wind stress is accompanied by a northward pulse in the alongshore current at speeds over 100 cm/sec at mooring C-3. However, unlike the previous storm event, the current at mooring C-4A shows little correlation with this behavior, being directed weakly onshore. In fact, there is little coherence between the two moorings after 7 August through the end of the deployment. This contrasts strongly with the appearance of the two records prior to 7 August when the coherence is quite high.

This behavior is consistent with the interpretation advanced in subsection 3.3, that the first storm event served to draw the river plume offshore, thereby imposing a baroclinic field over mooring C-4A. The lack of alongshore coherence reflects the fact that mooring C-3 tends to lie offshore and upstream of the leading edge of the river plume, while C-4A falls within the zone of active frontal movement.

Another interesting observation from Figure 3-57 is that the surge amplitude decreases from C-3 to the vicinity of the South Mouth, in contrast with the normal tendency for surge to increase with distance toward the coast. Apparently, the platform break marks the approximate position of maximum surge amplitude. Dissipative processes, presumably including wave-enhanced bottom friction, are likely to be magnified by the extremely shallow depths over the majority of the platform area. Accordingly, the platform acts as partial buffer to storm surge flooding of the coastal margin of the Delta.

The relatively brief period of observation shown in Figure 3-57 provides useful dynamical insights into storm surge events, but does not display the greater magnitude of surge levels expected later in the season when more severe storms are likely to occur. Also, as stated previously, the dynamical behavior may change from the western to the northern coast of the Delta. In an attempt to examine the wider range of spatial variability, Figures 3-59 and 3-60 present concurrent records from each distributary mouth. As before, these records have been detided, but remain uncorrected for atmospheric pressure variations.

The visual coherence is surprisingly consistent among all of these records, indicating that the surge is dominated by a large-scale barotropic response to the storm passage. Although the scale of the plots makes it difficult to discern, there is a progressive phase lag from South to North Mouth estimated roughly in the range from 2 to 3 hours, indicating propagation along the coast to the north. This is consistent with the results obtained previously by tidal harmonic analysis. As described in subsection 3.3, for example, a phase lag of

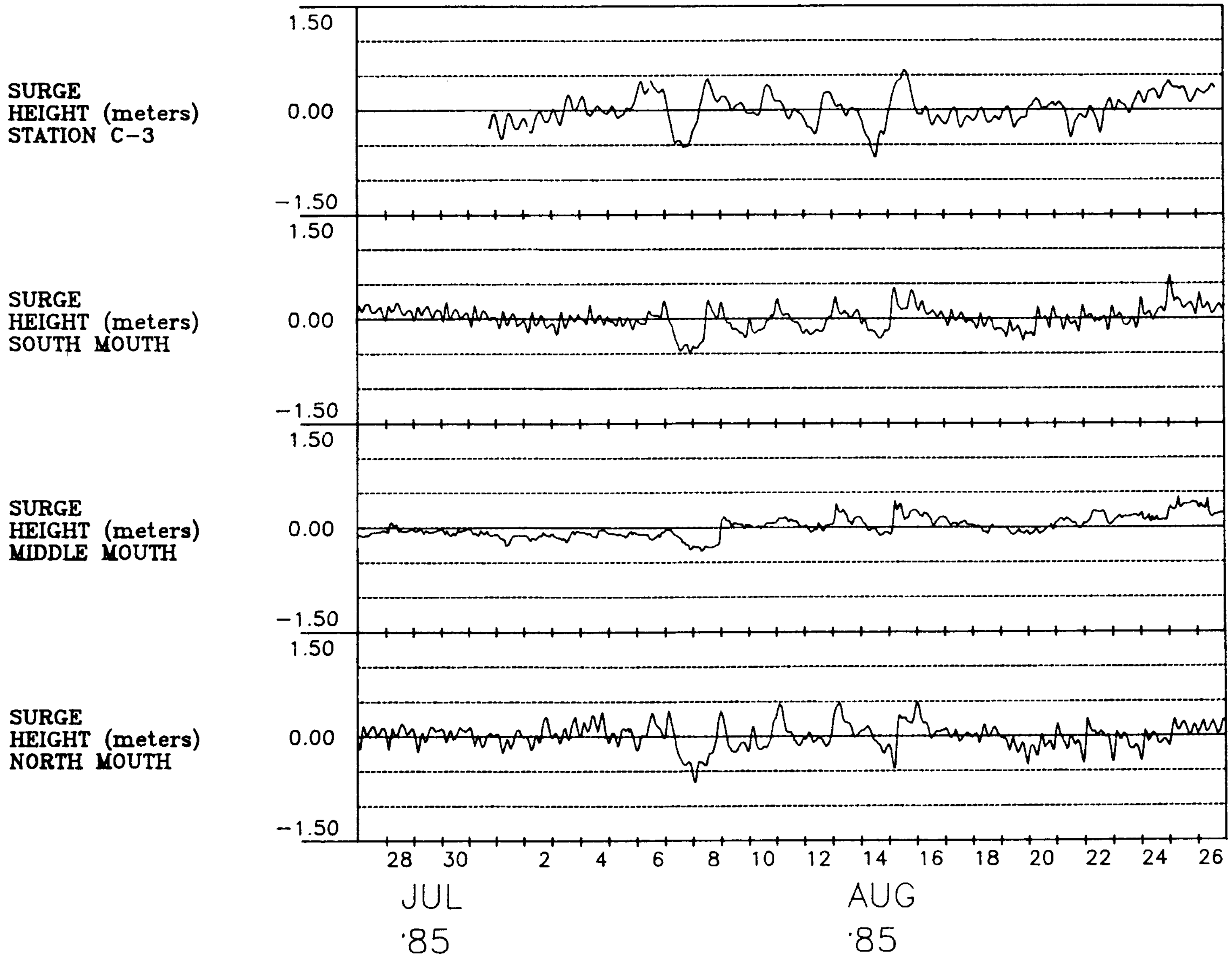


Figure 3-59. Composite time series plot of de-tided water-level (surge-height) records from offshore mooring C-3 and sites within the three major Yukon Delta distributaries for the period 27 July through 26 August 1985.

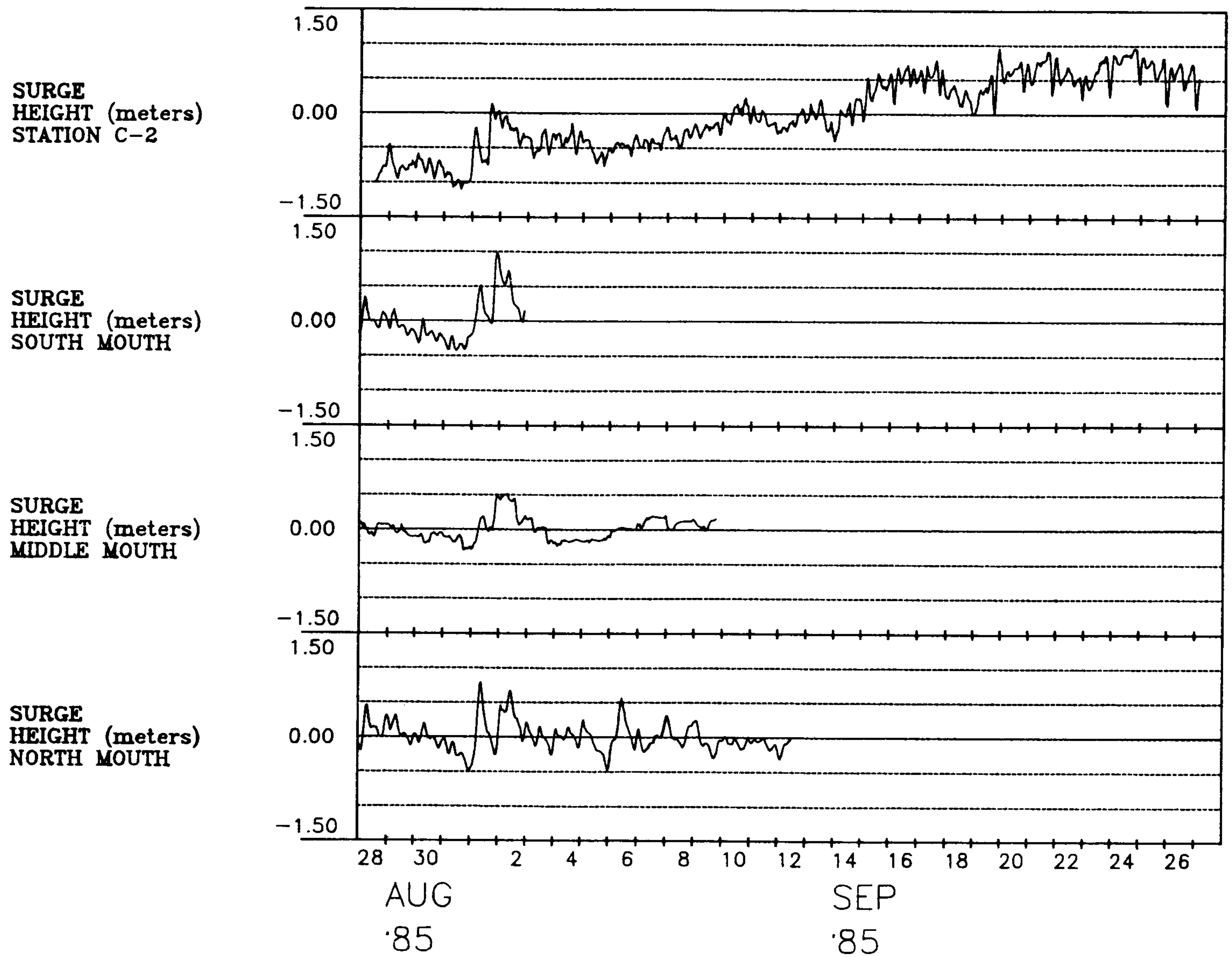


Figure 3-60. Composite time series plot of de-tided water-level (surge-height) records from sites within the three major Yukon Delta distributaries for the period 28 August through 27 September 1985.

2.8 hours was found between the North and South Mouths for the M_2 tidal constituent. This lag is equivalent to a phase speed of roughly 15 m/sec and is consistent with the propagation speed of a trapped wave along the offshore margin of the Delta platform in a mean water depth of roughly 20 m. The actual dynamics of storm surge events undoubtedly involve some complex combination of forced and free wave propagation, but the high coherence evident in Figure 3-59 offers encouragement that the problem can be treated successfully using well-established hydrodynamic modeling methods.

3.7 SEDIMENTOLOGY

Results from the analysis of sediment samples taken in the river and on the Delta platform and front during this study corroborate previous interpretations advanced in the literature; e.g., active progradation and growth of the fan-shaped Delta is due to the deposition of the large sediment load carried by the river during the period of heavy runoff (Dupre and Hopkins, 1976; Dupre and Thompson, 1979). Analyses of the suspended sediment samples and the current records (subsection 3.2) indicate that a portion of the fines remain in suspension over the Delta front and are advected northward into the Bering Sea during the open-water period. These observations support the contention that the Delta front is migrating to the north in the direction of dominant summer transport (Dupre and Thompson, 1979; Nelson and Creager, 1977).

3.7.1 Bottom Sediments

Analysis of the 22 bottom sediment samples taken from the first, third and fifth field trips (July and September 1985 and August 1986) indicated that: 1) there were no differences in the general grain size composition between stations sampled along the river channels and those from the Delta platform, and 2) the grain size composition of the river channel and the Delta platform sediments differed from that of the Delta front and from that of the less-active side channels and sloughs. Channel samples taken at 8-mile intervals ranging from Pitkas Point to the South Mouth entrance (Figure 3-61) were generally composed of 90% sand fractions (Tables 3-12 and 3-13). The exceptions occurred at stations R45S and Kobolunuk, where the samples may have been collected from the sides of the channel instead of from the channel axis. Nearshore samples taken along a transect from the South Mouth entrance along the navigable channel 17 nm due west to the Delta front were composed of 90% sand fractions

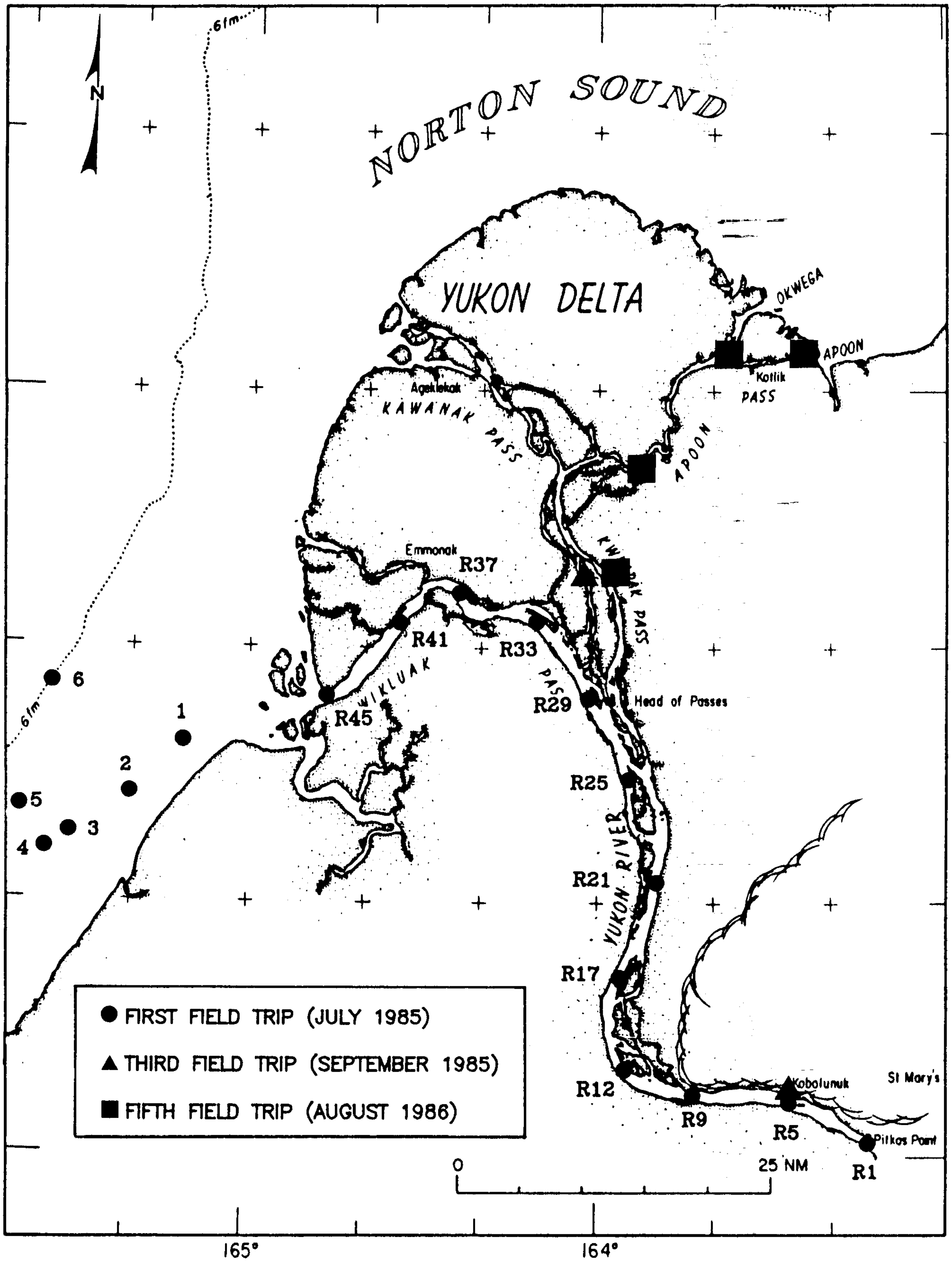


Figure 3-61. Map of sediment sampling locations during the first, third, and fifth field trips.

Table 3-12. Percentage composition of sand, silt, and clay fractions of bottom sediments collected during the first and third field trips (July and September 1985) and analyzed by the nested-sieve technique (Dr. A.S. Naidu, University of Alaska, Fairbanks). The carbon values reflect both inorganic and organic sources.

Station	Date	Sand (%)	Silt (%)	Clay (%)	Carbon (%)
R5N	7/85	95.9	4.0	0	1.6
R5S	7/85	98.4	1.6	0	1.2
Kobolunuk	9/85	48.9	48.9	2.2	4.4
R13S	7/85	93.4	6.2	0.4	1.7
R25W	7/85	95.9	4.1	0	1.6
R33W	7/85	86.9	12.9	0.1	2.4
R45S	7/85	3.3	88.0	8.7	6.3
C-2	9/85	99.4	0.6	0	1.1
#4	7/85	19.6	75.9	4.5	5.2
#6	7/85	29.6	60.4	10.1	5.6

Table 3-13. Percentage composition of sand, silt, and clay fractions of bottom sediments collected during the first, third, and fifth field trips (July and September 1985 and August 1986) and analyzed by the pipette technique (Dr. G.A. Jones, Woods Hole Oceanographic Institution). The carbon values reflect organic sources only.

Station	Date	Sand (%)	Silt (%)	Clay (%)	Carbon (%)
Kobolunuk	9/85	58.3	38.3	3.4	1.2
R5N	7/85	96.6	2.9	0.5	0.3
R17W	7/85	98.4	1.3	0.3	0.2
R29E	7/85	99.2	0.3	0.5	0.1
C-2	9/85	99.0	0.5	0.5	0.1
#1	7/85	98.7	0.7	0.7	0.1
Kwikpak	8/86	85.0	12.5	2.5	0.6
Aproka	9/85	18.1	71.8	10.1	1.3
Kawanak	9/85	97.9	1.2	0.8	0.2
Hamilton	8/86	59.3	33.8	6.9	1.9
Kotlik #1	8/86	97.4	1.9	0.7	0.1
Kotlik #2	8/86	48.8	41.4	9.7	1.3

within the channel, and 60 to 70% silt, 20 to 30% sand, and 5 to 10% clay fractions over the Delta front (Figure 3-61, Tables 3-12 and 3-13). Stations sampled in less active channels and on mid-river bars exhibited higher percentages of silt and clay. For example, during the August 1986 sampling period, the slough at Aproka Pass showed a composition dominated by the silt fractions (>70%). At Hamilton and Kobolunuk, samples taken in shallow areas located either next to the bank or on a mid-river bar contained low sand fractions, as well. Station 2 at Kotlik was sampled on a bar in the nearshore area of Pastol Bay, while Kotlik 1 was sampled within the river channel at North Mouth.

The analyses for weight loss on ignition demonstrated that the higher percentages of organic content were associated with higher percentages of silt. The higher values of loss on ignition were found at stations 4 and 6 and R45S and Kobolunuk (Table 3-12), and at stations Kobolunuk, Aproka, Hamilton, and Kotlik 2 (Table 3-13).

The large differences in the values for loss on ignition from 1985 and 1986 samples are primarily due to analysis procedures. In the 1985 samples, the carbonates were not removed prior to ignition, whereas during the analysis of the 1986 samples, the carbonates were purged with two rinses of dilute hydrochloric acid before ignition. Thus, the samples taken in 1985 contained inorganic as well as organic carbon, while those taken in 1986 were analyzed only for organic carbon.

The x-ray diffraction analysis of the clay fractions indicated that there were no differences in the mineral composition of five samples taken from the bottom sediments of the lower Delta and the Delta front. Percentages of smectite, illite, kaolinite, and chlorite showed no appreciable differences between samples taken within the Delta at R25W, Aproka Pass, South Mouth, and on the Delta front at stations 4 and 6 (Figure 3-61 and Table 3-14). Generally, the Biscaye values of smectite taken from the

Table 3-14. Percentage composition in Biscaye values of clay mineralogy for bottom and suspended sediment samples collected during the first and third field trips (July and September 1985).

Station	Type	Date	Percentage Composition			
			Smectite	Illite	Kaolinite	Chlorite
R25W	Bottom	7/85	13.7	43.7	15.9	26.7
R45S	Bottom	7/85	14.7	40.8	15.6	28.9
R45S	Suspended	7/85	10.1	35.9	19.9	34.1
#4	Bottom	7/85	14.6	37.9	17.6	29.9
#6	Bottom	7/85	15.5	40.7	14.6	29.2
Aproka	Bottom	9/85	16.1	38.7	15.3	29.9
Aproka	Suspended	9/85	13.3	35.9	18.1	32.7

deposit samples were about 13%, and the illite values were usually close to 40%. Kaolinite values for the samples were typically 17%, and chlorite values were about 30%. Thus, the mineralogy of the deposited sediments appeared to be similar within the Delta and over the Delta front.

The Biscaye values from this study fell within the range of values reported by Naidu and Mowatt (1983) in an extensive survey of the Bering Sea. Ranges of 10 to 20% for expandables (smectites), 38 to 48% for illites and a ratio of 0.5 for kaolinite and chlorite were reported for the Yukon Delta front stations, and values of 21% for smectites, 41% for illites, 12% for kaolinites and 26% for chlorites were reported from the Yukon River samples.

The relative proportions of the clay components and their bedrock sources have been investigated for the major rivers which empty into the Bering Sea (Naidu and Mowatt, 1983). The relatively high values of chlorite are characteristic of sediment samples from the Yukon River drainage area due to the preponderance of feldspar sources from the weathering of metamorphic bedrock types found in this basin. The Yukon River is also the greatest source of kaolinite clays to the Bering Sea. The sources of kaolinite are granitic and basaltic bedrock.

3.7.2 Suspended Sediments

Analyses for suspended sediments revealed no large spatial and temporal differences during the open-water sampling periods within the river and distributary channels. Preliminary measurements obtained with a portable turbidity meter suggested no significant spatial difference between samples taken from Pitkas Point to station 3 offshore of South Mouth during the July 1985 field trip. Subsequent analysis of suspended sediments by filtering and weighing also indicated that no differences were evident between samples taken along the river (Table 3-15).

Table 3-15. Analyses of suspended sediment samples collected during the first field trip (July 1985). The means and standard deviations are listed for both concentrations of suspended sediments and turbidity.

