Section 2

PHYSICAL OCEANOGRAPHY

by

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2.1 SUMMARY

Wind, current, lagoon, and hydrographic data collected from the NAS during 1984 and 1985 are presented. The wind and current data confirmed the findings of previous investigators, i.e., that the currents are predominantly tidal. The mean flow was toward the north rather than toward the northeast as found by other investigators. This was, however, quite probably due to the short observation period (two to three weeks). Other investigators have observed bursts of off- and onshore flow during isolated periods of similar duration. Izembek Lagoon's effects (localized warming and freshening of surface waters) were limited to those areas immediately adjacent to the lagoon. The. hydrographic data, while generally supporting previous characterizations of a well-mixed coastal domain, suggested that occasionally stratification did occur. This vertical stratification was either local and resulting from terrestrial runoff, or extended over the entire NAS study area and was caused by an intrusion of central domain water (typically two-layer structure). Analysis of the field and historical data, incorporated into a conceptual physical model, indicated that: (1) water in the coastal zone was more likely to be dispersively exchanged with central shelf water than to pass to Cape Seniavin; (2) the typical residence time of a water parcel in the coastal domain was 10 to 20 days; (3) 60 to 80% of the water moving alongshore at Cape Seniavin entered the coastal domain by dispersive exchange across the inner front; and (4) with the exception of localized effects, net precipitation and runoff were insignificant in the water and salt balance of the NAS.

2.2 INTRODUCTION

Physical oceanographic and meteorological studies were conducted on the NAS (Fig. 1.2) between May 1984 and July 1985 as part of the Environmental Characterization and Biological Utilization of the North Aleutian Shelf Study. These studies were designed to augment physical oceanographic investigations previously conducted in the Bering Sea, with particular emphasis on the less studied NAS nearshore zone (i.e., that zone lying shoreward of the 50-m isobath and north of the Alaska Peninsula). These physical oceanographic and meteorological studies provided insight into the nearshore zone physical processes and their relationship to the various chemical and biological findings. Of particular interest, with regard to physical processes, was the importance of lagoons in providing nutrients and/or organic material to the nearshore zone, how the physical processes affect the biotic components of the NAS, and how these physical processes might affect offshore oil development impacts.

2.3 CURRENT STATE OF KNOWLEDGE

The current state of knowledge regarding the physical oceanography of the southeastern Bering Sea is thoroughly summarized in "Circulation, Water Masses, and Fluxes on the Southeastern Bering Sea Shelf" (Coachman 1986). No attempt will be made here to repeat the entire scope of this comprehensive article. Instead, a brief overview of southeastern Bering Sea physical oceanography, information specific to the NAS nearshore zone (coastal domain and inner front), and other information that would aid in the interpretation of our data, will be presented.

The eastern Bering Sea shelf, oriented northwest between the Alaska Peninsula and Cape Navarin and extending approximately 500 km seaward of the Alaskan coastline, comprises nearly one-half of the surface area of the Bering Sea (Fig. 2.1). This shelf is the widest continental shelf outside of the Arctic Ocean. The unique physiography of this shelf is responsible for some of the eastern Bering Sea's more distinctive physical oceanographic features (Coachman 1986). One of these features is the existence of hydrographic domains that are separated by quasi-permanent fronts that result (at least in part) from two sea-floor zones where the slope is two to three times greater than the mean slope of the shelf. These two zones of enhanced bottom slope naturally divide the southeastern shelf into three distinct domains (as shown in Fig. 2.2A): coastal (0-50 m), central (50-100 m), and outer [100-150 m (shelf break)]). According to Coachman (1986) this zonation plays a fundamental role in almost all aspects of the physical regime.