	Surface		Bottom	
Station	Conc. (mg/l)	Turb. (NTU)	Conc. (mg/l)	Turb. (NTU)
R1N	240.7±3.7	69.0±2.8	383.6+7.2	89.0±2.1
R1S	420.4±5.8	81.6±1.9	449.6±8.7	100.0±0.0
R5N	---	88.2±0.7	---	75.6±0.8
R5S	---	61.2±1.2	---	74.8±0.7
R9N	---	85.4±0.5	---	81.2±0.7
R9S	---	61.2±1.2	---	74.8±0.7
R13N	---	83.8±0.9	---	75.4±2.6
R13S	---	101.0±2.6	---	83.0±3.3
R17W	313.0±3.9	81.4±2.1	369.0±5.3	91.6±4.5
R17E	---	84.6±1.6	---	101.4±3.7
R21E	---	97.4±1.7	---	98.0±1.8
R25W	---	92.4±1.4	---	88.6±1.0
R25E	---	88.6±1.7	---	80.8±1.5
R29W	---	92.4±1.4	---	---
R29E	---	100.2±5.9	---	---
R33W	---	77.8±1.9	---	95.8±3.2
R33E	508.9±19.0	72.2±2.1	439.6±12.9	87.8±1.2
R37E	---	92.0±0.6	---	99.0±1.5
R41N	---	98.0±1.8	---	87.8±1.9
R41S	---	98.4±0.8	---	88.2±1.2
R45N	308.3±14.5	98.0±1.8	---	87.8±1.9
R45S	281.6±4.7	98.4±0.8	---	93.2±1.6
#1	---	85.6±4.1	---	72.0±1.1
#2	---	81.6±0.5	---	68.0±0.6
#3	---	67.2±0.7	---	72.8±0.7
#4	---	7.0±0.0	---	82.2±2.3
#5	---	5.0±0.0	---	33.2±0.4
#6	25.2±3.8	5.8±0.4	117.2±3.9	31.2±0.4

Offshore, noticeable differences were detected between surface and bottom samples taken over the Delta front at stations 4 to 6 during the first field trip (Table 3-15). At each of the three stations, higher concentrations were noted near the bottom (Table 3-15). CTD data collected concurrently with the suspended sediment samples indicated a highly stratified water column comprised of Bering Sea water overlain with brackish river water.

Temporal variations in sediment concentrations were also apparent in the river over the 2-year study (Table 3-16). The stations at Kobolunuk, Lamont, Hamilton, and Kwikpak showed greater suspended sediment concentrations in July 1985 than during any other sampling period. Variations were also found between seasons of the same year: stations sampled in July 1985 had greater sediment concentrations than in September 1985; concentrations in August 1986 were slightly greater than in June 1986. The interannual variations are not readily explained by the results of the discharge measurements (subsection 3.4). If a relationship exists between sediment load and discharge in the river, it was not demonstrated by the data at hand. This is possibly because the number of samples was too limited and the sampling was not frequent enough to resolve such a relationship.

The analysis of the mineral composition of two suspended sediment samples taken at Aproka Pass and at the South Mouth entrance showed no differences with the results of those samples taken from the deposited sediments of the lower Delta and the Delta front.

3.7.3 River Transport of Suspended Sediment

Transport of suspended sediment within the river appeared similar to that predicted in the literature; Dupre and Thompson (1979) estimated mean annual suspended sediment concentrations of 475 mg/l and a mean annual discharge of 185 km^3 of water. This yields a suspended transport of 88 million tonnes. For the

Table 3-16. Mean suspended sediment concentrations (mg/l) at Kobolunuk, Lamont, Kwikpak, and Hamilton for samples taken during the 1985-1986 field trips. The August 1986 sample at Kobolunuk is deemed suspect.

	Sampling Periods			
Station	7/85	9/85	6/86	8/86
Kobolunuk	435 mg/l	----	184 mg/l	1,220 mg/l
Lamont	475 mg/l	170 mg/l	165 mg/l	210 mg/l
Kwikpak	----	----	176 mg/l	263 mg/l
Hamilton	----	162 mg/l	214 mg/l	230 mg/l

present study, estimated average concentrations of suspended sediment from each of the sampling periods were as follows: 455 mg/l in July 1985; 166 mg/l in September 1985; 185 mg/l in June 1986; and 234 mg/l in August 1986. These averages were derived from the mean values of sample replicates. Of the samples taken, those from the entrances to the distributaries at C-2 and Kotlik were not used in the computation of the average values because of the influence of tidal effects; values at Aproka Pass were not used because they are not representative of a major distributory channel; and the extremely high value recorded for August 1986 at the Kobolunuk station was not used because the sample was taken from the bank instead of within the channel. Although the averages presented in this study are seasonal and do not represent the annually averaged load of suspended sediments in the river, the sampling occurred during peak flows, soon after the spring breakup, and, thus, should represent the major portion of the suspended sediment load carried to the Bering Sea.

Suspended sediment transports were calculated using river discharge estimates derived from the current profiling operations (subsection 3.4). The suspended load in September 1985 was 0.196 million tonnes/day; 0.209 million tonnes/day in June 1986; and 0.181 million tonnes/day in August 1986. Sediment loads were not calculated for July 1985 because river discharge measurements were not taken during the initial cruise of the program. These estimates are roughly 50% lower than those given by Dupre and Thompson (1979). The discrepancy appears to be mainly a result of the comparatively lower suspended sediment concentrations measured for September 1985 and June and August 1986.

Although estimates of bed load were not made in this program, a few field observations may be illustrative of the processes at work in the area of the Delta platform. During the July-August 1985 sampling period, the South Mouth channel across the platform was present and navigable by the NOAA boat. However, during the September 1985 sampling period, the channel had filled with sediment, making boat passage across the Delta platform difficult. Based on the coarse composition of the sediments, it is likely that the shoaling of the channel is the result of bed-load deposits. It is speculated that the subaqueous channels are initially gouged by ice floes and scoured by river currents during the early portion of the open-water season. As the ice clears and the river discharge subsides, bed-load transport gradually builds the channel bottom back up to the elevation of the surrounding platform. By late in the season, the channel is fully blocked by a broad distributary bar or shoal.

4. SUMMARY OF YUKON DELTA PHYSICAL PROCESSES

In the previous section, a variety of analyses were presented in order to describe and quantify the characteristics of the physical processes affecting the Yukon Delta. Here, we use these results to speculate on which processes would govern the transport and fate of water masses and constituent materials in the waters around the Delta. We emphasize that much of the following discussion is speculation, especially since the measurement program was confined to summer months and some of the more important processes (e.g., storm surge and salt-wedge intrusion) occur mostly during late fall and winter when no direct observations are available.

As an introduction to this discussion, it is informative to indicate the seasonal dependence of the processes involved and identify those processes which can act in concert and those which are mutually exclusive. Figure 4-1 presents a 1-year time line indicating the periods during which individual processes are active on the Delta. For instance, the Yukon and the nearshore areas around the Delta are ice covered (solid line in Figure 4-1) throughout winter and spring. During May or early June, at the time of peak river discharge, breakup occurs in the river and the nearshore area is swept free of ice. Ice formation begins again in the fall when mean air temperatures drop significantly, and the Yukon discharge drops to about 10% of the summer peak. The period of high Yukon discharge (see subsection 4.1) is therefore mutually exclusive with ice in the river. Similarly, the likelihood of salt penetration into the major Yukon distributaries is high only during periods of low river discharge.

Storm surge in the nearshore areas around the Delta is caused by intense meteorological storms which occur most

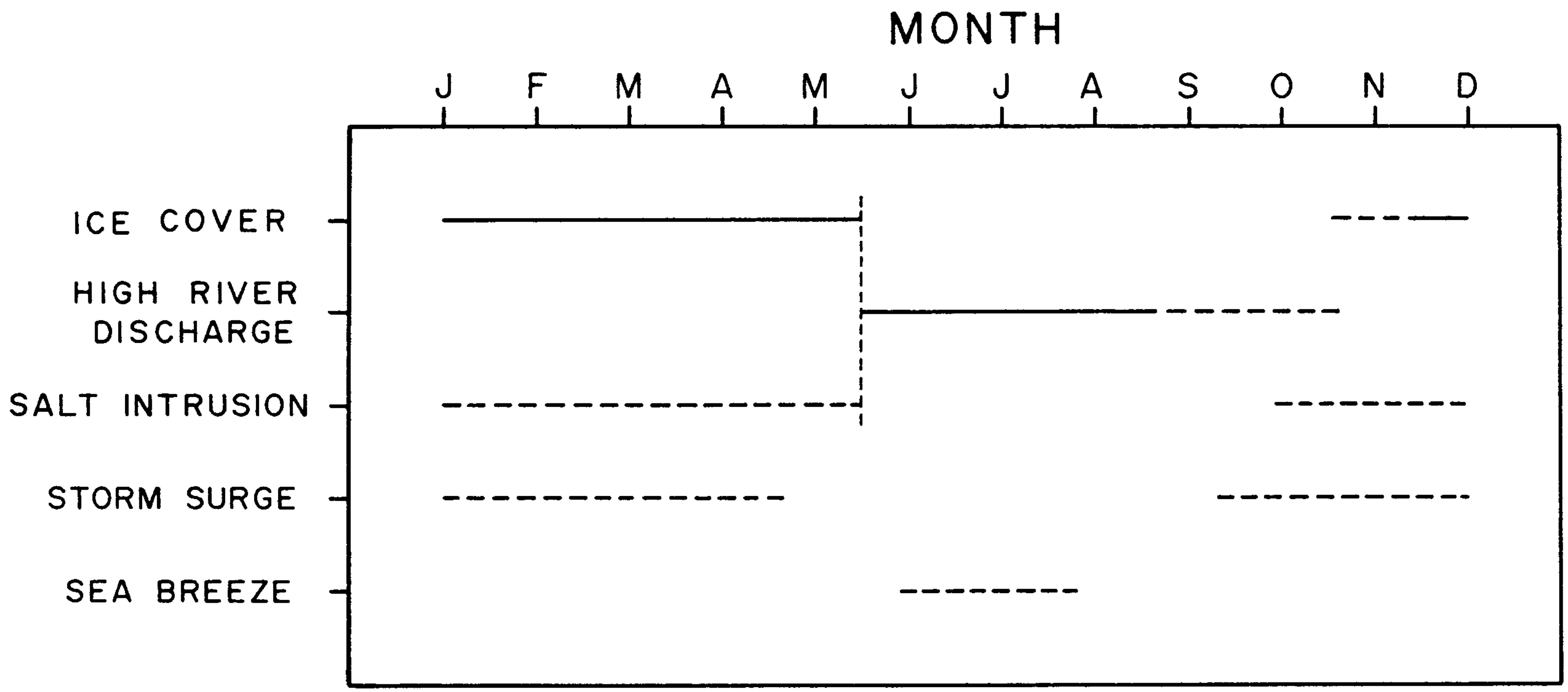


Figure 4-1. Conceptual summary of major physical processes which affect the Yukon Delta environment, and the approximate time periods during which each process is active. Solid lines represent relatively constant effects, whereas dashed lines represent intermittent processes or extreme conditions.

frequently during fall and winter. Sea breeze processes may be difficult to resolve from meteorological records, but it is relatively simple to predict that they occur only during summer when: 1) the Delta is much warmer than the offshore surface waters, and 2) their is no cloud cover to inhibit radiation and convection. Consequently, we would not expect sea breezes during intense meteorological storms or surge events (Figure 4-1). Regardless of the periods when sea breezes can be expected, we do not view this process as an important transport mechanism. Although sea breezes could drive surface waters toward the Delta, this would occur during the period of most intense Yukon discharge, and the breeze-driven currents would be relatively insignificant compared to the general circulation and tidal currents.

Tidal fluctuations in the water level around the Delta shoreline and within the major distributary mouths occur throughout the year, but they will have little effect upon the transport of nearshore materials except when a surge event occurs during an extremely high tide. Tidal currents, on the other hand, can play a major role because they represent a significant amount of the energy in the currents of this region. Orbital tidal currents on the Delta platform and front also represent an effective mechanism for resuspension of bottom sediments.

In addition to the processes mentioned above, the various results of the measurement program have been synthesized to formulate a simple model of the nearshore circulation around the Delta (subsection 4.2). The basic results indicate regions of suspected high sediment deposition (and progradation of the Delta), and allow estimation of residence times for river water on the Delta platform. Subsection 4.3 addresses sediment transport processes and salinity intrusion dynamics. Finally, subsection 4.4 presents a synopsis of the fisheries observations made by NOAA RU 660 with emphasis on why juvenile salmon were found in high concentrations near the Delta front, rather than near the distributary mouths. The vulnerability of this fish habitat to offshore pollutants is also discussed.

4.1 THE CYCLE OF YUKON RIVER DISCHARGE

The discharge of the lower Yukon is characterized by an annual cycle having peak flow in early summer and relatively weak flow from December through April. Significant fluctuations in discharge are observed on time scales of a few days, and major interannual variations are common. The USGS discharge measurements from Pilot Station represent the best time series for analysis of flow in the lower Yukon because daily observations are available since October 1975 (excluding the period October 1984 through September 1985). Ten-year averages of monthly mean discharge, presented in Figure 4-2, illustrate the annual hydrograph of the lower Yukon. An envelope of ± 1 standard deviation about the mean indicates that interannual variations in the monthly means are relatively small, whereas extreme daily discharges (maxima and minima) may vary greatly from the monthly average.

Figure 4-2 also illustrates that mean discharges are consistently less than 2,000 m^3/sec from January through April. Peak discharge occurs between mid-May and mid-June. An exception occurred during the summer of 1978 (the driest of the 10-year record) when the peak was not achieved until 8 July. Although peak daily discharge often occurs in May, monthly means for May are low because flow is minimal prior to breakup. In contrast, June exhibits the highest monthly mean because of gradual reductions in discharge after the peak is achieved in late May or early June. The reduction in the monthly means continues monotonically from June through April.

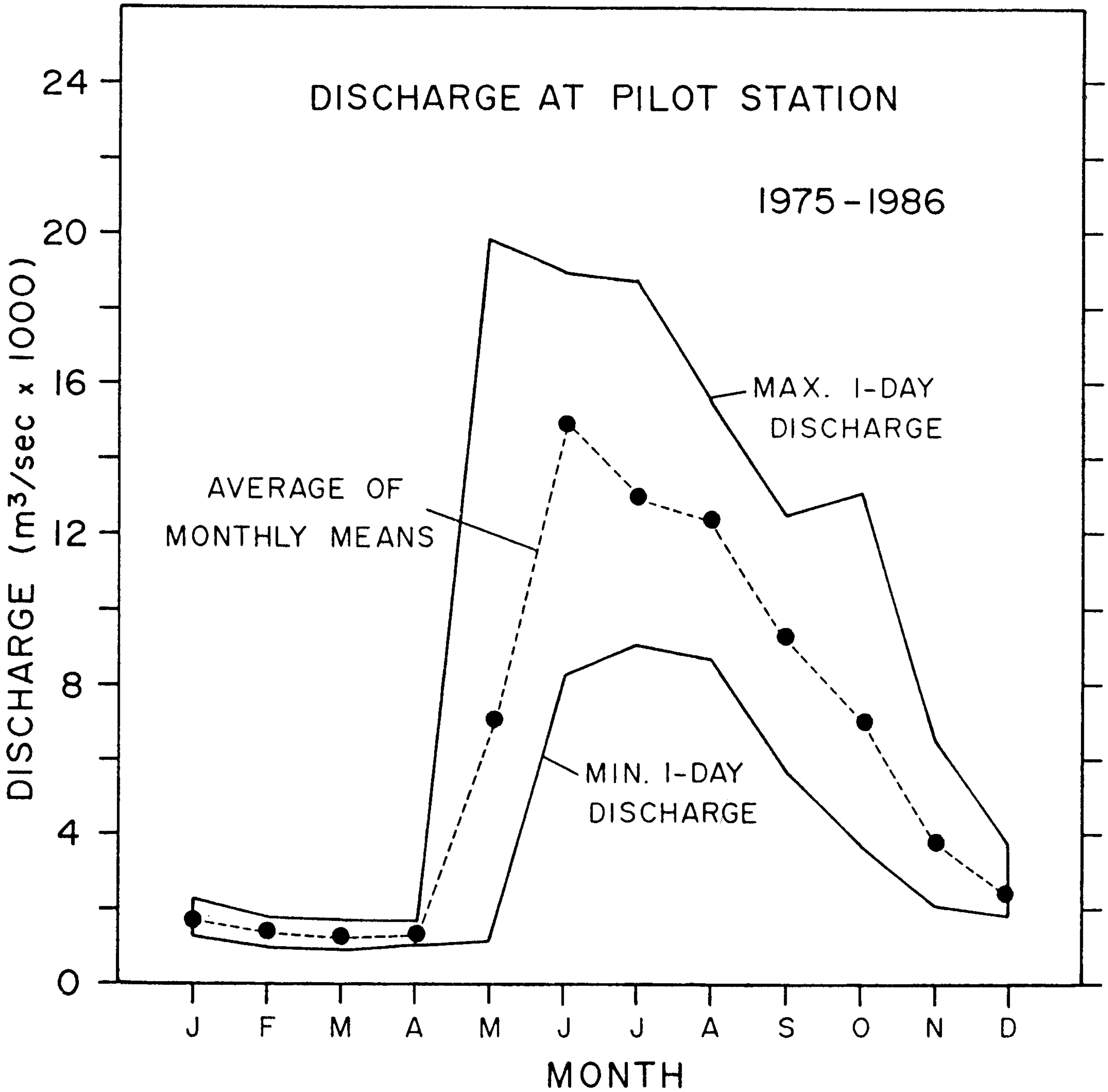


Figure 4-2. The annual hydrograph of Yukon River discharge at Pilot Station based upon USGS measurements for the period October 1975 through September 1986 (excluding the period October 1984 through September 1985). The dashed line represents 10-year averages of monthly mean discharge estimates. Solid lines represent 1-day extreme discharges for each month.

Over the summer and fall, the standard deviation envelope (Figure 4-2) exhibits a minimum in July, followed by more variability through autumn. This variability is associated with 1- to 2-week periods of increased discharge which occur during autumn of most years. This autumn increase occurred during both years (1985 and 1986) of this program. As shown in Figure 4-2, the maximum daily discharge from October 1985 exceeds that from September in all years.

The autumn of 1985 was characterized by some of the highest discharge rates measured over the past 10 years; e.g., 13,031 m^3/sec on 1 October 1985 was the highest daily discharge ever recorded in October, and the monthly means for December 1985 and January and February 1986 were also the highest in 10 years. Monthly means for the spring and summer of 1986 were relatively normal, but 1986 had the highest September mean of the past 10 years. At the time of this analysis, Pilot Station data were not available after 30 September 1986.

Recent discharge measurements within the three major distributaries of the Yukon Delta indicate that the partition among the distributaries is very stable when the river is high (June through September). Downstream of Head of Passes, the flow is distributed as follows: 66% to Kwikluak Pass, 26% to Kawanak Pass, and 8% to Apoon Pass. Measurements on the Delta are not available from other seasons, but we suspect that Kwikluak Pass may receive a higher proportion of the flow as the river subsides, due to hydraulic control within the complex erosional channels.

4.2 NEARSHORE CIRCULATION AROUND THE YUKON DELTA

The moored current measurements obtained from the west side of the Yukon Delta during summer 1985 are insufficient for resolution of the flow field around the entire Delta or throughout the year, but they do provide enough information to speculate on the fate of Yukon River waters during periods of high discharge. With a northward flow of roughly 12 cm/sec for the 3-week measurement period and an estimate of the Yukon discharge from the three major distributaries, it is possible to construct a simple box model of the nearshore flow around the Delta. A number of assumptions have to be made about the flow characteristics at various sites (in the absence of an adequate number of direct current measurements), but these uncertainties do not overshadow the most prominent results of the box model, as will be shown below.

For this model, the nearshore area around the Yukon Delta has been subdivided into three regions, each of which receives the discharge from a single major distributary. Figure 4-3 illustrates the three regions labeled S, M and N, which correspond with the South, Middle, and North Mouths, respectively. Since the offshore flow is apparently controlled by the local topography, we have selected the 20-foot (6-m) isobath as the offshore boundary and used 3 m as the average depth of the model domain. The sides of each region were selected somewhat arbitrarily, but with an attempt to delineate regions of equal area.

If we estimate the average Yukon discharge at Head of Passes to be roughly 11,400 m^3/sec during the period of the offshore current measurements, then the discharge from each distributary can be obtained from the discharge ratio 66:26:8 for South, Middle, and North Mouths, respectively. The discharges from the three distributaries, T_S, T_M, and T_N then become 7,500, 3,000 and 900 m^3/sec, respectively.

At the above discharge rates, the entire volume of region S could be filled with Yukon water in 5.8 days. This flushing time seems very short, but the hydrographic surveys in the nearshore regions around South and Middle Mouths indicated that brackish water covered the entire Delta shoreline out to a distance of 10 to 15 miles. We suspect this to be the case from

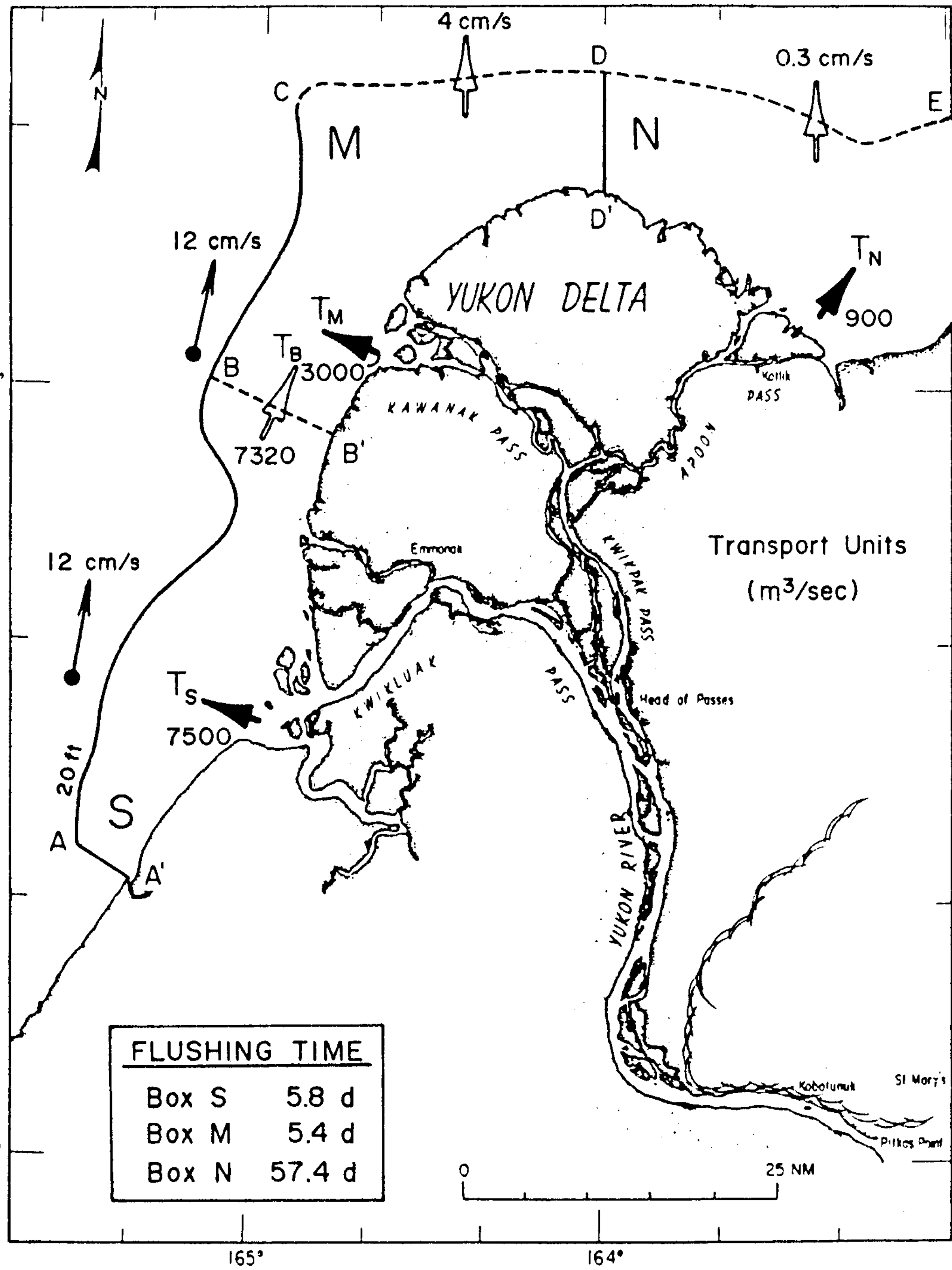


Figure 4-3. Map of the Yukon Delta region illustrating three coastal regions (S, M and N) which were prescribed in a simple box model of the summer circulation in the nearshore areas surrounding the Delta. The Yukon discharge from the three major distributaries is indicated by solid arrows and discharge values (m^3/sec). Open arrows represent transport between model regions. Average current vectors from offshore moorings C-3 and C-4A are also shown.