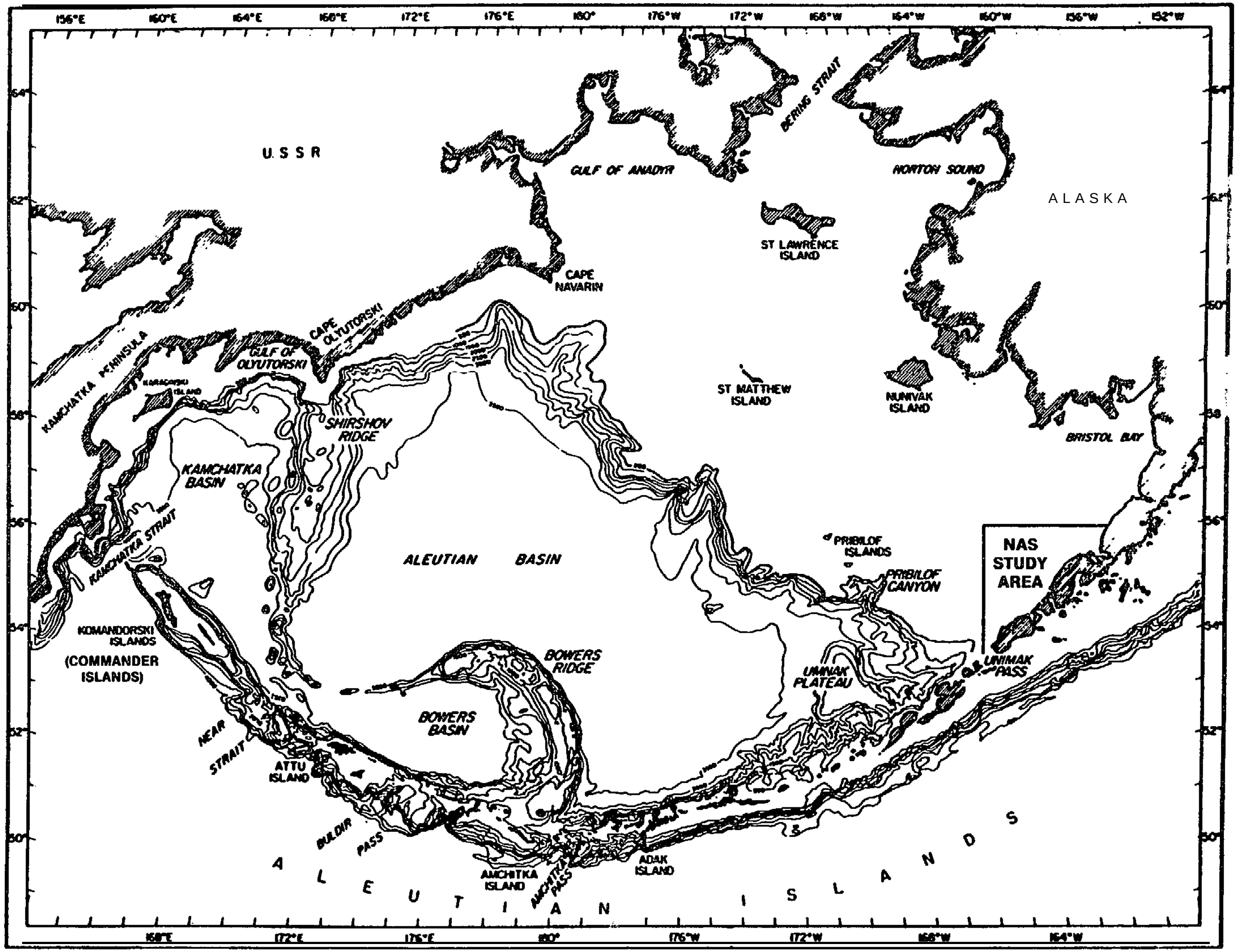
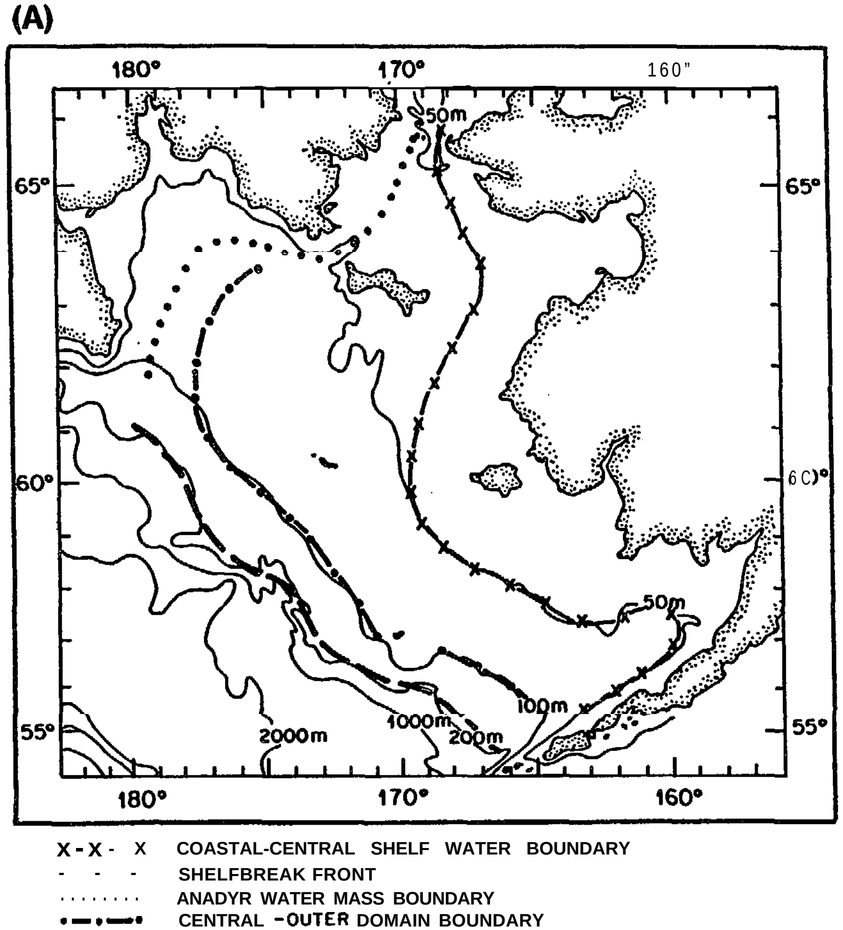


Figure 2.1. The Bering Sea and North Aleutian Shelf **(NAS)** study area (from Hood and Calder, 1981).



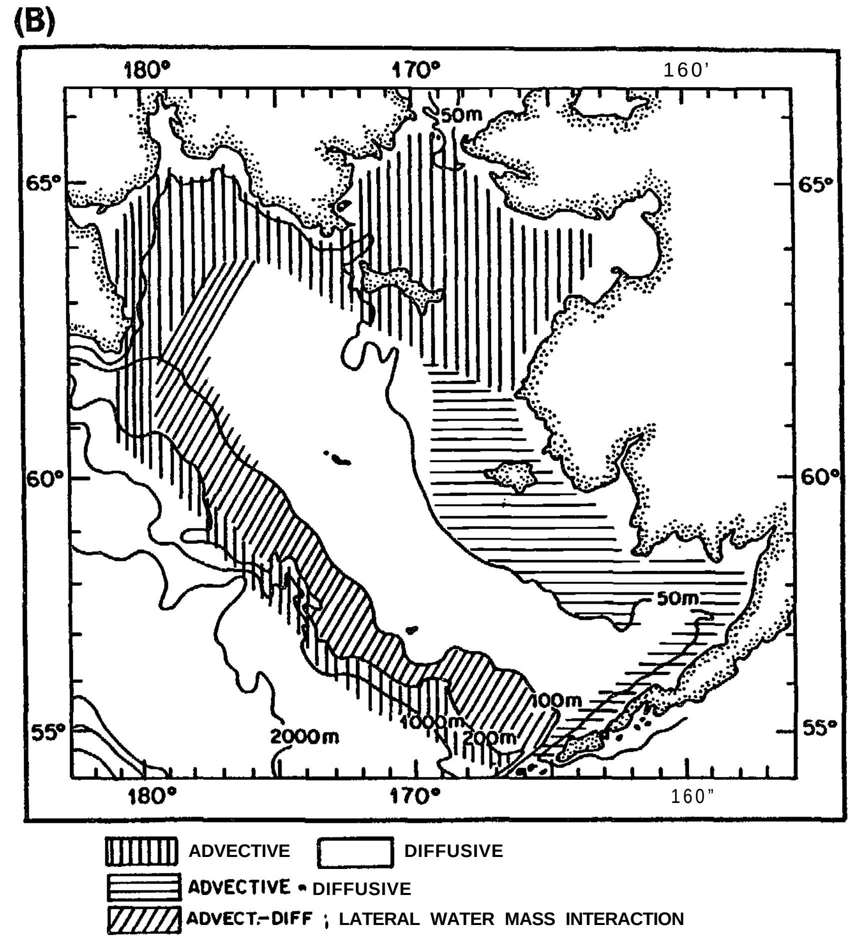


Figure 2.2. Approximate locations of the major hydrographic transition zones (A) and areal arrangement of the four different physical process regimes (B) of the eastern Bering Sea shelf (Coachman, 1986).

Unique physical processes and characteristics are associated with each of the three domains. A summary of these processes and characteristics is presented in Table 2.1 and Figures 2.2B and 2.3; a detailed discussion is presented in Coachman (1986). Our study involves primarily the coastal domain (and inner front) of the PAS, therefore, the following discussion will emphasize the physical processes and characteristics of these regions.

The coastal domain is bounded on the seaward side by the inner front and landward by the coastline and varies in width from 30 km on the NAS to 300 km (as defined by the 50-m isobath) in the vicinity of Nunivak Island. The coastal domain and inner front have been delineated using a variety of schemes. Schumacher et al. (1979) first defined the inner front as a transition zone about 20 km wide approximately following the 50-m isobath across which the two-layered structure of the central domain changes to a nearly homogeneous structure in the shallower coastal domain. These investigators noted, however, that the vertical structure of the inner front did not exist in winter, and during that season the waters were generally well mixed across most of the central domain. More recently, Coachman (1986) has suggested that the Bering Sea fronts may be defined as broad zones, much wider than the sea depth, in which horizontal property gradients are relatively stronger than elsewhere. Coachman (1986) concluded that the front exists year-round and is probably the result of dynamical activity focused near the 50-m isobath.

Seaward of the inner front lies the central domain which, during the summer, may be characterized as having a two-layered structure and dynamic features unique to that domain. The coastal domain lies landward of the inner front. This domain has been characterized as well mixed virtually all year (Coachman 1986, Schumacher and Moen 1983, Kinder and Schumacher 1981a, Ingraham 1981). Nevertheless, Schumacher and Moen (1983) observed vertical stratification within the coastal domain in the vicinity of Port Moller .

Schumacher and Kinder (1983) analyzed the proportional distribution of kinetic energy (KE) within various frequency bands associated with eastern Bering Sea currents. From this analysis they were able to divide the shelf into dynamical regimes that were coincident with the hydrographic domains. Within the coastal and central dynamical regimes,

Table 2.1 Physical process regimes (from Coachman, 1986).

	Outer	Central	Coastal
I. General characterization	**Advective–diffusive;** with lateral water mass interaction	Diffusive	Advective-diffusive
II. Energy			
A. Kinetic	Tidal -85% **Low.** freq. ~ 10%	Tidal -95%	Tidal **>90%** **Low** freq. -5%
B. Turbulent for mixing	upper layer, wind mid-layer, none lower layer, tidal	upper layer, wind lower layer, tidal	wind and tidal
III. Property **fluxes**			
A. Vertical	Enhanced by **finestructure** **(K_v -5 cm^2 s^{-1})**	Summer: suppressed by pycnocline **($K_V \sim 0.1$ cm^2 s^{-1})** Winter: some vertical convection	Greatly enhanced **(large K_V)**
B Horizontal			
1. Along-shelf			
surface layers	Wind, advection	Wind	Wind, advection
lower layers	Advection	Diffusion **($K_H \sim 10^6$ cm^2 s^{-1})**	
2. Cross-shelf			
surface layer	Wind	Wind	Wind; diffusion **(K_H 4.5 x 10^6 cm^2 s^{-1})**
mid-layer	Off-shelf *with* **finestructure**		
lower layer	Diffusion (on-shelf) **($K_H \sim 10$ x 10^6 cm^2 s^{-1})**	Diffusion **($K_H > 10^6$ cm^2 s^{-1})**	
IV. Hydrographic regime			
A. Freshwater	Melting of ice (precipitation)	Melting of ice (precipitation)	Runoff (precipitation)
B. Salt resupply			
upper layer	Up diffusion	Up diffusion	Freezing of ice; advection from near Unimak Pass
lower layers	Shelf basin mixtures; basin water at shelf break	Lateral diffusion across fronts; freezing in **polynyas** (northern area)	
C. Heating			
upper	Surface exchange	Surface exchange	Surface exchange; vertical mixing
lower	Shelf-basin mixtures; basin water at shelf break	Vertical exchange (very slow)	
D. Cooling	Surface exchange	Surface exchange; ice melting	Surface exchange; ice formation