June through September for most years; this coastal band of brackish water may, however, be displaced by saline waters during storm events which increase in frequency during late summer and fall.

The current mooring located to the west of Middle Mouth provides a good estimate of the flow regime at the northern boundary of region S. If we use the 12 cm/sec alongshore flow rate as an estimate of the northward flow through line B-B', then we arrive at a northward discharge at transect B (T_B) of 7,320 m^3/sec, which is not significantly different from the Yukon discharge at South Mouth, T_S. To a first order approximation, we can assume that the net flow through the seaward boundary of region S (line A-B) is near zero, in accordance with the progressive vector diagrams constructed from the offshore current records. It follows that the net flow through the southern boundary (line A-A' offshore of Black River) must also be near zero for region S to conserve mass.

In reality, we would doubt that the 12-cm/sec northward mean flow at the offshore mooring sites would be observed everywhere along lines A-A' and B-B'. In the nearshore areas where water depths are generally less than 1 m, we suspect there is little, if any, net flow to the north, and currents are dominated by oscillatory tidal flow and/or wind-driven currents of 1- to 3-day duration.

The persistent alongshore current at the 30-foot contour (both mooring sites) is most likely associated with the large-scale cyclonic circulation of the eastern Bering Sea. The Delta front represents the eastern boundary of this gyre, such that northward currents may decrease toward the shore due to bottom friction. This suggests the northward flow at point A may be less than at point B, which is located nearly twice the distance from the Delta shoreline. Therefore, if the cross-sectional area and the mean current at line A-A' are both about one-half of their respective values at line B-B', then we may expect the transport through line A-A' to be about one-quarter of the transport through line B-B', or roughly 1,800 m^3/sec. The estimated transport through line A-A' may be further reduced if we recognize that the actual water depth is less than 1 m for most of line A-A', and consequently, the cross-sectional area used for the transport calculation is less than originally estimated. Nevertheless, based upon these uncertainties, we may expect that the model of region S has an uncertainty of about 20%.

The primary result from this simple model is that nearly all of the Yukon discharge which leaves South Mouth is advected alongshore toward the north, and the residence time within this coastal region may be less than 1 week. This flow regime is expected to persist during summer months when Yukon discharge is high, and winds are variable or persistent from the south. The winds during summer 1985 (when the offshore current measurements were made) were generally variable, with very few periods of sustained northerly winds, which would be required to reverse the flow in the nearshore areas. During late June and early July 1986, however, there were sustained periods of northerly winds, and NOAA RU 660 observed southerly flow in the nearshore surface waters to the west of the Delta. This ability of the nearshore waters to reverse direction in response to the wind suggests that, during fall, when the prevailing winds are from the north, there may be a net southward transport of Yukon water on the west side of the Delta. During the period from October through December (the end of the open-water season) the Yukon discharge is less than one-quarter of its peak summer discharge, such that a much smaller plume of fresh water will be advected around the Delta shoreline, and it will be more susceptible to mixing with saline Bering Sea water.

In the absence of direct current measurements from the northern side of the Delta, a defensible model of the flow within regions M and N (Figure 4-3) cannot be constructed. The Yukon discharge from Middle Mouth (3,000 m^3/sec) and the northward transport through line B-B' (7,320 m^3/sec) do indicate, however, that region M receives more fresh water than region S, despite the 3:1 ratio in South Mouth to Middle Mouth discharges. At this influx rate (~10,320 m^3/sec), region M would be flushed in roughly 5 days (the same time as for region S).

The along-isobath flow at the mooring site west of Middle Mouth suggests there is no appreciable flow through the offshore boundary between points B and C (Figure 4-3). We suspect that most of the alongshore flow continues northward through the boundary C-D; vorticity constraints would cause the flow to seek paths of constant depth rather than flowing northward across isobaths, but on the shallow, flat Delta platform, this restoring force would not be sufficient to cause the flow to turn abruptly to the right and pass through line D-D'. To a first-order approximation, we may assume there is little net flow through line D-D', and all of the Yukon water must leave region M through its northern boundary (line C-D). If so, the vertically averaged northward current through this boundary (6 m deep by 25 nm in length) would be roughly 4 cm/sec.

Although region M can be totally flushed in about 5 days, the velocity of the northward flow exiting the region is weak on account of the broad and relatively deep northern boundary at the edge of the Delta platform. Since the northward currents have an opportunity to decelerate as the water depth increases (thus conserving mass transport), there is more time for suspended particulates to settle to the bottom, and deposition may be enhanced in this area. This hypothesis is discussed further in subsection 4.3 as it relates to sedimentation and the northward advancement of the Delta.

In the absence of any current measurements within box N, we cannot infer the circulation, but it is interesting to note that with the relatively small flow from North Mouth (900 m^3/sec compared to 7,500 m^3/sec from South Mouth), it would take 57 days to fill box N with Yukon water. If we assume the flow in this region is oscillatory tidal flow with zero net transport through lines D-D' and E-E', then all of the Yukon discharge from North Mouth would have to pass through the seaward boundary, line D-E. This boundary is 27 nm long, and with a depth of 6 m, the northward current would be only 0.3 cm/sec. Since this northward flow is extremely weak, we expect that Yukon waters remain in this area for a relatively long period of time.

Direct current measurements are needed to determine whether the assumption of near-zero alongshore drift in the region to the north of the Delta is correct, but this simple box model does illustrate that the Yukon River is not an effective mechanism for flushing this region, even during the summer when river flow is at a maximum. During winter and spring, the Yukon probably has little, if any, affect upon the water properties and circulation to the north of the Delta.

4.3 SEDIMENT TRANSPORT PROCESSES

The limited number of samples collected as part of the present study is insufficient to support firm conclusions regarding sediment transport and depositional processes throughout the study area. However, drawing on the growing scientific literature for the area and by analogy with other well-known river deltas, it is possible to develop generalized concepts of the seasonal processes at work. Although these concepts are speculative, they appear to be consistent with 1) the observed data, 2) discussions with other researchers and local residents, and 3) our general impressions gained through extensive field experience on the Delta.

Seasonal field observations and navigational experience, mainly in the vicinity of the South Mouth distributary channel, suggest that ice gouging and current scour are sufficient to cut relatively deep channels through the shallow Delta platform during the early stages of the open-water season. During summer, river discharge through these channels is sufficient to prevent any near-bottom salinity intrusion, despite channel depths of 10 m. Extremely high suspended sediment concentrations are found in the river during summer which, when combined with the peak discharge rates, produces a large flux of sediment through the distributary mouths. Currents approaching 100 cm/sec are believed to be typical of the offshore reaches of the distributary channels, implying a correspondingly high bed-load transport as well. Based on observations at the distributary mouths in the Mississippi Delta (Wright, 1971), the bed-load transport may be as high as 20 to 40% of the suspended load.

The fate of a large proportion of this material is almost surely deposition on the prograding face of the Delta platform and the broader area of the prodelta further offshore. This process is well-supported in the literature for the bed-load component and the coarser fractions of the suspended load. The fate of suspended fines, mainly silts and clays, is more uncertain. We have found substantial fractions of fines in the surficial sediments along the Delta front and relatively high suspended concentrations in the overlying benthic (nepheloid) boundary layer. Orbital tidal currents are strong enough in this region to maintain a wide range of particulates in suspension and, intermittently, resuspend fractions up to the size of fine sand.

The water-sediment boundary is undoubtedly a dynamic interface during the open-water season; however, we have no direct evidence that there is a long-term net depositional flux of fine sediment to the Delta platform or front. Our observations may reflect a highly mobile, surficial layer of material which is rapidly transported to deeper water, either offshore to the

Bering Sea via downslope turbidity currents or alongshore toward Norton Sound in accordance with the transport model of the previous subsection. Either process implies rapid resupply from riverine sources inshore, subduction or flocculation at the frontal boundary of the river plume, and settling into the benthic boundary layer.

Alternately, the fine sediment may represent material which is mainly held in suspension within the boundary layer, thus experiencing little net deposition or horizontal transport. This requires that advection within the boundary layer is decoupled from the overlying water column. Under this scenario, the rate of resupply from inshore is relatively low; the preferred fate of river-borne fines being perhaps entrainment and deposition within the coastal Delta environment consisting of the myriad of sloughs and minor distributary channels.

Under the assumption of a high offshore flux rate, a mechanism exists which could presumably scavenge and remove pollutants from the Delta region and provide effective dispersal into deeper water. Under the alternate assumption of a low offshore flux rate, there is a greatly increased likelihood for pollutants to be incorporated into nearshore sediments or maintained in suspension for relatively long periods. The actual situation may reflect such great seasonal variability that both of these scenarios are realized, with high fluxes occurring early in the season during peak runoff, followed by a more vulnerable low-flux period later in the summmer and early fall.

Another mechanism which may be of importance is near-bottom seawater intrusion into the distributary channels due to estuarine or gravitational circulation; i.e., a salt wedge. Such an intrusion would presumably provide a mechanism for landward bottom flow and a resulting turbidity zone at the toe of the wedge (Matthews, 1973). Given that the length of intrusion could be on the order of 10 km, there are obvious impacts which could result from offshore contamination sources within the otherwise isolated reaches of the major distributary channels. The dynamics of such a circulation regime and the actual length of the resulting intrusion are quite speculative and little data exists to confirm the assumptions made in the analysis presented in subsection 3.5. Regardless of the details of the hydrodynamics, it is clear that this form of salinity intrusion must be highly transient, being limited to a relatively brief period late in the open-water season when the river discharge is drastically reduced from its summer peak.

4.4 FISH HABITATS

The fish habitat of importance appears to be located on the Delta front during the period of high river runoff when salmon smolt are found in high concentrations. Fisheries observations by NOAA RU 660 during summer 1986 indicate a high degree of fish utilization over the Delta front. Smolts dominate the catch statistics at the frontal region of the river plume. Results further indicate that most of the smolts are caught at shallow depths within the brackish water on the inshore side of the plume boundary. Presumably the smolts are in the gradual process of acclimating to oceanic water property conditions.

Another important aspect of this area as a fish habitat is that it supplies food to the smolt during the period of saltwater acclimation. Stomach contents of smolts reveal that the fish were actively feeding on interstitial species of harpactacoid copepods and freshwater insects, further suggesting a high degree of useage of the Delta front by fish. The presence of the harpactacoids within the stomachs supports the concept of an energetic boundary layer with a high concentration of resuspended bottom sediments, making the motile benthic fauna available to the smolt.

Residence times for the fish caught between the South and Middle Mouth entrances during the fisheries study are estimated to be on the order of a week. As illustrated in the box model presented in subsection 4.2, residence times for water advected to the north along the Delta front are also on the order of a week. These results indicate that the fish may be passively advected along the front by the mean coastal circulation.

5. RECOMMENDATIONS

Throughout Sections 2 and 3, comments and recommendations have been made concerning the need for additional measurements or scientific analyses in order to further our understanding of Delta processes. This section attempts to summarize these earlier comments and to present a coherent set of objectives for future measurement programs. Suggestions concerning appropriate data collection methodologies and instrumentation are also presented. These suggestions are quite preliminary and are intended only to illustrate the many possible avenues open to future investigators.

As a general comment pertinent to each of the data categories, the present study has demonstrated conclusively that transport from offshore into the upper reaches of the Yukon River is quite unlikely, especially during the summer and early fall months. The hydrodynamics observed upstream of Head of Passes, for example, are completely dominated by river discharge. The same conclusion holds in general over the length of the distributary channels downstream from this point to their respective mouths during most of the open-water season. Future studies should focus on the area of the Delta platform, both the local areas surrounding the major distributary mouths and the extensive shoal areas fronting the minor coastal sloughs. This work will be quite challenging, especially from the logistical standpoint; however, it is clear that this is the most vulnerable portion of the Delta and the most critical in terms of developing a detailed scientific understanding of the physical, geological, and biological processes at work.

Bathymetry/Sediment Processes

Detailed bathymetric surveys should be conducted at the mouths of the three major Yukon distributaries to identify the depth, aerial extent, and seasonal changes of the subaqueous channels which extend across the Delta platform. This survey should be made in conjunction with a detailed sediment sampling program designed to estimate bedload transport across the Delta platform and suspended load transport of fines along the Delta front. The use of side-scan sonar and subbottom profiling may be desirable to provide a more detailed characterization of the spatial variability of bottom sediments. The shallow tidal flats surrounding the Delta should also be surveyed as they represent a major dissipator of tidal energy and a potential geochemical sink.

Currents

Moored current meters should not be used within the river to measure flow due to the steady nature of the velocity and the susceptibility to fouling by debris. Discharge measurements obtained with a profiling current meter provide more useful results, especially when combined with time series of water-level variations.

Near-surface and bottom current measurements should be obtained from moorings deployed in the distributary mouths and major sloughs during fall and winter to monitor flow during expected periods of salt-wedge intrusion. Moorings should also be instrumented with temperature and conductivity sensors for identification of water types and eventual modeling of salinity diffusion.

Additional moored current, temperature, and conductivity measurements from sites around the entire Delta are necessary to determine the general circulation, extent of river discharge, and spatial variations in the major oceanographic transport processes.

Water Level

Water-level gauges should be deployed in the major distributaries and sloughs around the Delta shoreline during fall and winter to monitor storm surge which accompanies intense extra-tropical storms.

Time series of water level should be obtained from various sites along the river to determine the downstream river slope and establish a relationship between river transport and water level. Measurements must be made with reference to reestablished USGS benchmarks.

A network of closely spaced (5- to 10-mile separation) water-level gauges should be deployed in the major distributary mouths, sloughs, and nearshore subaqueous channels to determine the tidal dissipation on the Delta flats and the extent of tidal penetration into the distributaries and sloughs.

River Discharge

River discharge measurements should be made using a profiling current meter during periods of peak flow (after breakup) and during fall or winter (under the ice) to accurately measure river flow during these important periods which were not sampled during the present investigation. An intercomparison test should be performed at Pilot Station to determine the source of the large (~30%) difference between the USGS discharge estimates and those obtained by EG&G during the present program.

Water Properties

A detailed CTD survey should be conducted in the major distributaries and nearshore regions of the Delta during fall for the purpose of monitoring the occurrence of salinity intrusion. In particular, salinity intrusion into the sloughs and minor distributary channels late in the open-water season needs to be monitored, as this appears to be the most likely mechanism for upstream transport. A complete understanding of the local tidal characteristics is also required for a meaningful analysis of this process.

A large-scale CTD survey around the Delta front should be made at various times during the summer and fall to determine the aerial extent of the Yukon River plume and its temporal variability. There is also a possibility that AVHRR satellite imagery may prove useful in examining the plume configuration.

Meteorology

Three to five remote meteorological stations should be deployed around the Delta in June and July to determine the spatial variability of the sea breeze process. A meteorological buoy could be moored within 50 km of the Delta to provide marine observations during the Delta wind measurement program.

Sedimentology

A more extensive bottom sediment survey within the distributaries, on the Delta front, and on the nearshore tidal flats should be conducted for identification of spatial variations in sediment characteristics. Likewise, more suspended sediment surveys and analyses must be conducted in the Yukon and offshore regions to determine the characteristics of suspended material and temporal variations in river transport of sediments.

The offshore moorings could be furnished with sediment traps and/or recording transmissometers to examine the behavior of suspended particulates over the Delta front. These measurements would also be helpful for analysis of the extent and persistence of the near-bottom nepheloid layer that was observed on the Delta front. It remains to be proven whether bottom sediment resuspension by tidal currents and/or wave activity is the mechanism responsible for maintenance of the high turbidity levels. The ability to tag Yukon-derived clays by the high proportion of chlorite may be useful in deriving a quantitative assessment of the fate of river-borne fines.

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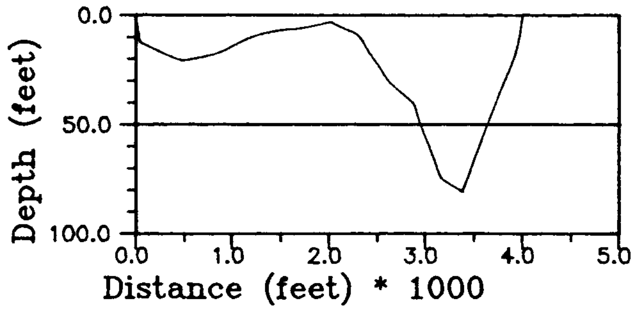
APPENDIX A

BATHYMETRIC PROFILES

Bathymetric Transect 1



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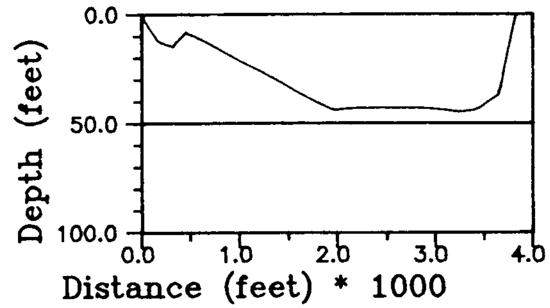

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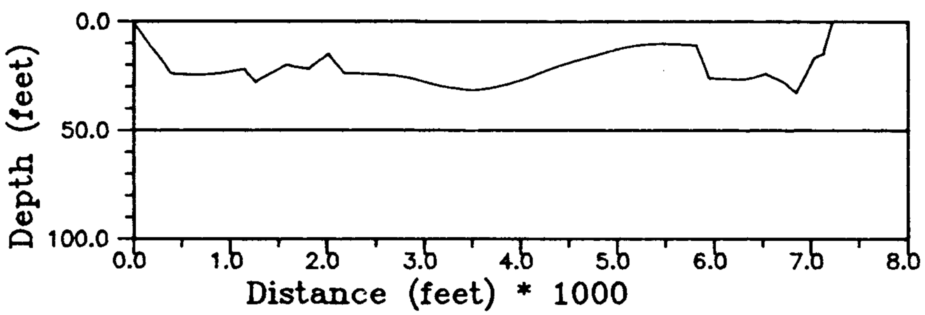

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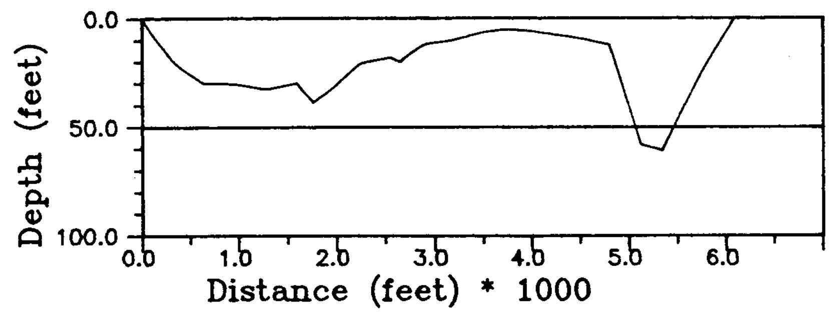

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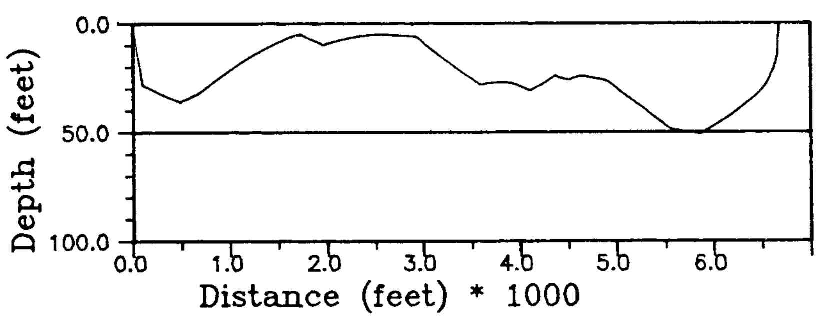

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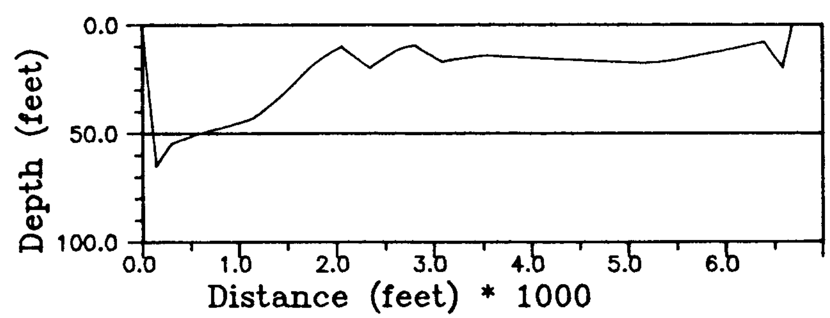

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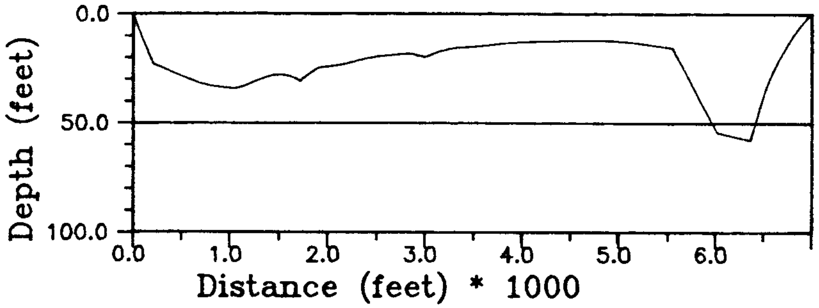

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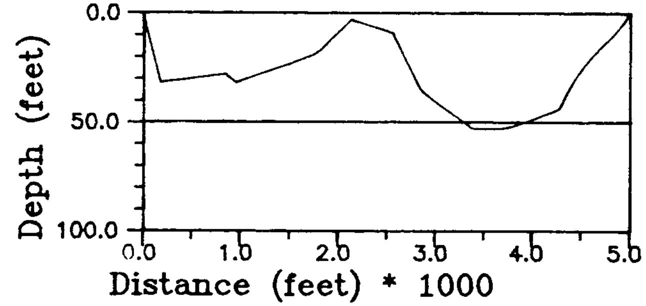

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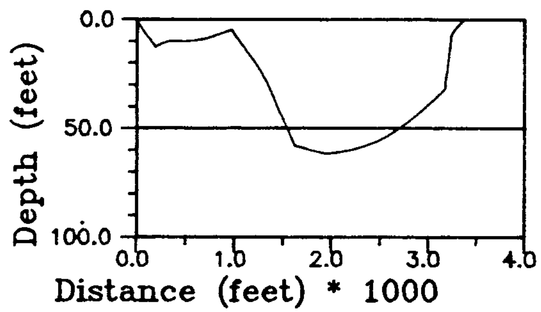

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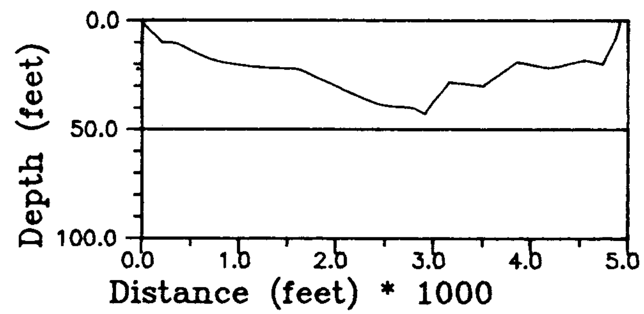

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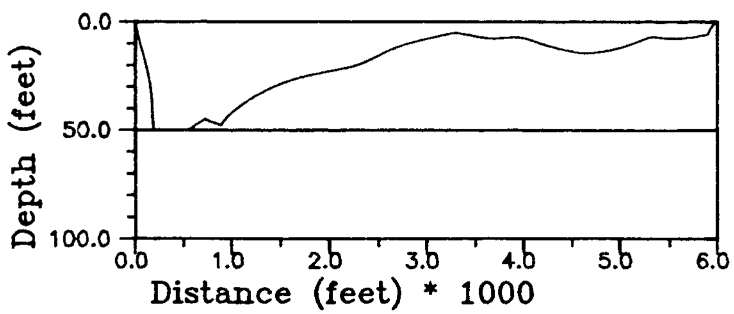

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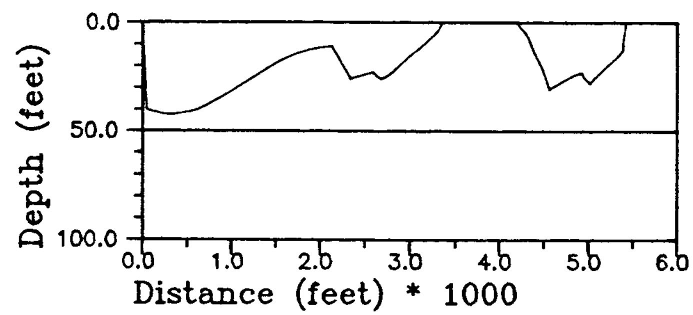

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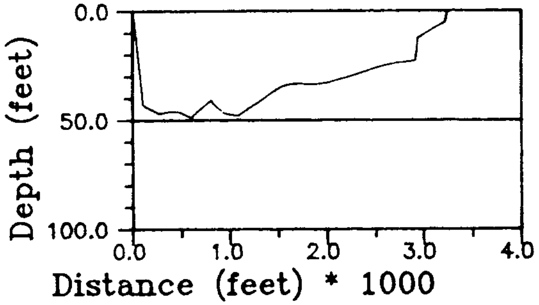

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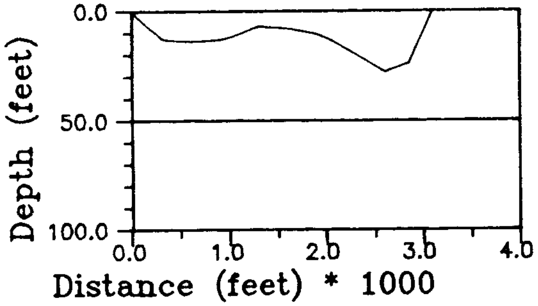

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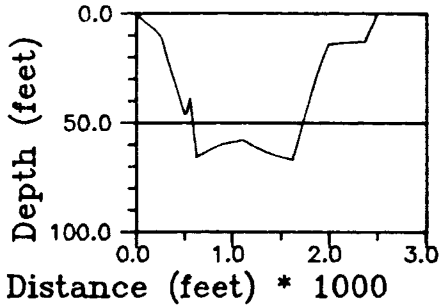

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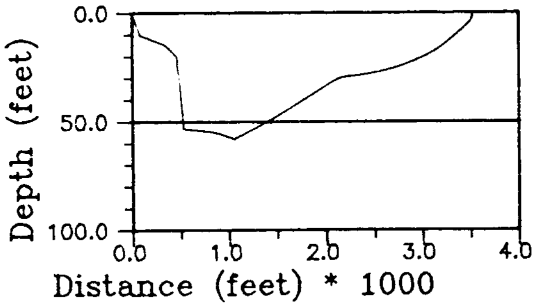

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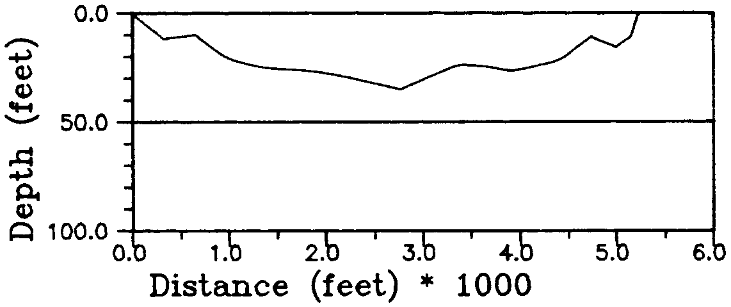

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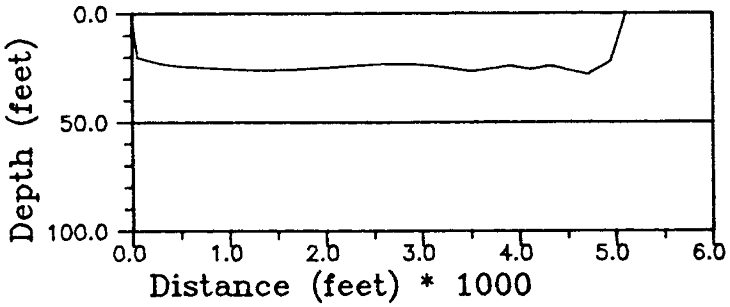

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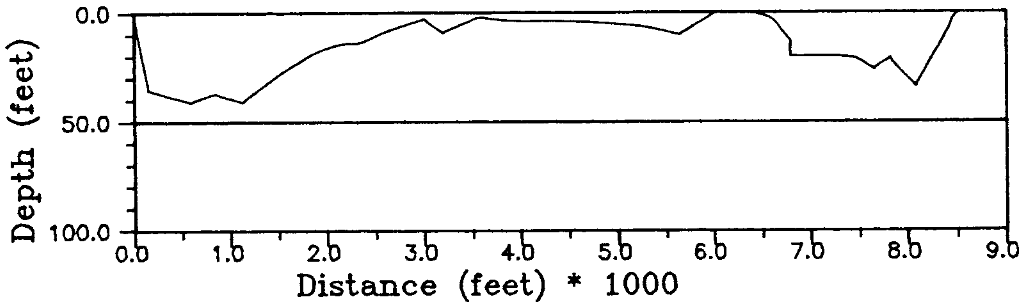

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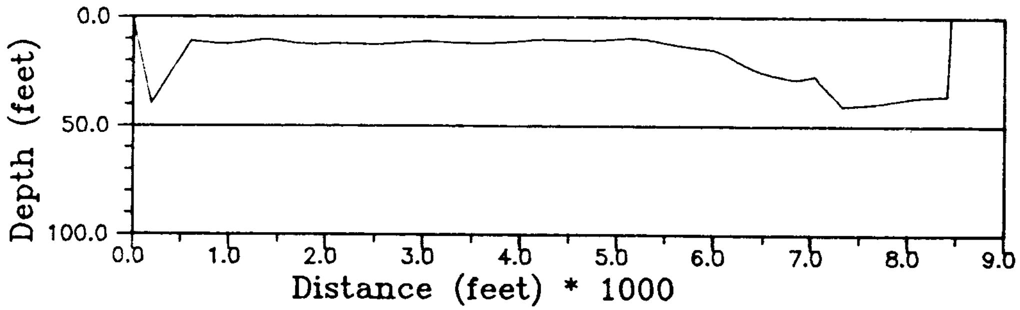

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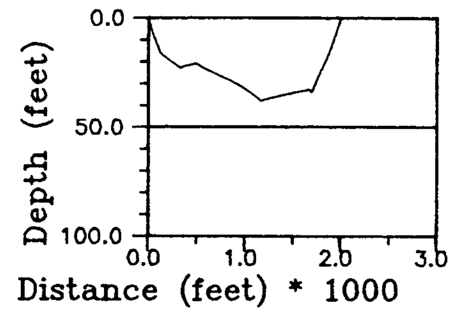

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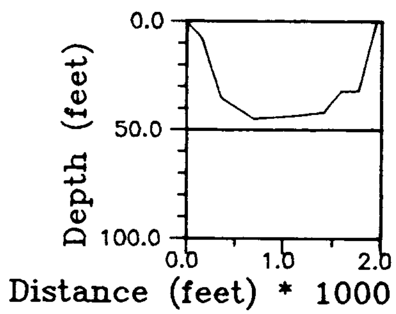

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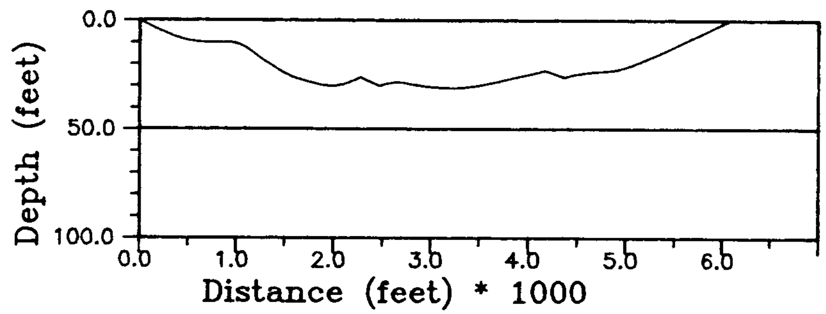

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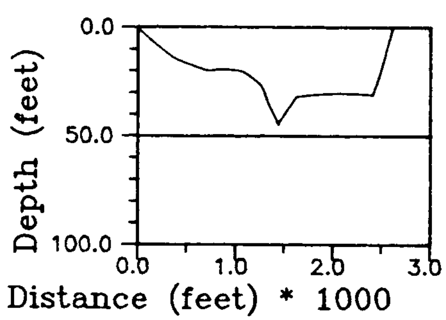

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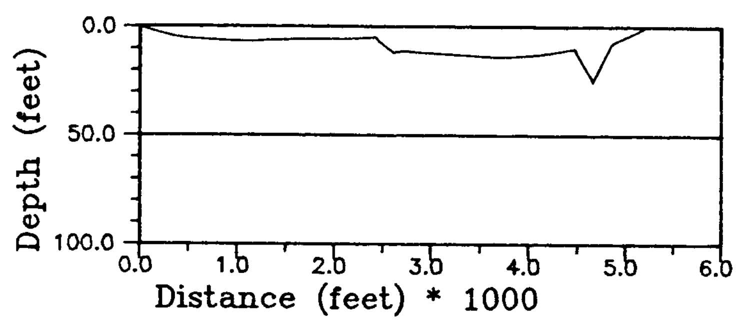

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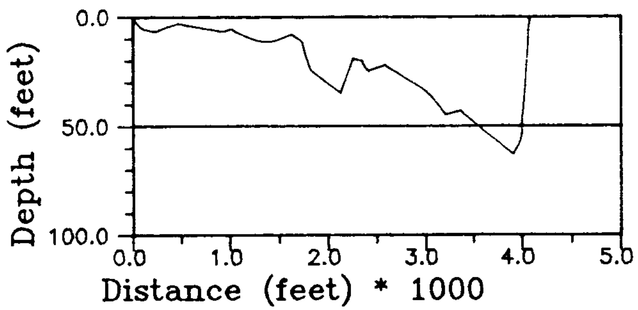

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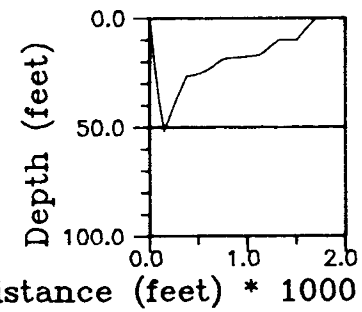

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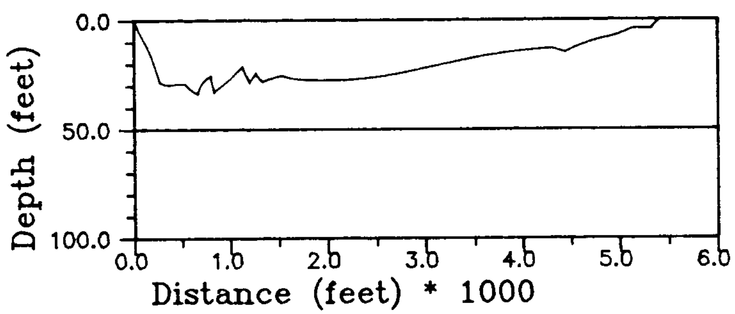

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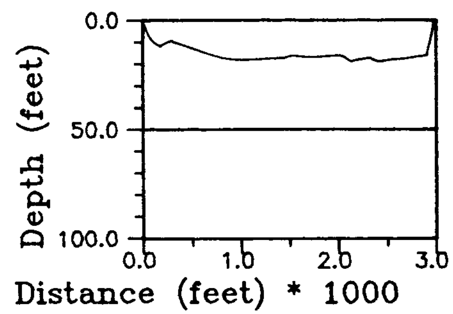

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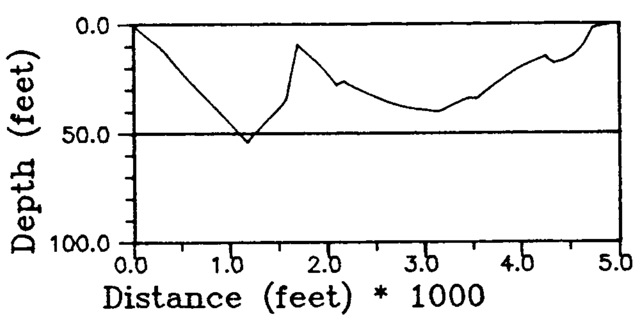
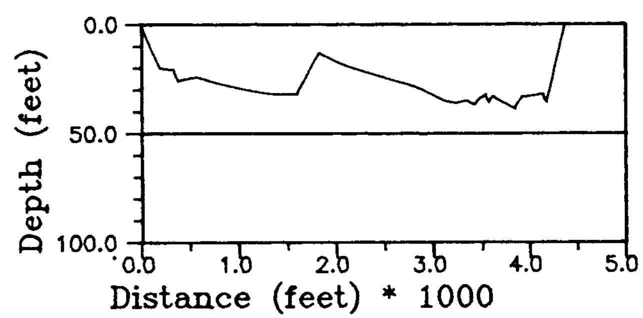


Bathymetric Transect 27



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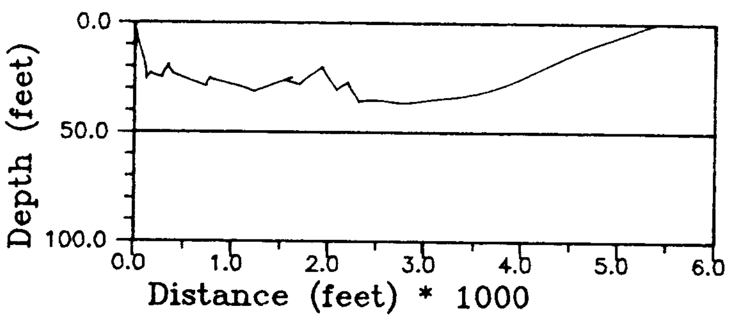

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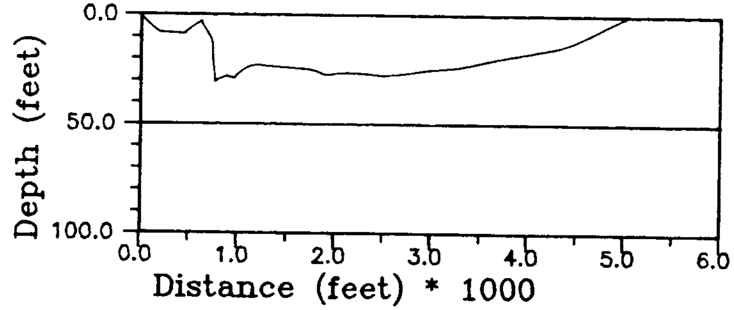

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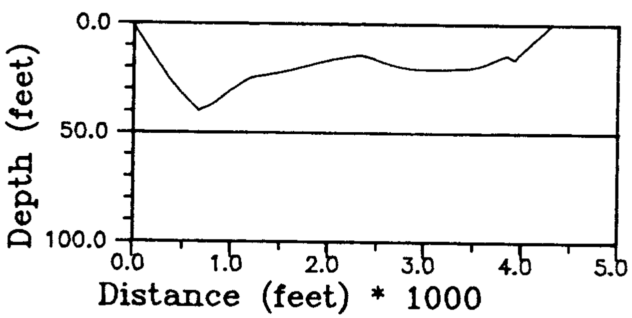

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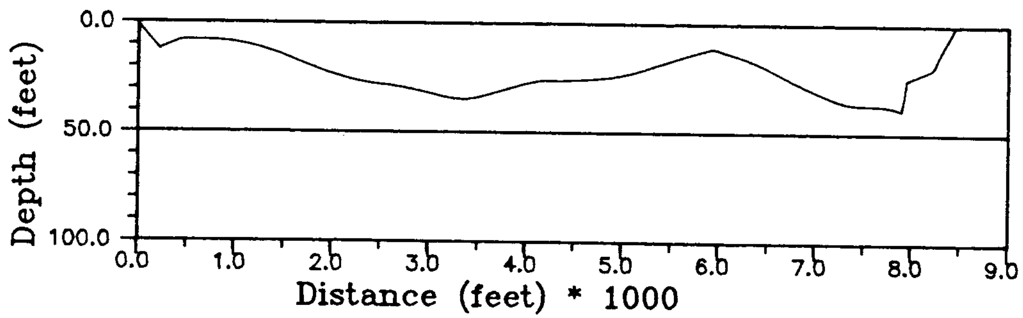

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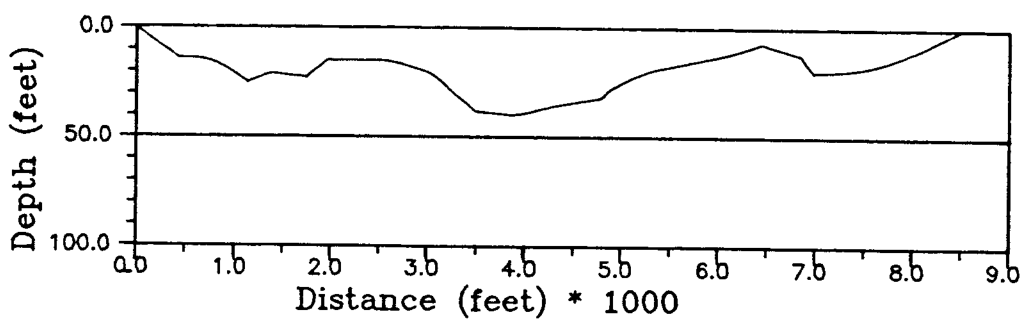

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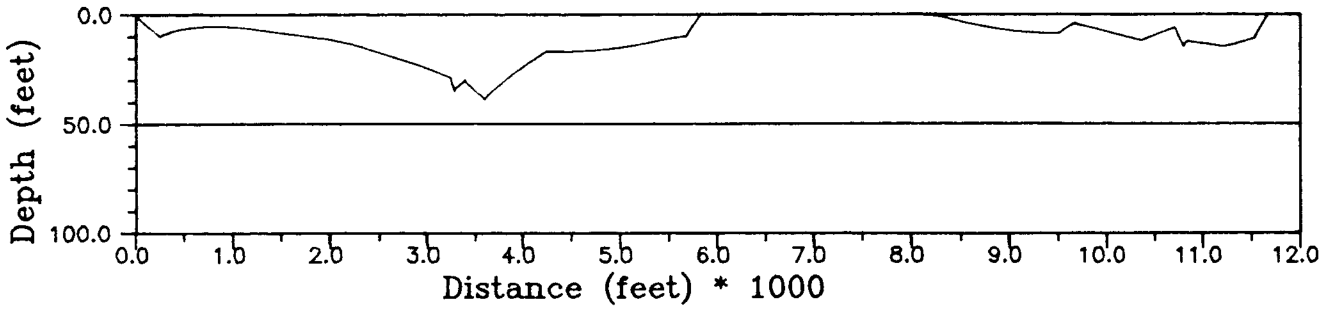

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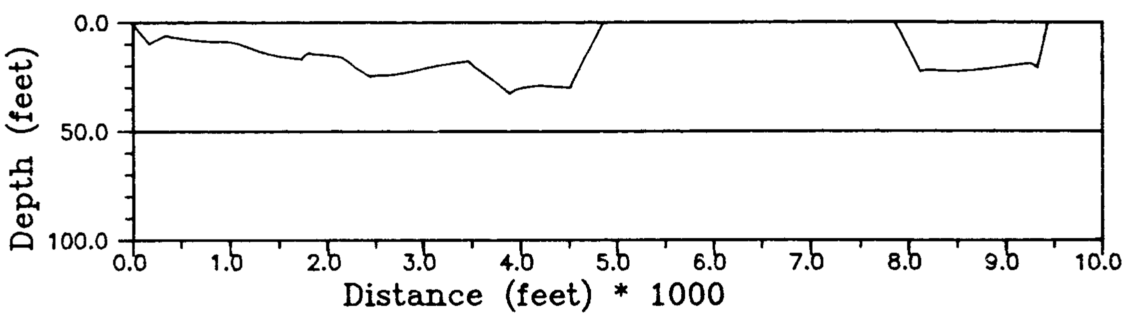

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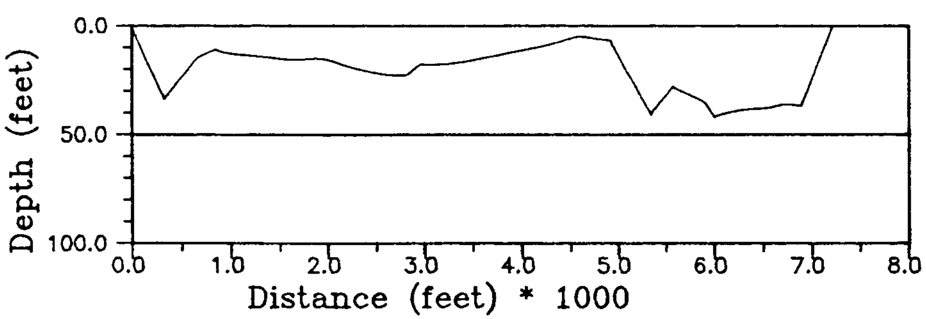