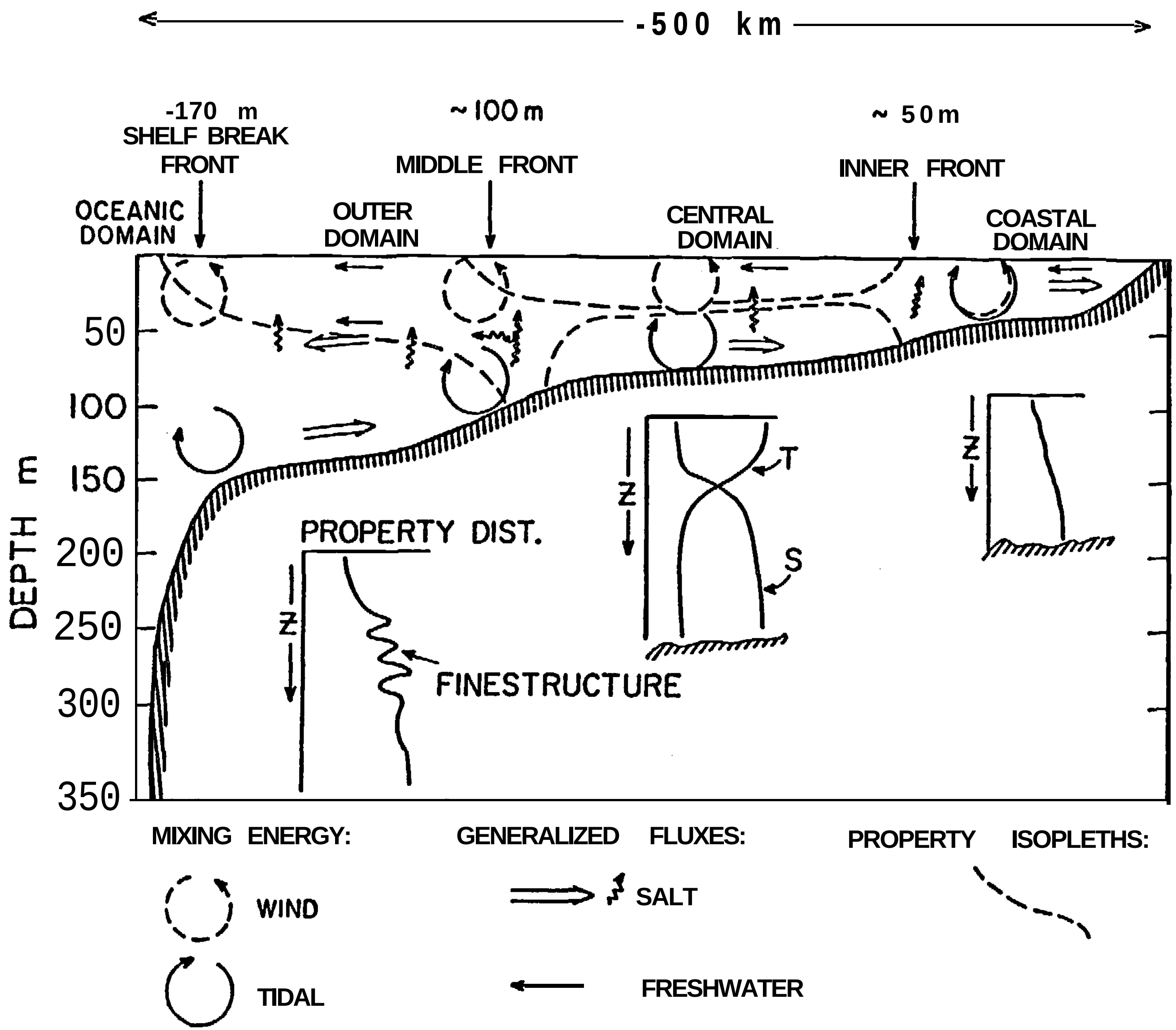


Figure 2.3. Schematic diagram relating vertical energy distributions to the typical horizontal and vertical property distributions and the fronts, and the inferred freshwater and salt fluxes (Coachman, 1988).

95% of the total KE was the result of tidal currents, 3% of the KE was associated with weather events with periods of 2 to 10 days, and the remaining 2% were associated with other fluctuating subtidal components (long period fluctuations).

Although the dynamical regimes coincided with the hydrographic domains (and, therefore, the depth zones), the boundaries between dynamical regimes did not precisely match the boundaries between the hydrographic domains. The inner front which separates the central and coastal hydrographic domains is usually about 15 to 20 km wide: the boundary between the central and coastal dynamical regimes, indicated by the distribution of mean flows (Fig. 2.41, is approximately 30 to 40 km wide (Coachman 1986).

The coastal domain differs from the central domain in that there are longer term mean flows of2 to 5 cm/s parallel to the bathymetry in the coastal domain, whereas the central domain exhibits mean flows of <1 cm/s (Fig. 2.5). The mean flow in the coastal domain is directed northeast into Bristol Bay. The driving forces of this mean flow are: (1) rectification of tidal currents due to interaction with the locally steeper bottom slope near 50-m depth; (2) some baroclinicity due to mass distribution differences between coastal and central shelf waters; (3) some possible rectification along isobaths of storm-generated subtidal components of the flow field; and (4) an influence of a decreasing sea level from Bristol Bay northward to the Bering Strait (Coachman 1986).

Some of the earlier circulation schemes (e.g., Takenouti and Ohtani 1974, Favorite et al. 1976) have some validity, however, tidal diffusion is also an important mechanism for property dispersal in the coastal domain. "A consequence is that freshwater introduced along the land boundary is readily mixed seaward across the domain, but near the inner front it enters the advective regime and is carried northward out of the system without significant amounts egressing seaward into the central domain ..." (Coachman 1986). Therefore, advection and diffusion play a significant role in the coastal domain.

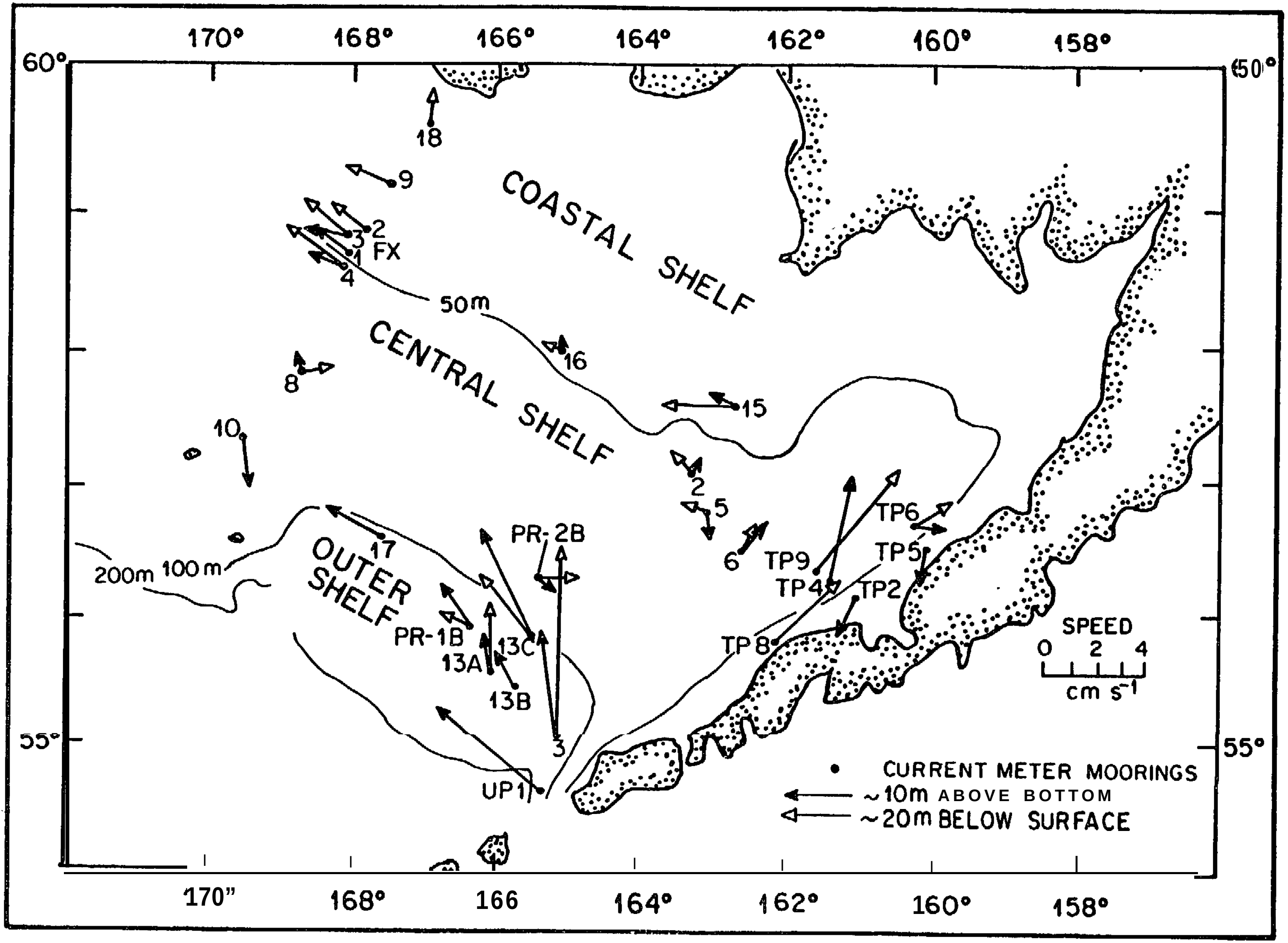


Figure 2.4. Vector-mean flows from long term current data from Schumacher and Kinder (1993).

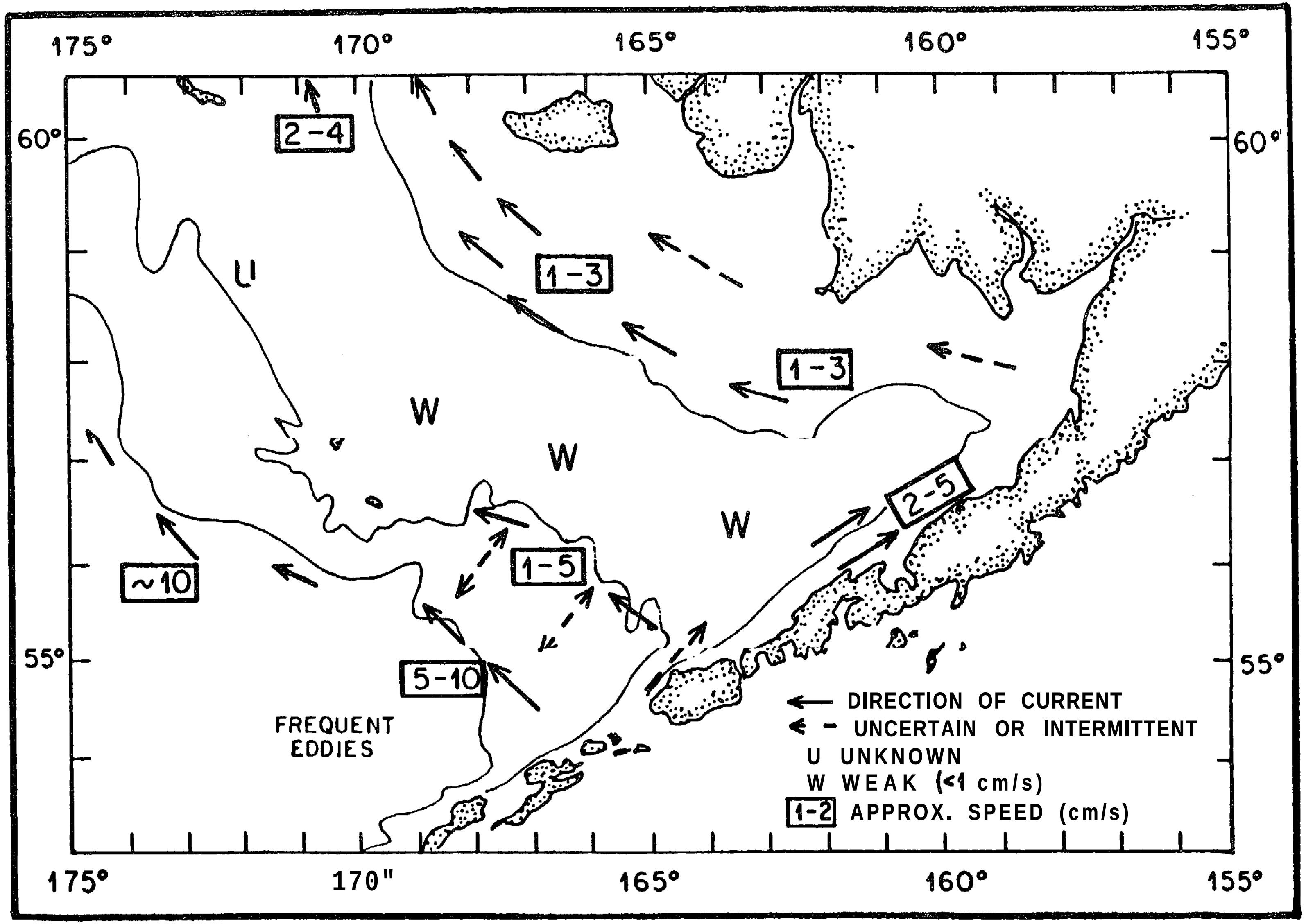


Figure 2.5. Estimated longer-term (mean) circulation (Coachman, 1986).