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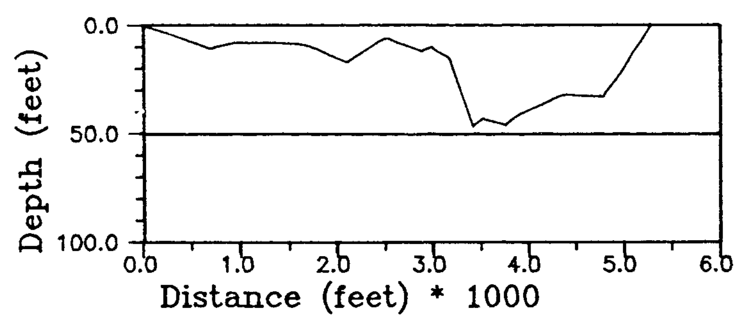

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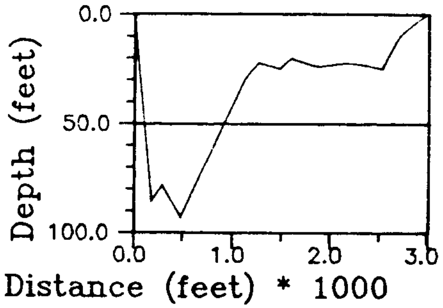

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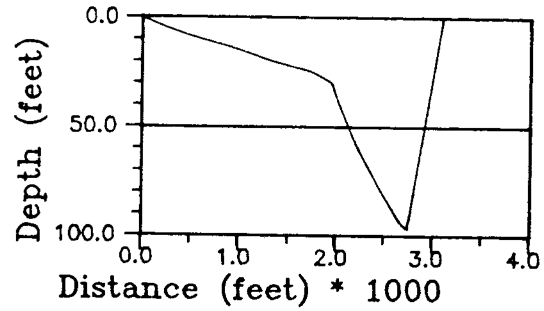

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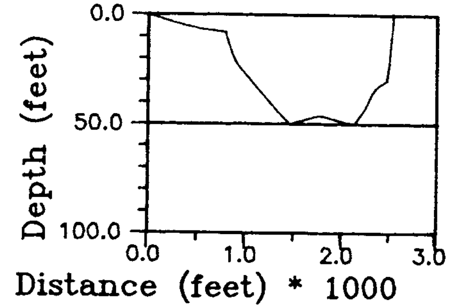

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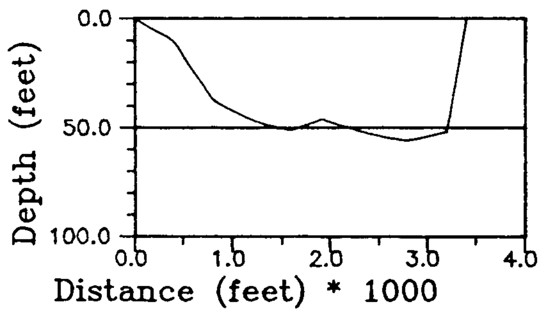

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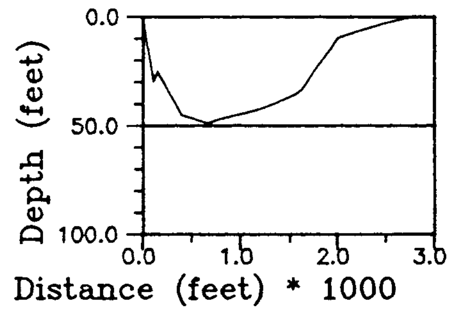

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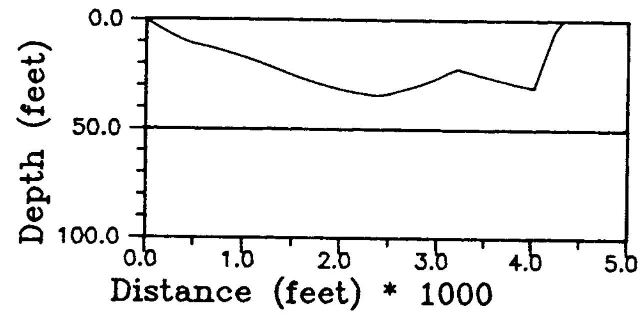

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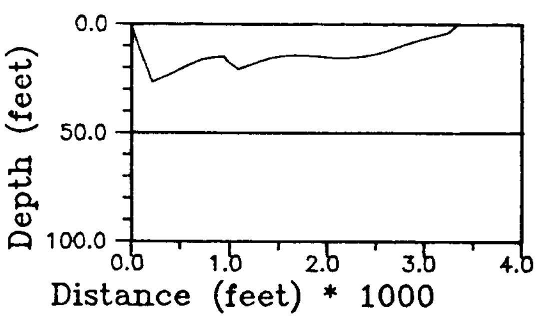

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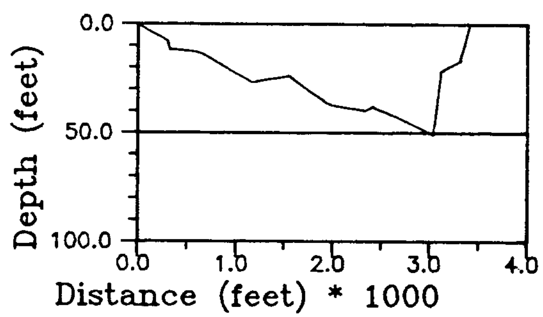

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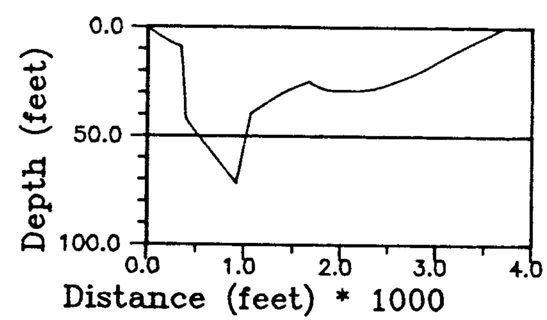

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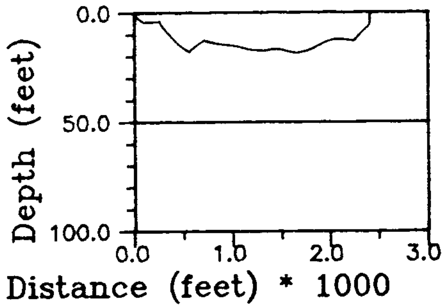

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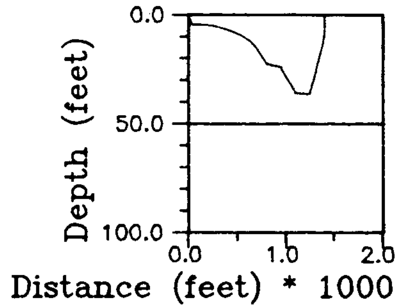

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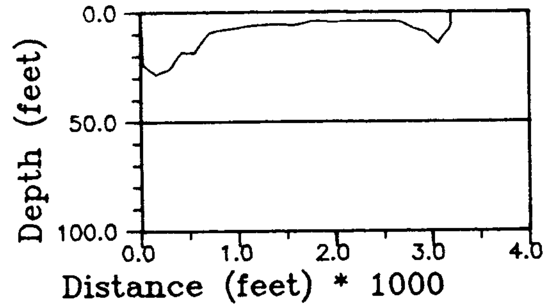

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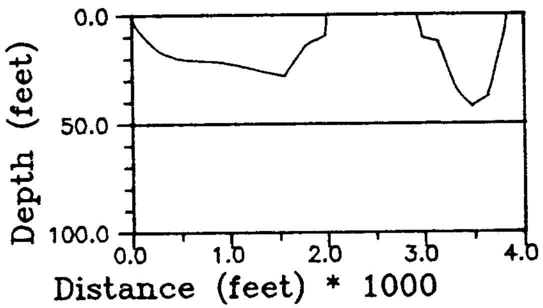

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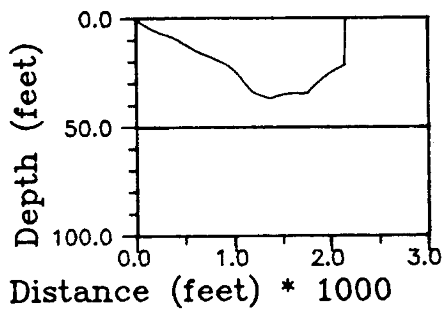

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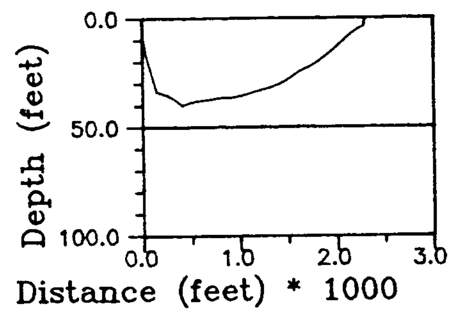

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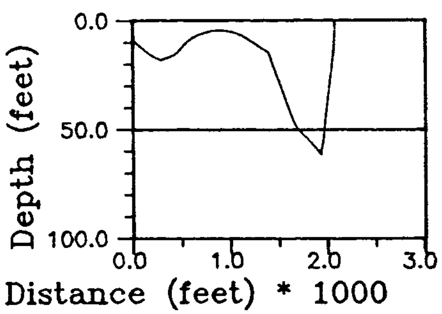

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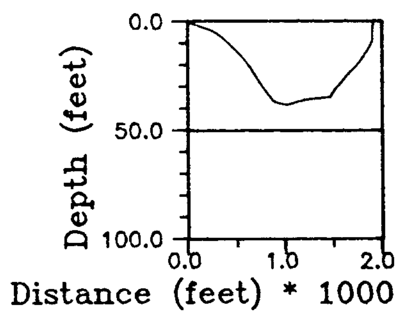

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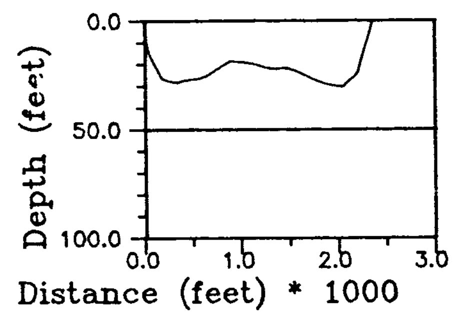

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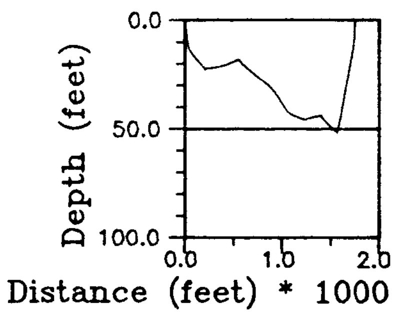

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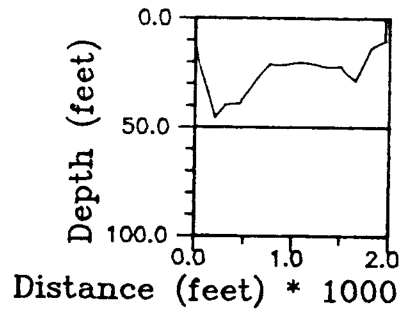

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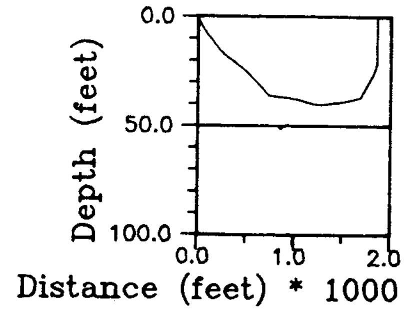

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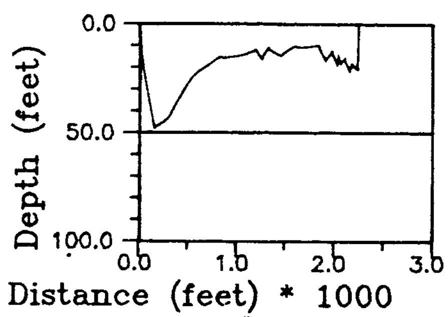

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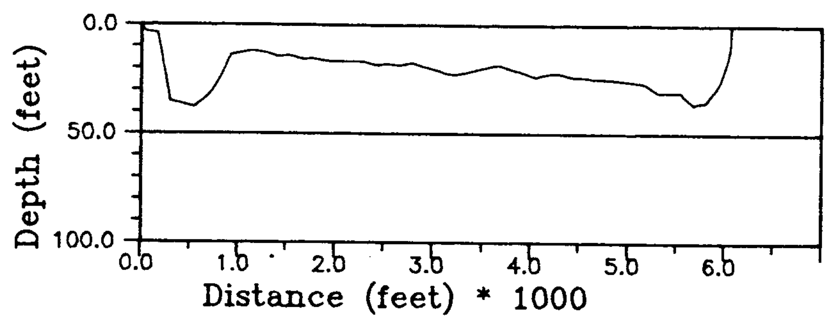


APPENDIX B

VELOCITY PROFILE DATA

Yukon Velocity Profiles
Second Field Trip

Section #: PA-5

Location: South Mouth (near mooring C-2)

Position: SE Bank - 62°35.2'N 164°48.4'W

NW Wall - 62°35.8'N 164°43.8'W

Date: 08/18/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 1	55	2.5	04	248	-	62°35.4'N
1620		2.2	20	248	-	164°48.5'W
		2.0	40	248	-	
		1.4	53	250	-	
EN 2	18	1.6	05	253	-	62°35.3'N
1652		1.6	15	253	-	164°48.6'W
EN 3	26	2.2	05	243	-	62°35.5'N
1705		2.2	15	243	-	164°48.7'W
		1.7	23	223	-	

Section #: N/A Location: Across Andreafsky Mouth

Date: 08/22/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 4	14	0.0	03	-	10.0	62^{o}02.03'N
1405		-	12	-	-	163^{o}15.13'W
EN 5	25	0.0	03	-	10.0	62^{o}02.01'N
1414		0.3	09	278	10.0	163^{o}15.15'W
		0.6	15	278	10.0	
		0.3	18	218	10.0	
		0.6	21	283	10.0	
EN6	15	0.2	03	198	10.2	62^{o}01.43'N
1419		0.3	12	218	10.4	163^{o}15.23'W

Section #: PA-1 (page 1 of 2) Location: Near Mooring C-1

Position: Northern Channel Date: 08/22/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 7	50	2.9	05	298	13.0	62°04.62'N
1530		2.6	15	308	12.9	163°28.52'W
		2.3	28	301	12.9	
		2.0	47	323	12.9	
EN 8	40	1.8	05	248	13.2	62°04.53'N
1600		1.7	18	300	13.2	163°28.54'W
		1.4	33	303	13.2	
EN 9	38	2.2	05	303	13.0	62°04.63'N
1613		2.0	16	308	13.0	163°28.48'W
		1.5	32	303	13.1	

Section #: PA-1 (page 2 of 2) Location: Near Mooring C-2

Position: Southern Channel Date: 08/22/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 10	26	1.9	05	288	13.2	62°03.88'N
1636		1.4	22	288	13.2	163°30.12'W
EN 11	18	1.4	05	288	13.0	62°03.82'N
1644		1.2	14	303	13.0	163°30.17'W
EN 12	18	1.8-2.0	05	298	13.4	62°04.05'N
1652						163°29.89'W
		1.4	17	291	13.3	

Section #: PA-4 (page 1 of 2)

Location: Kwikluak Pass (upstream of Lamont)

Position: Southern Channel

Date: 08/23/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 13	32	1.8	05	278	13.0	62°42.37'N
1315		1.5	15	278	13.1	164°18.71'W
		1.3	27	270	13.1	
EN 14	13	1.6	05	258	13.1	62°42.43'N
1325		1.6	10	263	13.1	164°18.73'W
EN 15	07	1.7	05	298	13.1	62°42.75'N
1340						164°18.66'W

Section #: PA-4 (page 2 of 2) Location: Kwikluak Pass (upstream of Lamont)

Position: Northern Channel Date: 08/23/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 16	25	1.7	05	248	13.0	62°42.92'N
1400		1.3	18	280	13.0	164°18.81'W
EN 17	55	2.4	05	263	13.2	62°43.02'N
1420		2.3	18	268	13.1	164°18.81'W
		2.4	27	268	13.1	
		2.0	42	268	13.0	
		1.9	52	263	13.0	
EN 18	44	2.4	05	265	13.1	62°43.04'N
1440		2.3	17	266	13.2	164°18.84'W
		1.9	37	273	13.2	

Section #: PA-3

Location: Aproka Pass (near Kravaksarak)

Date: 08/23/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 19	31	0.6	05	343	14.2	62^{o}47.69'N
1540		0.6	16	343	14.2	164^{o}07.41'W
		0.7	26	340	14.5	
EN 20	21	0.6	05	320	14.0	62^{o}47.63'N
1550		0.6	17	350	14.2	164^{o}07.43'W

Section #: PA-2

Location: Aproka Pass (near Kravaksarak)

Date: 08/23/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 21	28	1.3	05	328	13.5	62°48.50'N
1640		1.4	13	323	13.5	164°07.16'W
		1.3	26	320	13.6	
EN 22	17	1.7	05	318	13.5	62°48.54'N
1655		1.4	13	318	13.6	164°06.69'W

Section #: N/A

Location: Middle Mouth (offshore)

Date: 08/25/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 23	59	0.6	10	006	-	63°04.89'N
2030		0.6	28	006	-	164°40.34'W
		0.6	51	358	-	

Yukon Velocity Profiles
Third Field Trip

Section #: PB-1

Location: Kwikpak Pass
(downstream of Seagull Pt.)

Position: 63°03.03'N
164°23.27'W

63°02.96'N
164°23.71'W

Date: 09/26/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 40	10	1.7-1.8	03	343	13.4	63°02.99'N
		1.7-1.8	07	343	11.0	164°23.50'W
EN 41	05	1.5	02	353	13.0	63°03.00'N
						164°23.40'W

Section #: PB-2

Location: Kawanak Pass (at Seagull Pt.)

Position: 63°01.68'N 164°22.03'W

63°01.31'N 164°22.46'W

Date: 09/26/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 42	55	1.2	03	303	13.0	63°01.61'N
		1.1	48	248	13.0	164°22.07'W
		0.8	42	278	13.5	
EN 43	22	1.7-1.9	02	293	13.5	63°01.45'N
		1.2-1.3	15	293	13.5	164°22.28'W

Section #: PB-3

Location: Apoon Pass (at Hamilton)

Position: $62^{\circ}53.80'N$ $163^{\circ}54.92'W$

$62^{\circ}53.85'N$ $163^{\circ}55.15'W$

Date: 09/26/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. ($^{\circ}T$)	Temp. ($^{\circ}C$)	Position
EN 44	27	0.8-1.1	07	48	12.0	$62^{\circ}53.83'N$
		0.9-1.0	16	48	11.0	$163^{\circ}54.93'W$
		0.3-0.6	24	33	11.0	
EN 45	55	1.2	07	18	12.0	$62^{\circ}53.86'N$
		1.0-1.4	20	33	12.0	$163^{\circ}54.99'W$
		1.1-1.3	48	33	12.0	
EN 46	20	0.0-0.8	07	23	10.5	$62^{\circ}53.84'N$
		0.3	18	-	-	$163^{\circ}55.15'W$

Section #: PB-4

Location: Kwikpak
(downstream of Little Apoon Pass)

Position: 62°52.62'N
164°07.74'W

62°52.73'N
164°08.74'W

Date: 09/26/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 47	55	2.0-2.8	07	08	10.5	62°52.66'N
		2.1-2.5	22	13	10.0	164°07.87'W
		1.5-1.9	45	18	10.0	
EN 48	32	1.3	06	53	10.0	62°52.65'N
		1.0	16	23	10.5	164°08.08'W
		1.0	27	08	10.4	
EN 49	12	1.2	07	03	11.0	62°52.75'N 164°08.55'W

Section #: PB-5

Location: Aproka Pass
(near Naringolapak Slough)

Date: 09/27/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 50	47	0.6	07	353	12.5	62°47.63'N
		0.5	23	323	12.5	164°07.28'W
		0.6	40	313	12.5	
EN 51	20	0.6-0.8	07	323	12.5	62°47.65'N
		0.6	14	318	12.0	164°07.25'W
EN 52	36	0.5-0.7	07	318	13.0	62°47.64'N
		0.4-0.5	14	333	12.5	164°07.34'W

Section #: PB-6

Location: Kwikpak Slough (West Branch)

Position: No Stakes (line run is aproximately 50 m)

Date: 09/27/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 53	14	0.2-0.3	09	158	11.0	63°00.19'N 164°28.15'W

Section #: PB-7

Location: Kuwanak Pass (downstream of Seagull Pt.)

Position: $63^{\circ}01.94'N$ $164^{\circ}25.29'W$

$63^{\circ}01.48'N$ $164^{\circ}25.64'W$

Date: 09/27/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. ($^{\circ}T$)	Temp. ($^{\circ}C$)	Position
EN 54	21	0.7	07	268	11.0	$63^{\circ}01.62'N$
		0.5	15	278	10.5	$164^{\circ}25.61'W$
EN 55	27	0.7	07	284	11.5	$63^{\circ}01.69'N$
		0.6	15	284	11.2	$164^{\circ}25.59'W$
EN 56		0.7	07	284	11.5	$63^{\circ}01.81'N$
		0.6	15	284	11.0	$164^{\circ}25.45'W$

Section #: PB-8

Location: Lamont Kwikluak Pass

Position: $62^{o}43.06'N$
$164^{o}20.13'W$

$62^{o}42.37'N$
$164^{o}19.44'W$

Date: 09/28/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 57	58	3.7	07	278	11.0	$62^{o}43.01'N$
		3.3-3.4	21	278	11.0	$164^{o}20.16'W$
		2.6	50	278	11.3	
EN 58	25	3.0-3.2	07	275	12.0	$62^{o}43.05'N$
		1.5-2.1	23	280	12.0	$164^{o}20.21'W$
EN 59	22	0.6-0.8	07	288	12.2	$62^{o}42.78'N$
		0.7-0.8	16	278	10.0	$164^{o}20.08'W$
EN 60	08	0.7	03	303	13.0	$62^{o}42.65'N$
						$164^{o}20.17'W$
EN 61	27	3.0	07	288	13.5	$62^{o}42.48'N$
		2.6-2.8	15	283	-	$164^{o}20.17'W$
EN 62	12	1.4-1.7	07	268	13.0	$62^{o}42.42'N$
						$164^{o}20.13'W$

Section #: PB-9

Location: Kwikluak Pass (C-2 Mooring Site) Tincan Point

Position: 62°35.70'N 164°50.22'W

62°35.25'N 164°49.75'W

Date: 09/28/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 63	27	1.8-2.0	07	213	14.0	62°35.54'N
		2.3	15	223	14.0	164°50.03'W
EN 64	70	1.7	07	258	13.0	62°35.32'N
		1.7-1.9	28	248	13.0	164°49.84'W
		1.1-1.3	60	248	13.0	

Section #: N/A Location: West of Tincan Point

Position: $62^{\circ}36.77'N$
$164^{\circ}49.74'W$

$62^{\circ}36.92'N$
$164^{\circ}49.36'W$

Date: 10/01/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. ($^{\circ}T$)	Temp. ($^{\circ}C$)	Position
EN 65B	06	1.0-1.2	03	343	-	$62^{\circ}36.81'N$ $164^{\circ}49.41'W$
EN 66B	15	1.6-1.8	07	333	-	$62^{\circ}36.92'N$
		1.5-1-7	12	333	-	$164^{\circ}49.46'W$

Section #: PB-10

Location: Kwiguk Pass (at Emmonak)

Position: $62^{o}46.45'N$ $164^{o}32.41'W$

$62^{o}46.45'N$ $164^{o}32.40'W$

Date: 10/01/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 65	30	1.4	07	278	-	$62^{o}46.56'N$
		1.4	16	283	-	$164^{o}32.43'W$
		1.4	25	293	-	
EN 66	15	1.4	07	273	-	$62^{o}46.49'N$ $164^{o}32.42'W$

Section #: PB-11

Location: Kobolunuk (at C-1 Mooring Site)

Position: $62^{\circ}04.66'N$ $163^{\circ}28.17'W$

$62^{\circ}04.41'N$ $163^{\circ}28.66'W$

Date: 10/01/85

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. ($^{\circ}T$)	Temp. ($^{\circ}C$)	Position
EN 67	26	0.8-0.9	07	328	-	$62^{\circ}04.47'N$
		1.0	25	318	-	$163^{\circ}28.59'W$
EN 68	60	2.5	07	323	-	$62^{\circ}04.53'N$
		2.6	30	348	-	$163^{\circ}28.32'W$
		1.8-1.9	56	323	-	

Section #: N/A   Location: Downstream of Kobolunuk

Position: 62°03.59'N   Date: 10/01/85
163°28.89'W

62°04.03'N
163°28.21'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 70	07	2.0	06	283	-	62°03.09'N
(mid-river shelf)						163°28.57'W
EN 71	25	2.1-2.3	07	288	-	62°03.91'N
		1.8-1.9	15	288	-	163°28.57'W
		1.4-1.5	23	288	-	
EN 72	38	2.7-2.9	07	293	-	62°03.82'N
		2.3-2.5	20	293	-	163°28.69'W
EN73		2.7-2.8	07	293	-	62°03.66'N
		2.6-2.7	15	293	-	163°28.92'W
		1.7-1.8	24	288	-	

Yukon Velocity Profiles
Fourth Field Trip

Section #: PC-1

Location: Lamont

Position: North - $62^{\circ}43.06'N$
$164^{\circ}20.19'W$

South - $62^{\circ}42.37'N$
$164^{\circ}20.20'W$

Date: 06/21/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. ($^{\circ}T$)	Temp. ($^{\circ}C$)	Position
EN 101	28	1.7	27	273	15	$62^{\circ}42.97'N$
1600		2.6-2.4	15	280	15	$164^{\circ}20.19'W$
		2.9-3.1	03	283	15	
EN 102	16	1.6	03	278	15	$62^{\circ}42.40'N$
1615		1.5-1.6	10	273	15	$164^{\circ}20.08'W$
EN 103	12	2.2-2.4	03	280	15	$62^{\circ}42.52'N$
1625		1.8-1.9	10	283	15	$164^{\circ}20.10'W$
EN 104	5	0.4	02	288	15	$62^{\circ}42.67'N$
1640						$164^{\circ}20.12'W$
EN 105	25	2.4	03	263	15	$62^{\circ}42.88'N$
1650		2.4-2.5	12	263	15	$164^{\circ}20.16'W$
		2.1-2.2	22	268	15	
EN 106	17	0.9	06	283	15	$62^{\circ}42.81'N$
1705		1.1-1.2	14	268	15	$164^{\circ}20.12'W$
EN 107	38	2.7-2.9	05	273	15	$62^{\circ}43.04'N$
1715		2.8	15	268	16	$164^{\circ}20.18'W$
		2.4-2.6	30	263	16	
EN 108	50	3.1-3.2	05	268	15	
1740		3.1-3.2	18	268	15	No
		3.2-3.3	30	263	15	Position
		3.2-3.4	50	268	15	

Section #: PC-2

Location: Kwikpak Pass

Position: Northeast Bank - 62°48.78'N
164°06.13'W

Date: 06/21/86

Southwest Bank - 62°48.47'N
164°07.20'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (°T)	Temp. (°C)	Position
EN 109	15	1.2-1.3	03	323	15	62°48.47'N
2110		1.1	12	318	14.5	164°07.20'W
EN 110	33	1.5	03	343	15	62°48.49'N
2117		1.6	12	328	15	164°_7.13'W
		1.2-1.5	26	323	15	
EN 111	17	2.0-2.2	03	318	15	62°48._2'N
2127		1.8-2.0	12	313	15	164°07.04'W
EN 112	21	2.1-2.3	03	318	15	62°48.64'N
2140		1.9-2.1	16	318	15	164°06.54'W
EN 113	15	1.7-1.9	03	333	15	62°48.72'N
2147		1.4-1.6	12	328	15	164°06.34'W
EN 114	03	0.5-0.6	01	303	15	62°48.73'N
2152						164°06.18'W
EN 115	13	0.9-1.0	03	343	15	62°40.78'N
2159		1.0	10	328	15	164°06.15'W

Section #: PC-3 Location: Hamilton

Position: East - 62°53.87'N
163°54.86'W

Date: 06/21/87

West - 62°53.92'N
163°55.07'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (°T)	Temp. (°C)	Position
EN 116	18	1.7-2.0	03	33	15	62°53.87'N
2302		1.9-2.0	12	33	15	163°54.89'W
EN 117	30	1.4-1.6	03	28	15	62°53.90'N
2340		1.5	14	28	15	163°54.98'W
		1.5	24	28	15	
EN 118	48	1.4-1.9	03	33	15	62°53.88'N
2345		1.6	20	33	15	163°59.89'W
		1.3-1.5	36	43	15	
		1.4-1.5	42	28	15	

Section #: PC-4 Location: Aproka Pass

Position: East - 62°47.66'N
164°07.32'W

West - 62°47.62'N
164°07.41'W

Date: 06/22/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (°T)	Temp. (°C)	Position
EN 119	32	0.4-0.6	03	343	16	62°47.61'N
0058		0.5-0.7	12	323	16	164°07.38'W
		0.6-0.7	28	313	16	
EN 120	25	0.7	03	328	16	62°47.63'N
0110		0.5-0.7	12	323	16	164°07.33'W
		0.6-0.7	30	323	16	
EN 121	47	0.6-0.7	03	328	16	62°47.62'N
0118		0.6-0.7	12	333	16	164°07.36'W
		0.6-0.7	30	313	16	
		0,7	42	313	16	

Section #: PC-5 Location: Mountain Village

Position: North - 62°05.18'N 163°44.00'W Date: 06/22/86

South - 62°04.35'N 163°43.86'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (°T)	Temp. (°C)	Position
EN 122	18	1.6-1.7	03	278	16	62°04.37'N
1910		1.4-1.5	12	278	16	163°43.87'W
EN 123	28	2.9-3.2	03	283	17	62°04.46'N
1925		2.7-2.9	12	283	16.5	163°43.88'W
		1.7-1.9	24	283	16.5	
EN 124	15	1.7-1.9	03	288	16.5	62°04.67'N
1940		1.4-1.5	12	283	16.5	163°43.91'W
EN 125	08	1.0	05	278	16.5	62°04.81'N
1950						163°43.91'W
EN 126	30	0.9-1.1	03	278	16.5	62°04.84'N
1955		1.0-1.1	12	273	16.5	163°43.92'W
		0.9-1.0	26	263	16.5	
EN 127	27	1.3-1.4	03	273	16.5	62°05.11'N
1610		1.4-1.6	12	268	16.5	163°44.09'W
		1.2-1.4	26	258	16.5	
EN 128	56	2.2-2.3	03	268	16.5	62°04.96'N
1623		2.3-2.4	12	268	16.5	163°44.23'W
		1.3-1.5	38	263	16.5	
		1.3-1.5	44	258	17	

Section #: PC-6

Location: Kobolunuk

Position: South - $62^{o}04.11'N$ $163^{o}32.29'W$

Date: 06/22/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 129 2140	28	1.8-1.9	03	283	16.5	$62^{o}04.14'N$
		1.5-1.6	12	283	16.5	$163^{o}32.72'W$
		1.5-1.6	24	278	16.5	
EN 130 2151	43	2.9-3.1	03	283	16.5	$62^{o}04.23'N$
		2.9-3.1	12	278	16.5	$163^{o}32.60'W$
		2.6-2.7	24	278	16	
		2.0-2.2	34	283	16	
EN 131 2210	15	1.8-2.0	03	288	16	$62^{o}04.34'N$
		1.7-1.9	14	288	16	$163^{o}32.59'W$
EN 132 2220	05	1.0-1.2	03	298	16	$62^{o}04.39'N$ $163^{o}32.56'W$
EN 133 2228	34	1.5-1.6	03	268	16	$62^{o}04.65'N$
		1.7-1.9	12	258	16	$163^{o}32.43'W$
EN 134 2138	30	2.4-2.6	03	278	16.5	$62^{o}05.11'N$
		2.4-2.6	12	278		$163^{o}32.49'W$
		1.9-2.1	27	278		

Section #: PC-7 Location: Kotlik

Position: North - $63^{o}02.36'N$ Date: 06/25/86
$163^{o}39.97'W$

South - $63^{o}02.26'N$
$163^{o}40.02'W$

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 135 2040	05	1.1-1.3	02	103	14.5	$63^{o}02.36'N$ $163^{o}40.00'W$
EN 136 2053	08	0.8-0.9	02	93	13.5	$63^{o}02.28'N$ $163^{o}40.02'W$

Section #: PC-8 Location: Okwega Pass

Position: East - 63°02.63'N
163°40.56'W

West - 63°02.75'N
163°40.79'W

Date: 06/25/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (°T)	Temp. (°C)	Position
EN 137 2115	11	1.8-2.8	03	48	13.5	63°02.67'N 163°40.49'W
EN 138 2150	08	1.7	03	48	14.5	63°02.73'N 163°40.62'W
EN 139 2158	13	2.0-2.1	03	48	14.5	63°02.70'N 163°40.50'W
EN 140 2205	13	2.0-2.1	04	48	14.5	63°02.70'N 163°40.47'W

Section #: PC-9 Location: Apoon Pass

Position: East - 63°01.91'N Date: 06/25/86
163°44.62'W

West - 63°02.99'N
163°40.93'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (°T)	Temp. (°C)	Position
EN 141	21	1.5-1.7	06	63	14.5	63°02.04'N
2305		1.4-1.7	13	63	14.5	163°44.81'W
		1.3-1.6	18	58	14.5	
EN 142	15	1.4-1.5	04	58	14.5	63°01.97'N
2315		1.2-1.3	12	58	14.5	163°44.64'W
EN 143	23	1.9-2.1	03	68	14	63°02.02'N
2400		1.4-1.6	12	63	13	163°44.83'W
		0.9-1.1	20	73	13.5	

Section #: PC-5 Location: Mountain Village

Position: North - $62^{o}05.09'N$
$163^{o}31.41'W$

Date: 06/27/86

South - $62^{o}04.04'N$
$163^{o}81.35'W$

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 144	22	1.6-1.7	03	263	17	$62^{o}05.07'N$
1815		1.5	12	268	17	$163^{o}31.43'W$
		1.3	18	260	17	
EN 145	42	2.6-2.7	03	273	17	$62^{o}05.03'N$
1900		2.5	12	273	17	$163^{o}31.46'W$
		1.9-2.0	18	263	17	
		2.0-2.5	30	268	17	
		1.8-1.9	38	273	17	
EN 146	31	1.3-1.4	03	276	17	$62^{o}04.79'N$
1918		1.3	12	283	17	$163^{o}31.62'W$
		1.0-1.1	18	263	16.5	
		1.3	28	258	16.5	
EN 147	18	0.7-0.8	03	293	17	$62^{o}04.60'N$
1927		0.7	12	283	17	$163^{o}31.68'W$
EN 148	04	0.6	02	283	17	$62^{o}04.50'N$
1934						$163^{o}31.69'W$
EN 149	16	2.1-2.3	03	273	17	$62^{o}04.29'N$
1940		1.9-2.1	12	278	17	$163^{o}31.82'W$
EN 150	21	2.4-2.5	03	273	16.5	$62^{o}04.06'N$
1947		2.2-2.3	12	268	16.5	$163^{o}31.90'W$
		1.8	18	268	16.5	
EN 151	36	1.6	03	280	16.5	$62^{o}04.16'N$
2005		1.4-1.5	12	283	16.5	$163^{o}32.32'W$
		1.2-1.3	18	278	16.5	
		0.8	30	278	16.5	

Section #: PC-3 Location: Hamilton

Date: 06/28/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{O}T)	Temp. (^{O}C)	Position
EN 152	16	0.7-0.8	03	343	17	62^{O}53.88'N
1511		0.3-0.5	12	25	17	163^{O}55.06'W
EN 153	46	0.7-0.8	03	53	16	62^{O}53.89'N
1518		0.7-0.9	12	40	16.5	163^{O}54.92'W
		0.7	24	38	16.5	
		0.9	32	28	16.5	
EN 154	50	0.8-0.9	03	33	16.5	62^{O}53.88'N
1530		1.0-1.1	18	33	17.0	163^{O}54.87'W
		0.8-1.0	30	18	16.5	
		0.8-0.9	43	18	16.5	

Section #: PC-2 Location: Kwikpak

Date: 06/28/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 155	07	0.7	03	88	15.5	62°48.82'N
1705						164°06.25'W
EN 156	12	0.7-0.8	03	318	17	62°48.81'N
1707		0.6	9	348	17	164°06.22'W
EN 157	15	0.9-1.0	03	328	16.5	62°48.81'N
1714		0.6-0.7	10	323	16.5	164°06.19'W
EN 158	24	1.7-1.9	03	318	16.5	62°48.75'N
1727		1.5-1.6	12	318	16.5	164°06.46'W
		1.3-1.5	20	313	16.5	
EN 159	19	2.0	03	313	16.5	62°48.64'N
1735		1.5-1.7	12	313	16.5	164°06.80'W
		1.4-1.6	16	308	15.5	
EN 160	15	1.2-1.3	03	318	16.5	62°48.53'N
1745		1.1-1.2	12	328	15.5	164°07.15'W
EN 161	25	1.4-1.5	03	308	17	62°48.48'N
1751			12	313	17	164°07.20'W
		1.1-1.3	27	313	17	

Section #: PC-4 Location: Aproka

Date: 06/28/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 162 1818	32	0.7	03	303	16.5	62°47.64'N 164°07.34'W
		0.6-0.7	12	303	17	
		1.6-1.7	20	313	17	
		0.7	28	308	17	
EN 163 1830	35	0.7-0.8	03	333	16.5	62°47.63'N 164°07.38'W
		0.6-0.7	12	323	16.5	
		0.6-0.7	18	328	16.5	
		0.6-0.7	30	308	16.5	
EN 164 1838	47	0.5-0.6	03	348	17	62°47.64'N 164°07.39'W
		0.6-0.7	14	343	17	
		0.5	24	318	16.5	
		0.4-0.5	35	303	16.5	

Section #: PC-1

Location: Lamont

Date: 06/28/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 165	39	2.5-2.6	03	263	16.5	62^{o}43.04'N
1915		2.2-2.4	12	240	16.5	164^{o}20.18'W
		2.2-2.3	18	258	16.5	
		2.2-2.3	30	243	16.5	
		1.7-1.9	36	258	16.5	
EN 166	60	3.4-3.5	03	268	16.5	62^{o}42.99'N
1926		3.1-3.2	12	258	16.5	164^{o}20.20'W
		3.1-3.2	18	258	16.5	
		3.0-3.1	30	258	16.5	
		2.7-2.8	42	268	16.5	
EN 167	33	3.0-3.1	03	258	16.5	62^{o}42.90'N
1951		2.5-2.6	18	258	16.5	164^{o}20.14'W
		2.4-2.5	30	258	16.5	
EN 168	27	3.0-3.1	03	278	16.5	62^{o}42.48'N
2010		1.6-1.7	12	273	16.5	164^{o}20.08'W
		1.9-2.0	18	273	16.5	
		1.6-1.7	24	268	16.5	
EN 169	30	2.5-2.6	03	268	17.0	62^{o}42.41'N
2118		2.4-2.5	12	263	17.0	164^{o}20.06'W
		1.6-1.0	28	273	16.5	

Yukon Velocity Profiles
Fifth Field Trip

Section #: PD-1

Location: Kobolunuk

Date: 08/12/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 170	20	1.0-1.4	02	283	-	No Loran
1650		0.9-1.3	12	278	-	75 ft. off
		0.9-1.1	18	278	-	South Bank
EN 171	35	1.8-1.9	05	286	-	300 ft. off
1705		1.7-1.9	12	286	-	South Bank
		1.6-1.8	18	286	-	in Channel
		1.1-1.4	24	286	-	
		0.9-1.2	32	278	-	
EN 172	18	1.5-1.7	05	283	-	200 yds. off
1720		1.4-1.6	12	283	-	South Bank
		1.3-1.5	18	283	-	
EN 173	15	0.3-0.4	05	263	-	Middle of
1740		0.2-0.3	12	348	-	River
EN 174	34	1.2-1.4	05	278	-	No Loran
1755		1.3-1.5	12	273	-	250 yds. off
		1.2-1.4	18	273	-	North Bank
		1.1-1.3	24	273	-	
		1.0-1.2	32	268	-	
EN 175	45	2.0	05	278	-	75 yds. off
1810		1.9-2.0	18	273	-	North Bank
		1.8	24	268	-	
		1.6-1.8	36	273	-	
		1.0-1.2	45	258	-	

Section #: PD-2

Location: Mountain Village

Date: 08/12/87

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 176	22	1.5-1.6	05	263	-	North Bank
1925		1.5-1.6	12	273	-	
		1.4-1.5	18	263	-	
EN 177	60	2.0-2.2	05	273	-	North Channel
2005		2.0-2.2	18	268	-	
		1.9-2.1	30	268	-	
		1.7-1.8	42	268	-	
		1.7-1.9	48	273	-	
EN 178	30	0.5-0.6	05	273	-	300 yds. off
2020		0.5-0.6	12	263	-	North Bank
		0.8-1.0	24	268	-	
EN 179	20	1.4-1.6	05	288	-	No Loran
2028		1.3-1.5	15	298	-	
		1.2-1.4	20	293	-	
EN 180	30	1.9-2.1	10	283	-	South Bank
2035		1.7-1.9	22	278	-	
		1.2-1.4	30	278	-	

Section #: PD-3 Location: Kwikpak Pass

Position: West Bank - $62^{\circ}48.50'N$ $164^{\circ}07.16'W$ Date: 08/13/86

East Bank - $62^{\circ}48.77'N$ $164^{\circ}06.44'W$

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 181	32	1.0-1.2	04	328	-	62°48.50'N
1515		1.0-1.1	12	328	-	164°07.16'W
		0.9-1.0	18	328	-	
		0.8-1.0	24	323	-	
		0.7-0.9	30	308	-	
EN 182	18	0.9-1.1	06	323	-	62°48.54'N
1530		0.8-1.1	12	323	-	164°06.93'W
		0.6-1.0	18	323	-	
EN 183	20	1.0-1.2	06	323	-	62°48.64'N
1550		0.9-1.1	12	323	-	164°06.65'W
		0.9-1.1	18	318	-	
EN 184	10	0.8-1.1	05	323	-	62°48.83'N
1620		0.8-1.0	10	348	-	164°06.17'W
EN 185	18	1.2-1.4	06	328	-	62°48.77'N
1635		1.1-1.3	12	318	-	164°06.44'W
		0.9-1.1	18	333	-	

Section #: PD-4

Location: Aproka Pass

Position: West Side - $62^{o}47.62'N$ $164^{o}07.41'W$

East Side - $62^{o}47.66'N$ $164^{o}07.32'W$

Date: 08/13/86

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (^{o}T)	Temp. (^{o}C)	Position
EN 186	18	0.4-0.6	06	333	-	$62^{o}47.66'N$
1725		0.5-0.6	12	328	-	$164^{o}07.32'W$
		0.4-0.6	18	328	-	
EN 187	40	0.4-0.5	05	328	-	$62^{o}47.69'N$
1735		0.3-0.5	18	328		$164^{o}07.34'W$
		0.3-0.5	24	333	-	
		0.7-0.8	30	303	-	
		0.4-0.5	40	308	-	
EN 188	25	0.3-0.5	05	318	-	$62^{o}47.62'N$
1800		0.4-0.6	12	333	-	$164^{o}07.38'W$
		0.3-0.5	18	318	-	
		0.3-0.5	24	328	-	

Section #: PD-5 Location: Lamont

Position: North Bank - 62°43.04'N 164°20.18'W Date: 08/13/86

South Bank - 62°42.40'N 164°20.18'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 189	40	1.7-1.9	05	273	-	62°43.04'N
1920		1.8-2.0	12	273	-	164°20.18'W
		1.6-1.8	18	268	-	
		1.4-1.7	24	273	-	
		1.2-1.5	30	268	-	
		1.0-1.2	36	278	-	
EN 190	60	2.0-2.2	06	273	-	mid-channel
2005		2.1-2.2	24	273	-	
		1.9-2.1	36	273	-	
		1.8-2.0	42	273	-	
		1.3-1.5	50	263	-	
EN 191	35	1.5-1.6	05	273	-	62°42.90'N
2020		1.5-1.6	12	268	-	164°20.09'W
		1.3-1.5	18	268	-	
		1.2-1.4	24	268	-	
		1.0-1.2	30	268	-	
EN 192	15	0.3-0.4	05	298	-	62°42.81'N
2040		0.3-0.4	12	258	-	164°20.10'W
EN 193	20	1.4-1.6	05	283	-	62°42.50'N
2050		1.1-1.3	12	273	-	164°20.20'W
		1.0-1.1	18	278	-	
EN 194	30	1.7-1.9	05	278	-	62°42.45'N
2100		1.7-1.8	12	273	-	164°20.23'W
	30	1.4-1.6	18	273	-	
		1.3-1.4	24	278	-	
		0.9-1.1	30	283	-	
EN 195	21	0.8-1.0	06	273	-	62°42.40'N
2110		0.9-1.1	12	278	-	164°20.18'W
		0.8-0.9	18	273	-	

Section #: PD-6 Location: Hamilton

Position: West Bank - 62°53.92'N 163°54.99'W Date: 08/14/86

East Bank - 62°53.87'N 163°54.86'W

Station/ Hours	Bottom Depth (ft)	Speed	Sensor Depth (ft)	Dir. (°T)	Temp. (°C)	Position
EN 197	15	0.9-1.1	05	023	-	62°53.92'N
1415		0.8-0.9	13	023	-	163°54.99'W
EN 198	38	0.9	05	038	-	62°53.89'N
1430		0.7-0.9	18	038	-	163°54.93'W
		0.7-0.9	24	033	-	
		0.7-0.9	30	028	-	
		0.8	36	023	-	
EN 199	50	0.9-1.1	05	038	-	62°53.88'N
1500		0.9-1.1	12	033	-	163°54.90'W
		0.9-1.0	18	038	-	
		0.8-1.0	24	023	-	
		0.7-0.9	30	023	-	
		0.7-0.9	36	028	-	
		0.8-0.9	42	038	-	
		0.7-0.9	48	033	-	

APPENDIX C

CTD PROFILE DATA

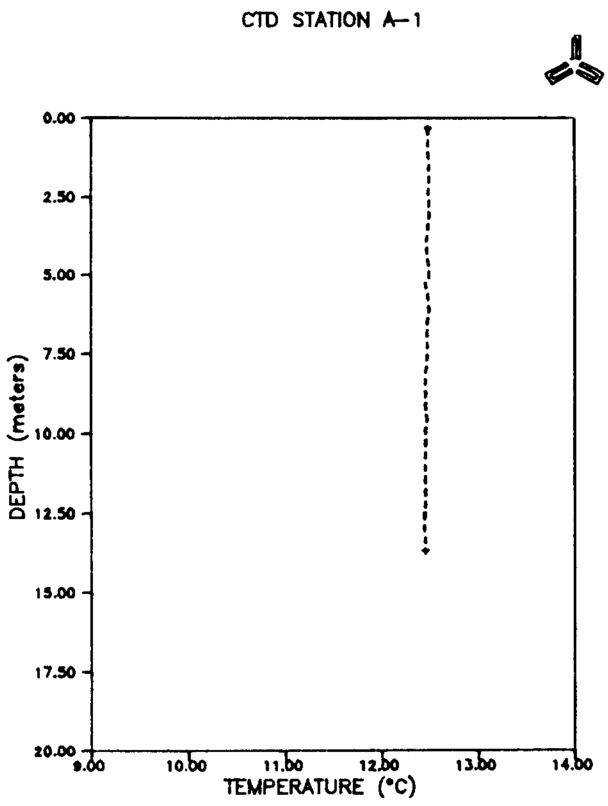
Summary of CTD data, including profiling depths and positions collected during the second field trip to the Yukon Delta, summer 1985.