2.4 STUDY AREA

The physical oceanographic and meteorological investigations of the nearshore NAS included the collection of wind, current, tide, bathymetric, and hydrographic data. The field data were collected from numerous nearshore and onshore locations (Fig. 2.6) using various methods. The collection and analytical methods are discussed in subsection 2.5.

Wind velocity and air temperature were continuously monitored at Grant Point from 11 May through 28 May 1984, and from 15 September through 26 September 1984. Current velocity was continuously measured from 12 May through 24 May 1984, and again from 18 September through 8 October 1984. These data were collected at two stations, one located in 20 m of Water and the other in 50 m of water. Continuous tide measurements were also taken immediately offshore of Grant Point from 11 May to 25 May 1984; a tide gage failure precluded similar measurements near Cape Glazenap. Additionally, a 24-hr inlet survey was conducted on 18 and 19 May 1984, at the south inlet (Cape Glazenap Inlet) of Izembek Lagoon. As a result of the high tidal current velocities and the inadequacy of the boats available, 24-hr surveys were not conducted at the middle and northern inlets. Nevertheless, bathymetric surveys were conducted at all three inlets, and drogue studies were conducted at both the north and south inlets of Izembek Lagoon (Moffet Point and Cape Glazenap).

A series of CTD hydrographic transects (Fig. 2.6) were sampled by NOAA's R/V Miller Freeman during May and September-October 1984, and January, March, April, and July 1985.

2.5 METHODS

Various methods were used to collect and analyze data for the NAS physical characterization. These methods are presented in the following subsections categorized by data types: meteorology, tides, currents, hydrography, lagoon survey data, and existing data.

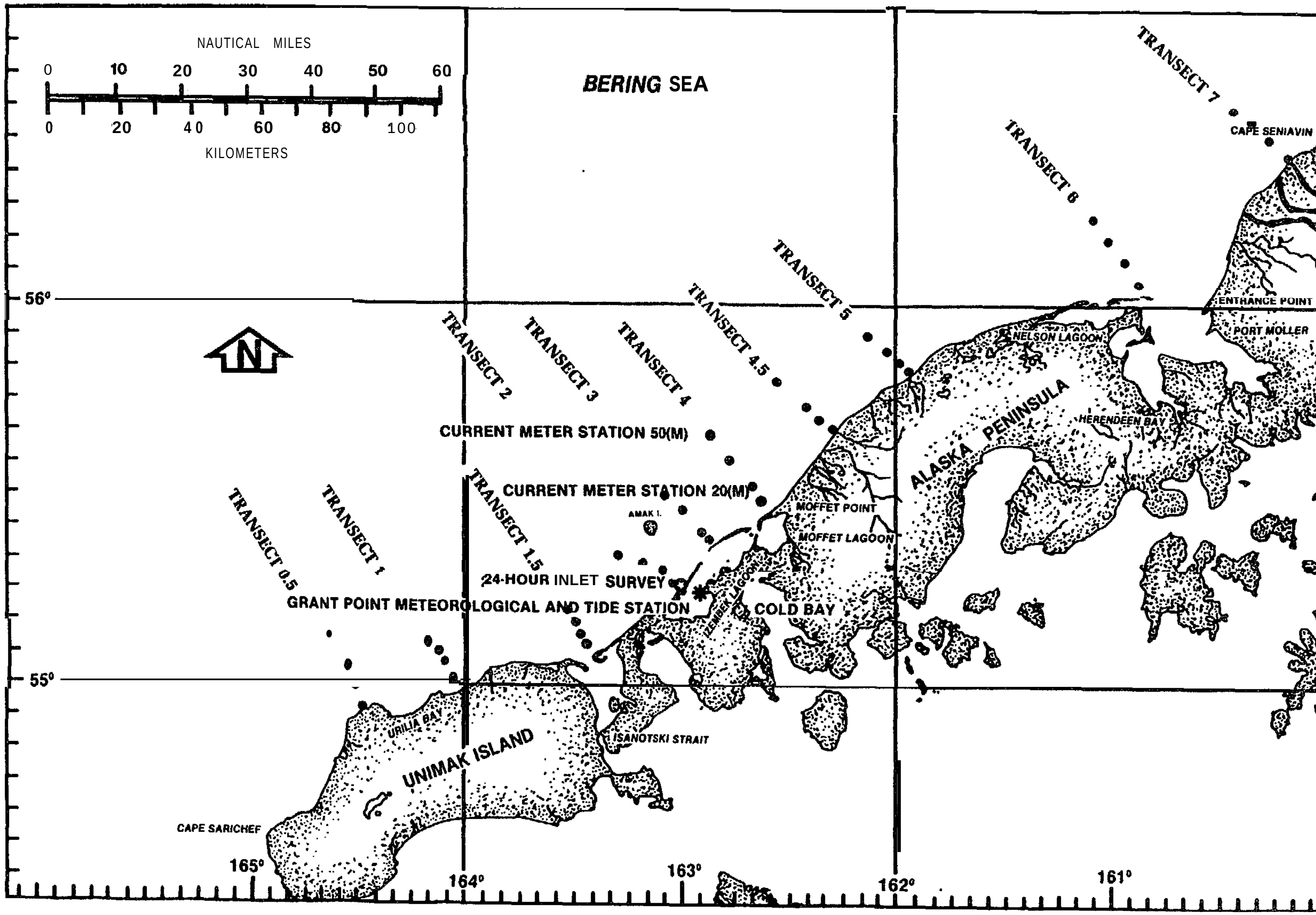


Figure 2.6. Physical investigation station locations.