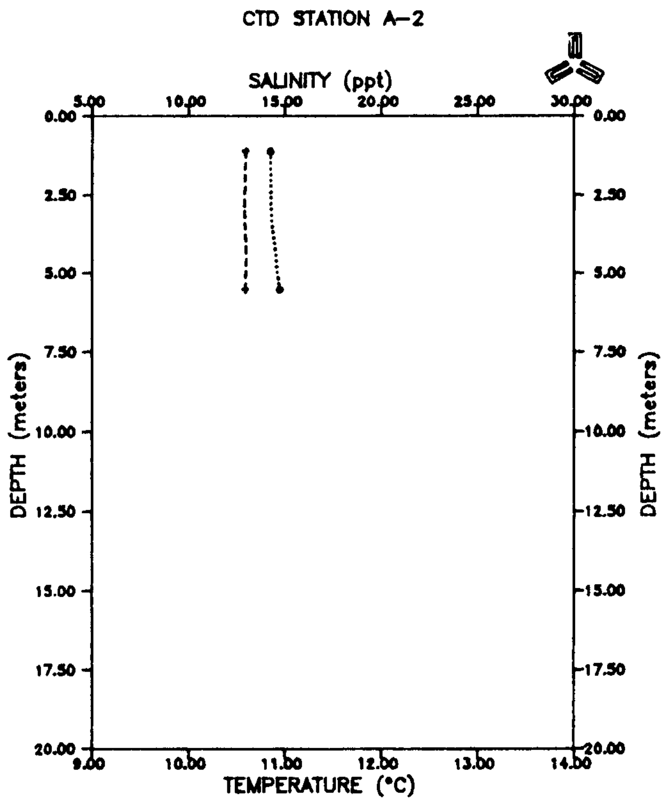
CTD Station	Date	Water Depth (m)	Profile Depth (m)	Temperature Top/Bottom (°C)	Salinity Top/Bottom (ppt)	Latitude	Longitude
A-1	08/24/85	15.2	13.7	12.48/12.45	No Salt		
A-2	08/25/85	7.6	5.5	10.59/10.59	14.28/14.74	63°04'40"N	165°09'86"W
A-3	08/25/85	7.3	6.6	11.90/11.98	No Salt	63°08'14"N	164°46'35"W
A-4	08/25/85	18.0	17.0	12.07/12.09	No Salt	63°04'85"N	164°40'34"W
A-5	08/26/85	4.3	4.3	10.77/10.77	26.83/26.85	62°32'06"N	165°31'19"W
A-6	08/26/85	9.8	8.0	10.81/10.80	27.24/27.26	62°36'14"N	165°34'41"W
A-7	08/28/85	18.3	16.5	11.67/11.67	No Salt	62°35'70"N	164°51'82"W
A-8	08/28/85	6.1	4.4	11.64/11.66	No Salt	62°36'35"N	164°58'80"W
A-9	08/28/85	6.1	5.2	11.59/11.63	No Salt	62°36'12"N	165°02'80"W

Summary of CTD data, including profiling depths and positions collected during the third field trip to the Yukon Delta, summer 1985.

CTD Station	Date	Water Depth (m)	Profile Depth (m)	Temperature Top/Bottom (°C)	Salinity Top/Bottom (ppt)	Latitude	Longitude
B-1	09/24/85	18.3	16.5	6.67/6.65	No Salt	62°35'28"N	164°49'99"W
B-2	09/24/85	8.2	6.7	6.51/6.52	No Salt	62°34'63"N	165°02'74"W
B-3	09/24/85	20.4	18.8	6.51/6.52	No Salt	62°34'63"N	165°04'69"W
B-4	09/24/85	7.9	6.6	6.49/6.36	No Salt	62°31'17"N	165°12'93"W
B-5	09/24/85	10.1	8.7	6.37/6.23	No Salt	62°28'70"N	165°17'87"W
B-6	09/24/85	6.7	6.1	5.91/5.85	No Salt	62°27'01"N	165°24'07"W
B-7	09/24/85	2.4	1.7	6.04/6.16	0.94/ 5.42	62°25'36"N	165°28'99"W
B-8	09/24/85	4.0	3.4	6.57/6.81	8.29/17.04	62°26'88"N	165°34'55"W
B-9	09/24/85	7.1	6.2	7.04/7.37	20.02/24.82	62°26'30"N	165°39'24"W
B-10	09/25/85	14.3	13.3	6.26/6.21	No Salt	63°01'67"N	164°22'27"W
B-11	09/25/85	9.1	7.3	6.26/6.27	No Salt	63°01'85"N	164°28'00"W
B-12	09/25/85	15.2	11.6	6.26/6.26	No Salt	63°02'17"N	164°41'04"W
B-13	09/25/85	12.8	10.9	6.29/6.29	No salt	63°02'14"N	164°41'04"W

CTD station plots of depth vs. temperature and salinity. At stations where salt was absent, depth and temperature are plotted.


CTD STATION A-1
DEPTH (meters)
TEMPERATURE (°C)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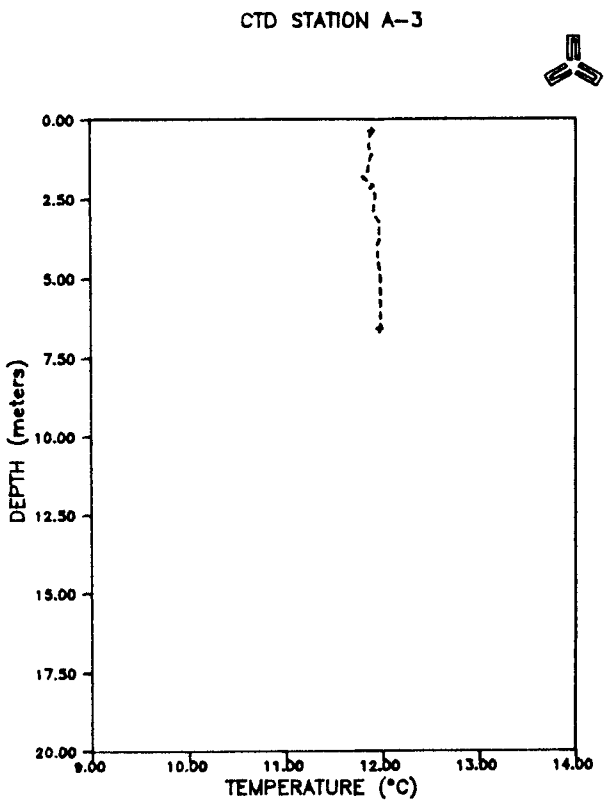
SALINITY (ppt)
DEPTH (meters)
TEMPERATURE (°C)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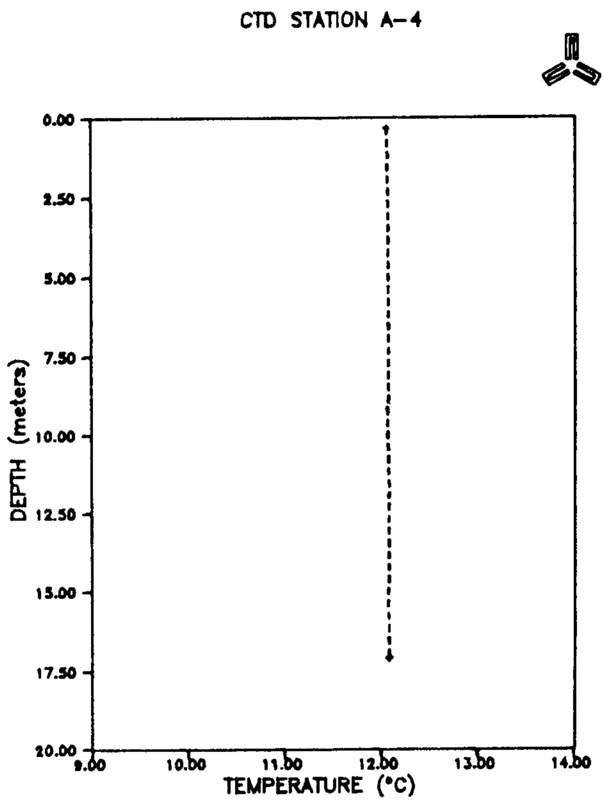
DEPTH (meters)
TEMPERATURE (°C)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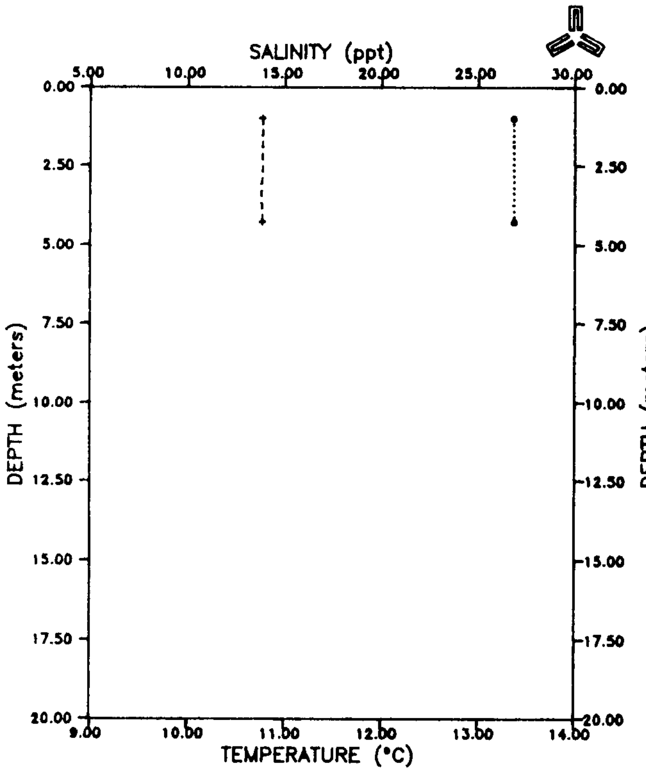
DEPTH (meters)
TEMPERATURE (°C)

CTD STATION A-5



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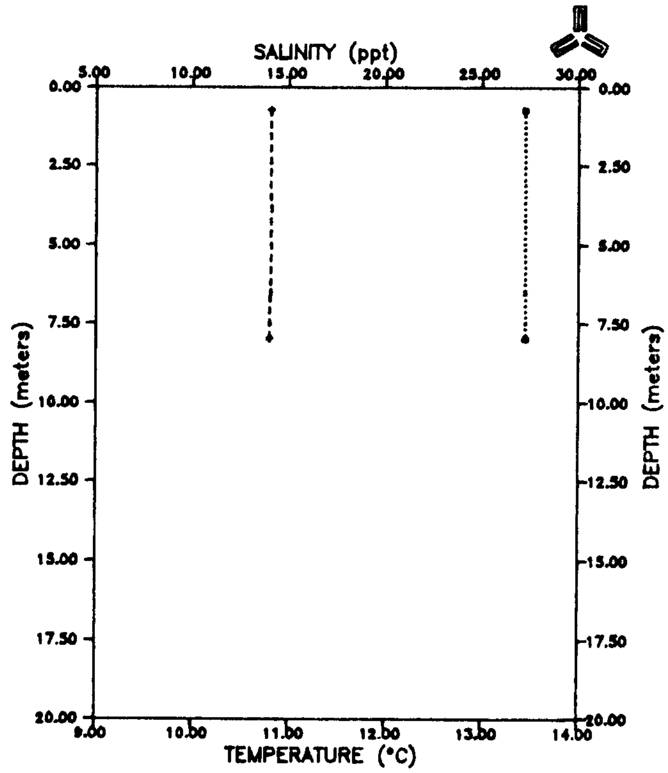

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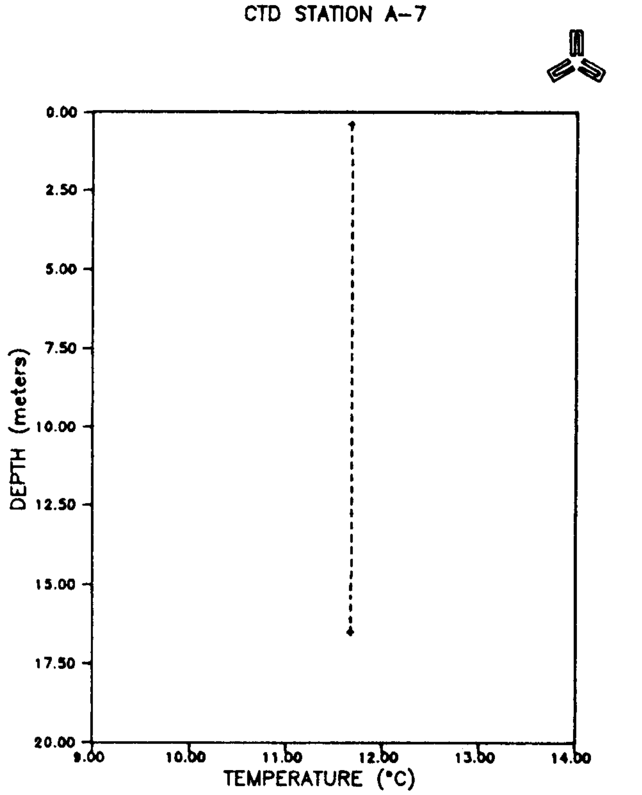

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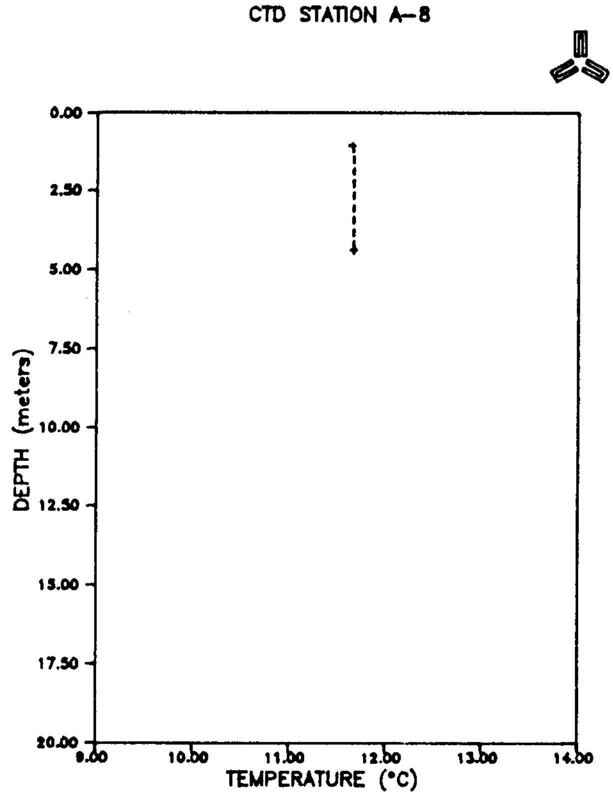

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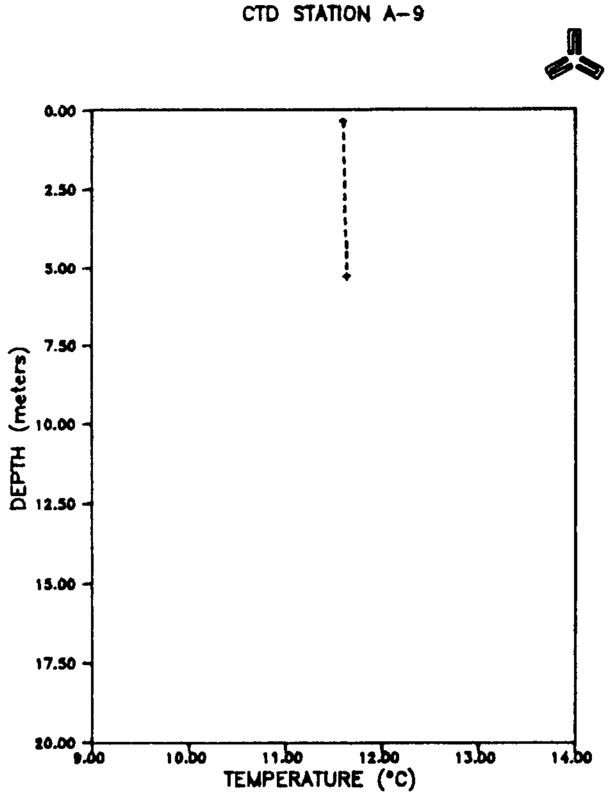

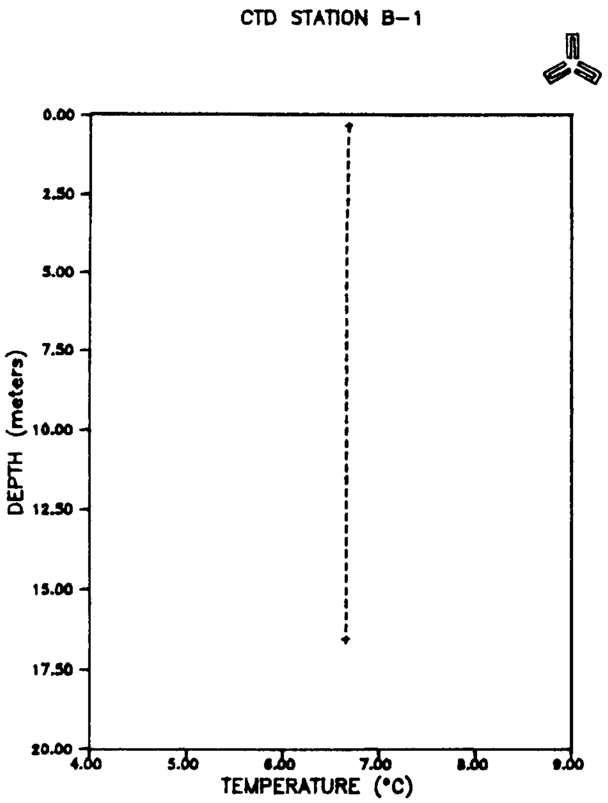
CTD STATION B-1
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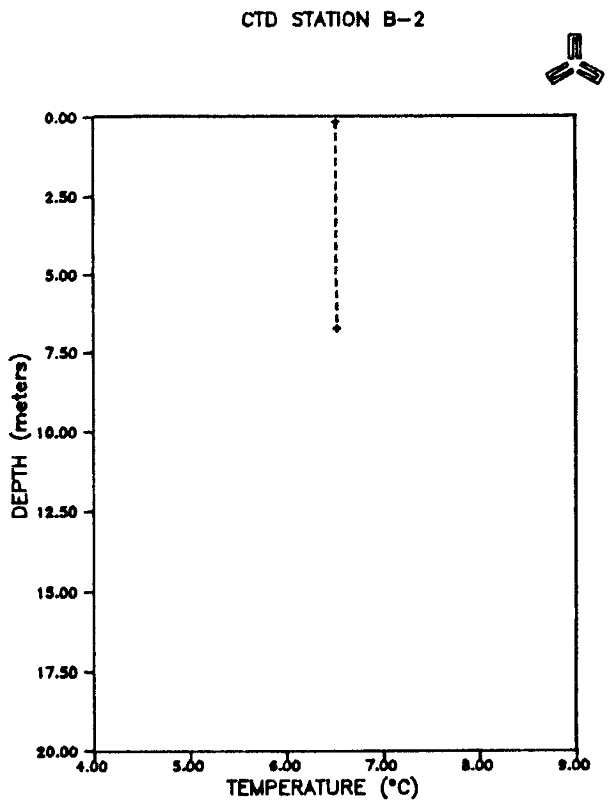
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)