2.5.1 Meteorology

Meteorological measurements were obtained from a self-contained remote weather station erected approximately 20 m above the sea level on Grant Point in Izembek Lagoon. This station recorded 30-minute average values for air temperature and wind speed and direction. In addition, three-hour averaged barometric pressure, wind speed and direction, and air temperature data were obtained from the National Weather Service (NWS) Cold Bay station. These data were then tabulated and time history plots were prepared. The barometric pressure measurements from May 1984 were used to correct tide gage pressure records for atmospheric pressure fluctuations.

2.5.2 Tides

Tides were measured near Grant Point with a Sea Data TDR-1 pressure gage. Pressure measurements were recorded internally on magnetic tape at 5-minute intervals. Converting pressure data from the tide gage to depth of water was performed in two steps. First, the barometric pressure obtained from the NWS Cold Bay station was subtracted from the total pressure measured by the tide gage. Second, the depth of water over the pressure gage was calculated from an assumed constant density calculated from salinity and temperature measurements in Izembek Lagoon.

The water depths calculated from pressure measurements were referenced to mean lower low water (MLLW) by comparing the difference between measured depths and the corresponding predicted water depths from the NOAA Tide Tables for Grant Point. The mean difference between corresponding observed heights and predicted heights was assumed to be the depth of the tide gage below MLLW. That number was then subtracted from all measured depths to provide water levels relative to MLLW.

Time history plots of measured and predicted tides were produced, and the differences between predicted and observed heights and times of occurrence were calculated and plotted for comparison.

2.5.3 Currents

Current speed and direction were continuously measured at two stations located on a line normal to the shore at Moffet Point at nominal depths of 20 and 50 m. A taut-wire current meter mooring was deployed at each station with a current meter positioned 5 m below the surface and 2 m above the bottom. Two types of current meter were used: the ENDECO Model 105 current meter (CM105) and the EG & G Model CT/3 current meter.

The CM105 is an axial-flow, ducted-impeller instrument specifically designed for use in wave zones. These instruments were calibrated by the manufacturer prior to deployment. The threshold speeds were determined to be between 2 and 3 cm/s; the accuracy of speed measurement was within ±0.6 cm/s of the true speed; and the current direction accuracy was ±5° at threshold speed, ±3.6° above threshold speed, and resolvable to ±1.0°. This instrument recorded 30-minute average values of current speed and direction on 16-mm film. These films were digitized and transferred to the computer for analysis.

The CT/3 is an electromagnetic current meter with an internal compass. Digital current speed and direction data are recorded on magnetic tape cassettes. The CT/3 is capable of measuring current speeds from 3 to 300 cm/s with an accuracy of ±1.5 cm/s. Current direction, measured from 0° to 359° is accurate to ±5°. The data recorded on the magnetic tape are transferred to the computer and analyzed.

The current meter data were presented as time history plots, joint frequency tables (JFTs) of current speed and direction, and progressive vector diagrams (PVDs).

Drogue studies (discussed in subsection 2.5.5) were conducted at two of the three entrances to Izembek Lagoon to augment continuous current meter data and evaluate trajectories of suspended materials issuing from the lagoon.

2.5.4 Hydrography

Hydrographic measurements were made along a series of cross-shelf transects extending from approximately the 20-m to beyond the 50-m isobath. These measurements, consisting of conductivity and temperature versus depth, were obtained with the WV Miller Freeman's **Plessey/Grundy** Model 9041 CTD. These measurements were made approximately five times per second and recorded on magnetic tape. The values recorded by the CTD were checked against salinity samples obtained from rosette-mounted 5-L Niskin bottles and temperatures obtained from deep sea reversing thermometers mounted on these bottles.

The CTD data tape and calibration and quality control information were sent to the University of Washington for reduction. The resulting product was a tabulation of temperature, salinity, sigma-t, and geopotential anomaly averaged over l-m intervals. These reduced data were then presented as vertical profile plots of temperature, salinity, and sigma-t. Hydrographic data for the entire study area that were collected within approximately 48 hours were presented as vertical and horizontal contour plots of temperature and salinity.

2.5.5 Lagoon Surveys

Several data collection and analytical methods were used to identify and quantify the effects lagoons might have on the NAS nearshore environment. Rather than attempt to study all of the lagoons or embayments along the Alaska Peninsula in a cursory fashion, efforts concentrated on a single important lagoon, Izembek Lagoon. The methods used to gain insight into the processes and influence of Izembek Lagoon included examination of remote sensing imagery, bathymetric surveys of the lagoon's three entrances, a 24-hour entrance survey of currents and temperature, and current drogue studies conducted at two entrances to Izembek Lagoon.

2.5.5.1 Remote Sensing

Recent information on the morphology and area1 extent of Izembek Lagoon was obtained from remote sensing imagery. Satellite imagery (e.g., LANDSAT) was not used because the optimum 80-m resolution was considered inadequate for the purposes of this study. The National Cartographic Information Center (NCIC) was contacted, and a computer search of aerial (aircraft) imagery was instigated. The photographs obtained from NCIC were used to construct photomosaics from which information such as entrance dimensions and areal extent of the lagoon and its drainage channels was determined.

2.5.5.2 Bathymetry

Three transects were run in alternate directions at the north and south entrances (Moffet Point and Cape Glazenap), and two transects were run at the middle entrance. Depth measurements were obtained with a Raytheon 719B Fathometer. During the survey the boat speed and heading were maintained as constant as possible, given the varying current speeds and obstructing shoal areas.

The water depths recorded on the fathometer paper chart were digitized and input to the computer for reduction and analysis. The tides measured at Grant Point were used to correct the depths to MLLW. The widths of the entrances were obtained from the aerial photographs. From these data, cross sections referenced to MLLW were prepared and the cross-sectional area at different stages of the tide were determined.