CTD STATION B-2
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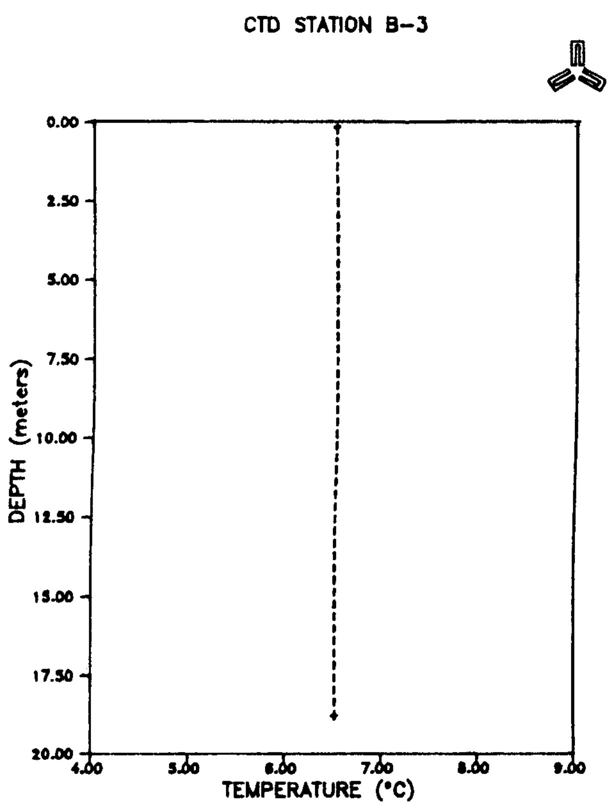
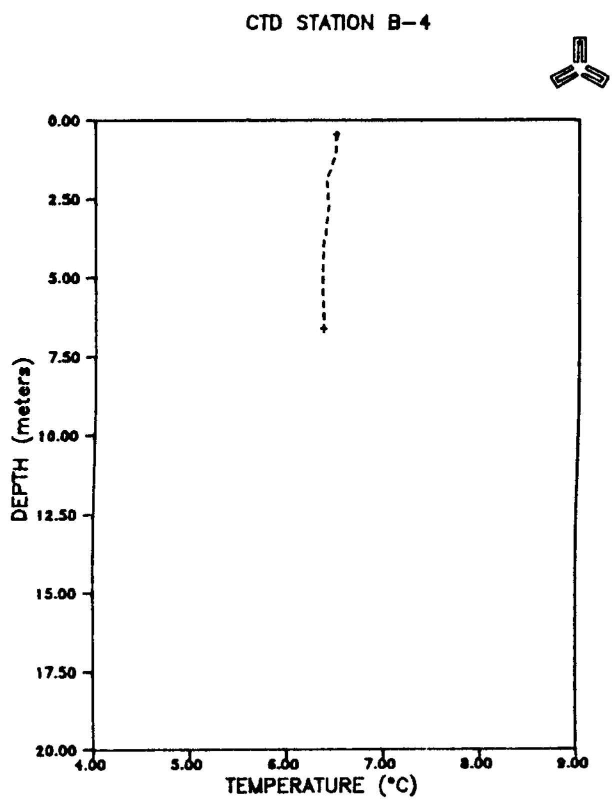
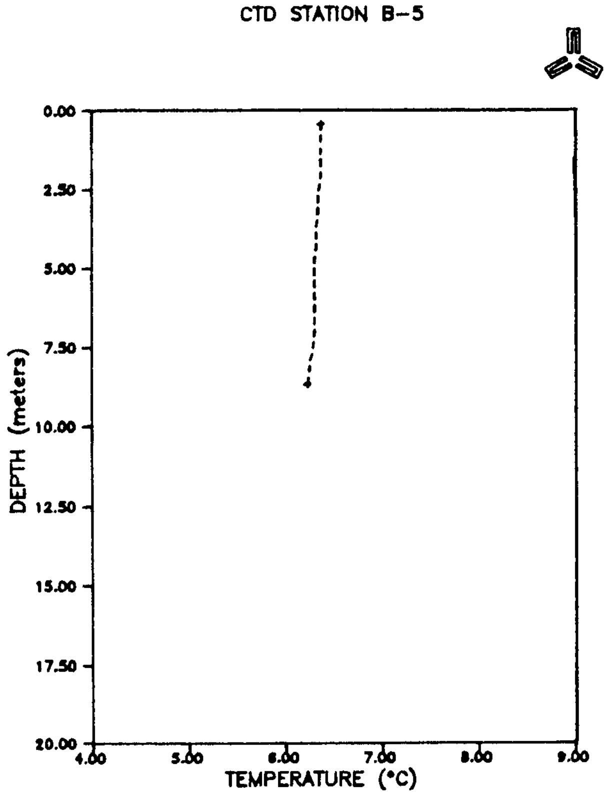
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)


CTD STATION B-3
0.00
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)


CTD STATION B-4
0.00
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)

CTD STATION B-5



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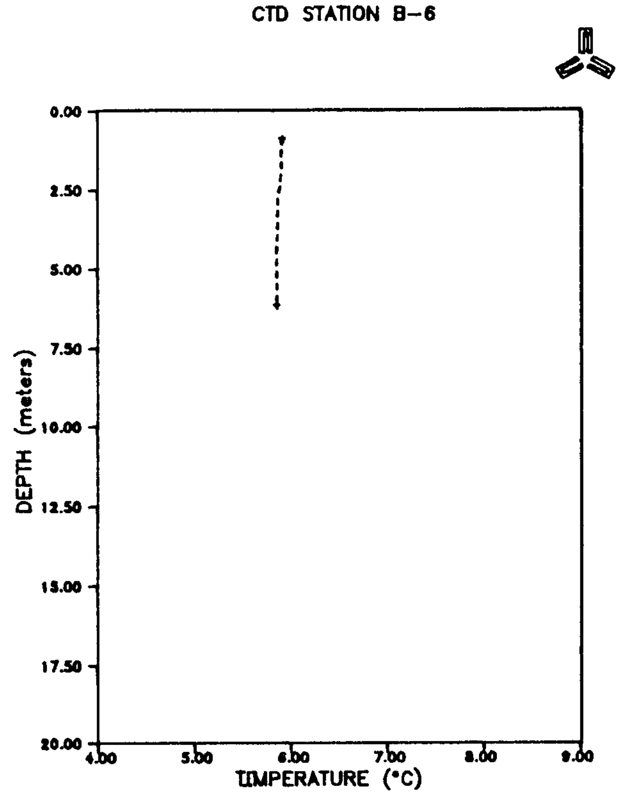

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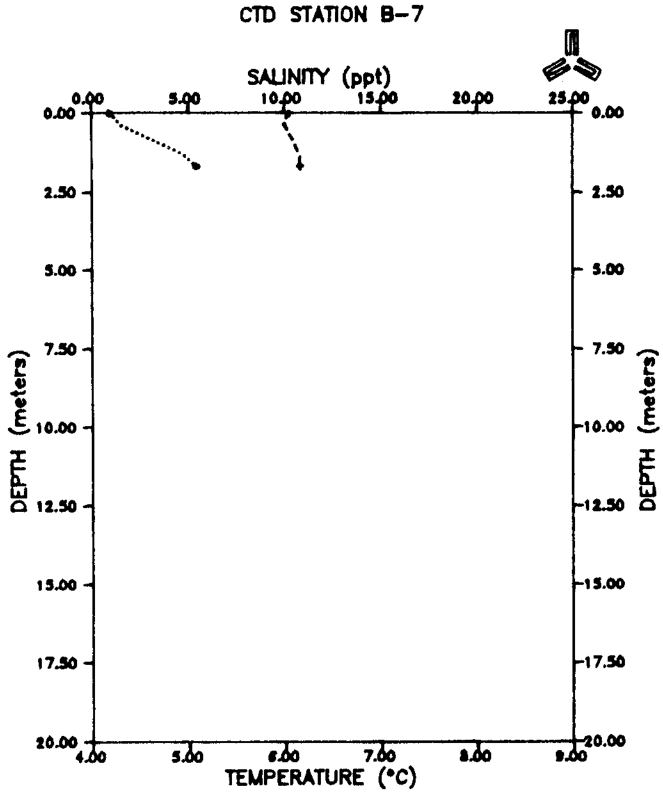

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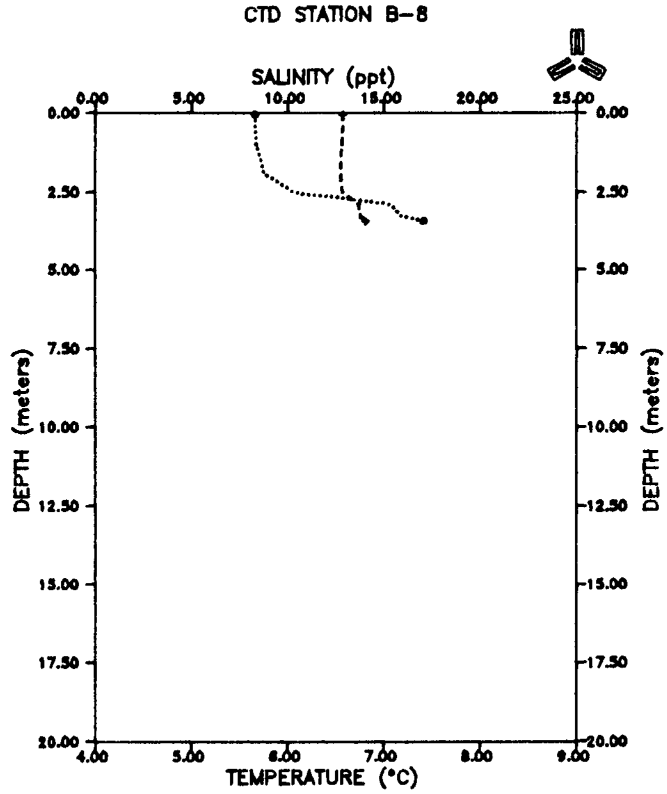
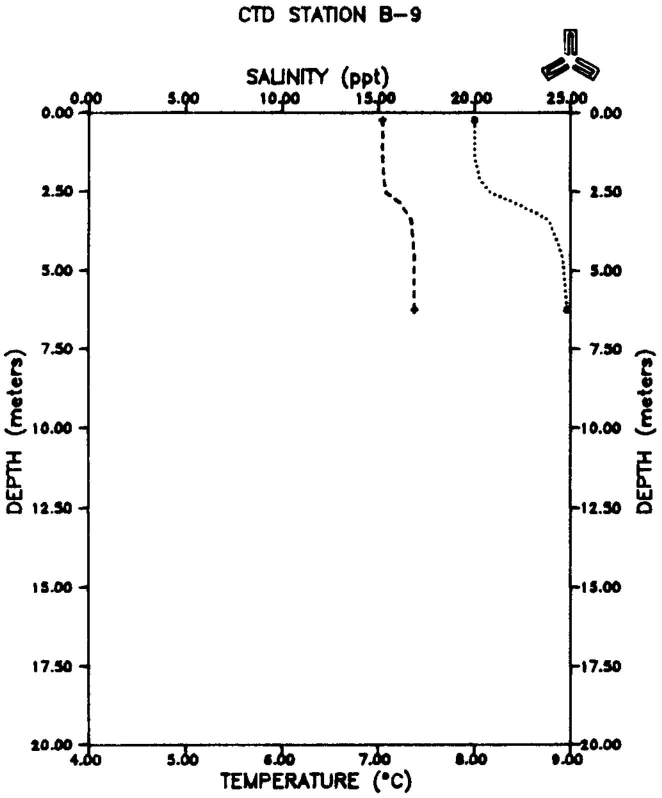
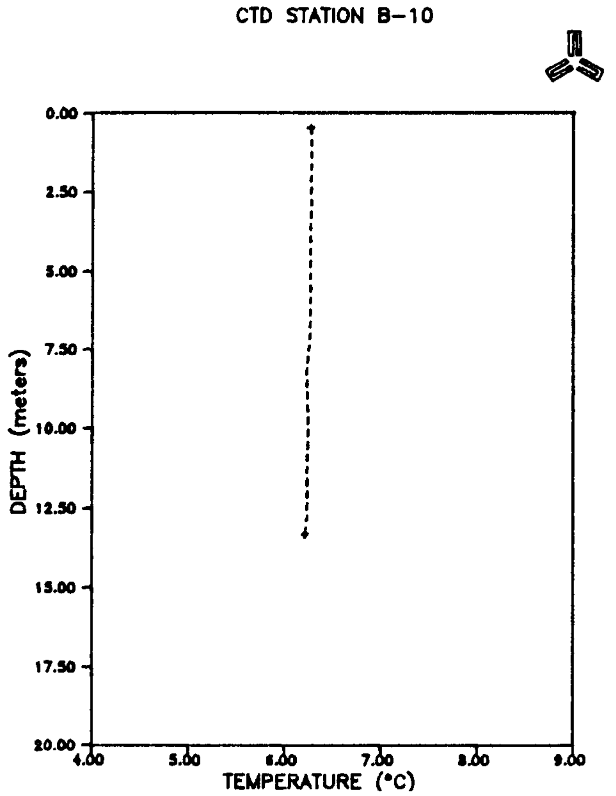



CTD STATION B-9
SALINITY (ppt)
0.00
5.00
10.00
15.00
20.00
25.00
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)


CTD STATION B-10
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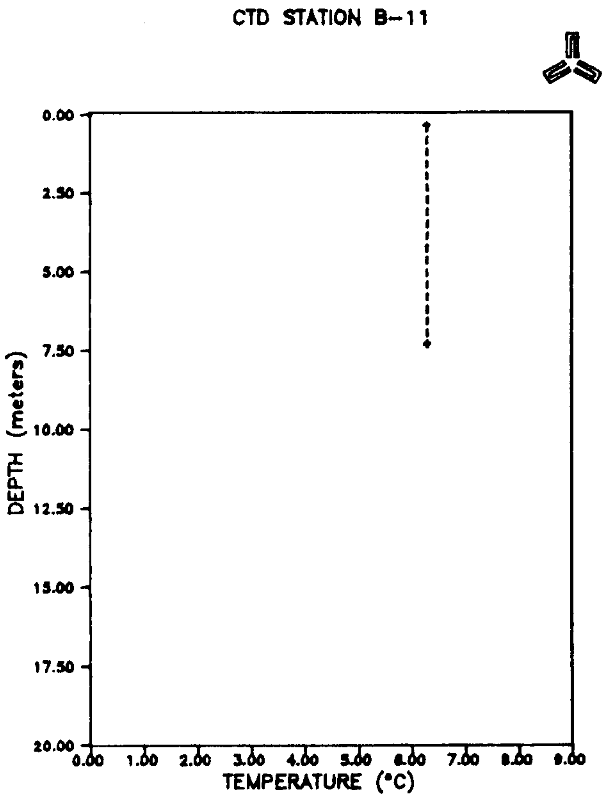
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)


CTD STATION B-11
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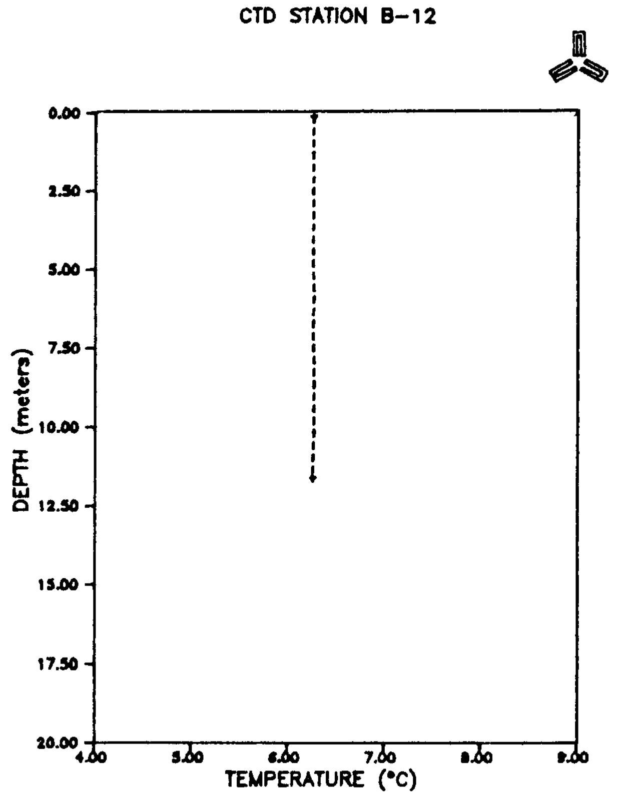
5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)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5.00
7.50
10.00
12.50
15.00
17.50
20.00
DEPTH (meters)
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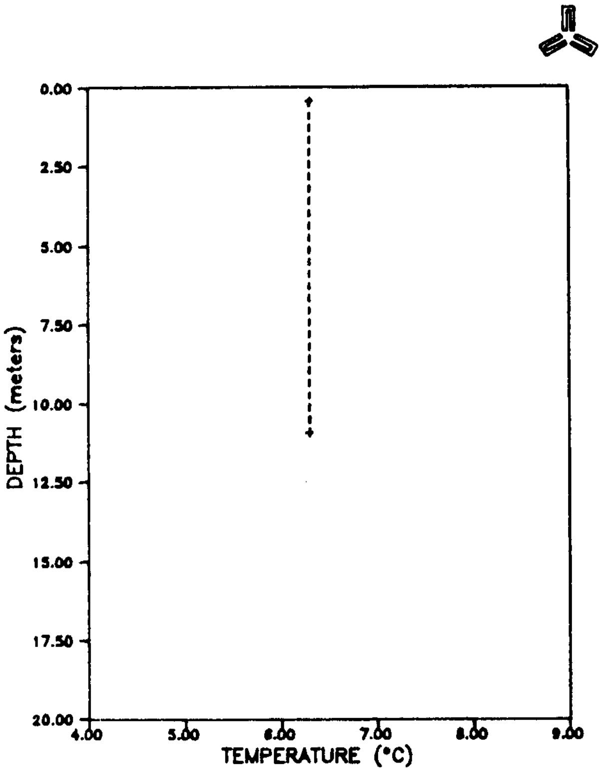
5.00
6.00
7.00
8.00
9.00
TEMPERATURE (°C)

CTD STATION B-13



APPENDIX D

BOTTOM SEDIMENT DATA

Latitude and longitude positions of sediment sample stations occupied during summer and fall 1985 and analyzed by the pipette technique (Dr. G.A. Jones, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts) (see Table 3-12 of report).

Station	Date	Position	
		Latitude	Longitude
R5N, Kobolunuk, north side	7/85	62°04'84"N	163°31'25"W
R5S, Kobolunuk, south side	7/85	62°04'24"N	163°31'96"W
Kobolunuk	9/85	62°04'53"N	163°28'32"W
R13S, Kazhutak	7/85	62°07'75"N	164°57'60"W
R25W, Ten Mile Island	7/85	62°28'68"N	163°55'98"W
R33W, Kwikluak Pass near Lamont	7/85	62°42'01"N	164°11'86"W
R45S, Tin Can Point	7/85	62°35'72"N	164°47'97"W
C-2, South Mouth	9/85	62°35'20"N	164°47'48"W
#4, 7 nm offshore of South Mouth	7/85	62°24'00"N	165°32'20"W
#6, 14 nm offshore of South Mouth	7/85	62°36'87"N	165°32'01"W

Latitude and longitude positions of sediment sample stations occupied during summer and fall 1985 and summer 1986 and analyzed by the nested-sieve technique (Dr. A.S. Naidu, University of Alaska, Fairbanks) (see Table 3-13 of report).

Station	Date	Position	
		Latitude	Longitude
Kobolunuk	9/85	62°04'24"N	163°31'96"W
R5N Kobolunuk	7/85	62°04'84"N	163°31'25"W
R17W Head of Passes	7/85	62°14'40"N	163°56'55"W
R29E near Pektotolik Slough	7/85	62°35'45"N	164°01'41"W
C-2, South Mouth	9/85	62°35'20"N	164°48'15"W
#1, 4 nm offshore of South Mouth	7/85	62°32'50"N	165°09'50"W
Kwikpak	8/86	62°50'34"N	164°06'60"W
Aproka	9/85	62°47'63"N	164°07'28"W
Kawanak	9/85	62°52'66"N	164°07'87"W
Hamilton	8/86	62°53'92"N	163°54'99"W
Kotlik #1	8/86	63°02'27"N	163°39'20"W
Kotlik #2	8/86	63°02'91"N	163°19'53"W

Sediment sample designation:

```
R 13 S
|  |  |_ _ South side of river
|  |_ _ 13th bathymetric transect
|_ _ River
```

Latitude and longitude positions for bottom and suspended sediment samples collected during the first and third field trips (July and September 1985) (see Table 3-14 of report).

Station	Type	Date	Position: Latitude	Position: Longitude
R25W	Bottom	7/85	62°28'68"N	163°55'98"W
R45S	Bottom	7/85	62°35'72"N	164°47'97"W
R45S	Suspended	7/85	62°35'72"N	164°47'97"W
#4	Bottom	7/85	62°24'00"N	165°32'20"W
#6	Bottom	7/85	62°36'87"N	165°32'01"W
Aproka	Bottom	9/85	62°47'63"N	164°07'28"W
Aproka	Suspended	9/85	62°47'63"N	164°07'28"W

Latitude and longitude positions of suspended sediment samples collected during the first field trip (July 1985).

Station	Position Latitude	Position Longitude
R1N	62°01'73"N	163°17'44"W
R1S	62°01'16"W	163°17'69"W
R5N	62°04'83"N	163°31'15"W
R5S	62°04'18"N	163°32'25"W
R9N	62°04'92"N	163°46'94"W
R9S	62°04'69"N	163°46'64"W
R13N	62°08'73"N	163°58'78"W
R13S	62°07'69"N	163°58'63"W
R17W	62°14'55"N	163°56'44"W
R17E	62°14'83"N	163°57'68"W
R21E	62°20'83"N	163°51'29"W
R25W	62°28'68"N	163°55'98"W
R25E	62°29'85"N	163°51'89"W
R29W	62°35'37"N	164°02'90"W
R29E	62°35'45"N	164°01'41"W
R33W	62°42'01"N	164°11'86"W
R33E	62°42'42"N	164°09'26"W
R37E	62°44'36"N	164°26'12"W
R41N	62°41'27"N	164°36'42"W
R41S	62°41'74"N	164°35'19"W
R45N	62°36'46"N	164°48'08"W
R45S	62°35'72"N	164°47'97"W
#1	62°32'20"N	165°06'10"W
#2	62°28'30"N	165°16'00"W
#3	62°25'10"N	165°28'50"W
#4	62°24'00"N	165°33'05"W
#5	62°26'90"N	165°39'50"W
#6	62°36'75"N	165°29'50"W

Latitude and longitude positions for suspended sediment samples used to determine mean values at Kobolunuk, Lamont, Kwikpak, and Hamilton (see Table 3-16 of the report).

Station	Date	Position	
		Longitude	Latitude
Kobolunuk	7/85	62^{O}04'84"N	163^{O}31'25"W
	9/85	----	----
	6/86	62^{O}04'34"N	163^{O}32'59"W
	8/86	62^{O}03'50"N	163^{O}29'40"W
Lamont	7/85	62^{O}42'01"N	164^{O}11'86"W
	9/85	62^{O}42'37"N	164^{O}19'94"W
	6/86	62^{O}05'03"N	163^{O}31'46"W
	8/86	62^{O}42'40"N	164^{O}23'50"W
Kwikpak	7/85	----	----
	9/85	----	----
	6/86	62^{O}48'52"N	164^{O}07'04"W
	8/86	62^{O}50'34"N	164^{O}06'60"W
Hamilton	7/85	----	----
	9/85	62^{O}53'72"N	163^{O}54'56"W
	6/86	62^{O}53'88"N	163^{O}54'89"W
	8/86	62^{O}53'92"N	163^{O}54'99"W

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