2.5.5.3 Twenty-four Hour Inlet Survey

The information from the bathymetric surveys was used to determine the optimum location for the 24-hour current and temperature entrance survey. Because l-knot tidal currents rendered the available Zodiacs inadequate, only a single survey at the south entrance was completed.

During the survey, a boat was anchored for 24 hours at a location in the lagoon entrance deemed most representative of mean flow conditions (based on bathymetry data). An ENDECO Model 110 remote-reading ducted-impeller current meter (capable of measuring current speed and direction, temperature, and depth) was lowered periodically to discrete depths and the data manually recorded. These data were then plotted as a series of vertical profile plots. From these data and from estimates of the tidal prism (obtained from tide data and aerial imagery), tidal flushing rates were calculated for the Cape Glazenap entrance and extrapolated to the middle and northern (Moffet Point) entrances.

2.5.5.4 Drogue Studies

Current drogue studies were conducted in the nearshore water off Izembek Lagoon to evaluate the trajectories of suspended materials leaving the lagoon. Six window-shade drogues were released concurrently from each of the north and south lagoon entrances at hourly intervals during ebb tide. Each drogue consisted of a marker flag, a buoy with identification number, and a polyethylene sail (or window shade). The sail measured 1 m to a side and was suspended directly below the buoy (i.e., there was no tether), therefore the movement of the drogue represented the movement of the top 1.5 m of water. The cross-sectional area of the buoy was less than 10% of the area of the sail to ensure that the movement of the drogue was representative of the water and not the result of the wind acting on the drogue. The decision was made to suspend the sail directly below the buoy, thereby measuring the movement of the top 1.5 m of water, rather than using a tether to observe water movement at deeper depths. This decision was made because of the high probability of the buoy stranding shortly after deployment at the entrances to Izembek Lagoon. The drogues were then tracked for approximately two days with an aircraft equipped with a LORAN C navigation system. This navigation system was checked against known positions at the start of each flight. The drogue position data were hand plotted and velocities were calculated.

2.5.6 Existing Data

In addition to the remote sensing imagery obtained from NCIC and meteorological data from the NWS, other sources of existing data were investigated. The most valuable sources of information were: Dr. J.D. Schumacher of NOAA, who provided published and unpublished information; the very comprehensive "Circulation, Water Masses, and Fluxes on the Southeastern Bering Sea Shelf" (Coachman 1986); and "The Eastern Bering Sea Shelf: Oceanography and Resource@ (Hood and Calder 1981) .

2.6 RESULTS AND DISCUSSION

Meteorological, tide, current, and hydrographic data were collected as described in previous sections to better understand the physical processes of the nearshore NAS. In addition, the effects lagoons have *on* the nearshore environment *were* also studied. The results of these studies are presented and discussed in the following subsections.

2.6 .1 Meteorology

2.6.1.1 May 1984 Results

The winds were offshore from the southeast or onshore from the west-northwest approximately 17% of the time from each direction. These winds tended to persist for several days. For example, winds were primarily offshore from 12 to 16 May, and onshore from 18 to 23 May. The strongest winds were offshore from the east-southeast with speeds up to 18 meters per second (m/s>. Winds were greater than 5 m/s 60% of the time. The most common speeds ranged between 5 and 7.5 m/s (34%). The air temperature at Grant Point ranged from 0° to 9°C, with a typical diurnal variation of 5°C. Time history plots of wind speed and direction, air temperature and barometric pressure are presented in an appendix (see Section 2.11).

2.6.1.2 September 1984 Results

Winds measured during this period were more frequently onshore with about 26% of the total from the north or north-northwest. The maximum speeds ranged between 15 and 17.5 m/s and were not confined to a particular direction. Winds were greater than 5 m/s 84% of the time with the most common speed range between 10 and 12.5 m/s (24.3%). Air temperatures averaged about 10°C, ranging from approximately 7° to 13°C. Time history plots of wind speed and direction, air temperature, and barometric pressure are presented in an appendix (see Section 2.11).

2.6.1.3 Comparison with Historical Data

Selected meteorological parameters measured at the Cold Bay NWS station during May, September, and October 1984 were compared with Cold Bay historical means for those same months (Table 2.2). This comparison indicates that May 1984 was less windy (6.6 m/s versus 7.2 m/s), drier (3.0 cm versus 6.3 cm), and cooler (3.3°C versus 4.2°C) than average, based on 30 years of data. September was more windy (7.6 m/s versus 7.2 m/s), drier (7.3 cm versus 9.6 cm), and warmer (9.9°C versus 8.4°C). October was slightly drier and warmer than average. The local climatological data for 1984 (LCDs) are presented in an appendix (see Section 2.11).

2.6.2 Tides

The predicted tide and the difference between the predicted and the tide measured in May 1984 at Grant Point are presented in Figure 2.7, The measured tide heights ranged from approximately 0.3 to 0.5 m higher than those predicted. Higher-high water was generally higher than predicted, although the other stages were not consistently high or low.

The times of the high and low water differed from approximately 1.3 hours before to 1 hour after the predicted time. The occurrence of lower-high water was generally later than that predicted (up to 1 hour) and the occurrence of higher-low water was generally earlier than predicted (up to 1.3 hours). Higher-high water and lower-low water usually occurred within 30 minutes of the predicted time with higher-high earlier and lower-low later than predicted.

2.6.3 Currents

Measurements of current speed and direction were collected at the 20- and 50-m isobaths seaward of Moffet Point. Both near-surface (meters 20S and 50S) and near-bottom (20B and 50B) measurements were obtained for 12 through 24 May and 18 September through 8 October 1984, with the exception of 20B in September-October, when a failure of one current meter resulted in no data.

Table 2.2. Comparison of selected Cold Bay, Alaska meteorological parameters with historical mean values* for May, September, and October.

Meteorological Parameter	May 1984	May Historical	September 1984	September Historical	October 1984	October Historical
Mean Wind Speed (m/s)	6.6	7.2	7.6	7.2	7.6	7.5
Prevailing Wind Direction	—	SSE	—	SSE	—	WSW
Resultant Wind Speed (m/s)	1.0	—	2.1	—	2.5	—
Resultant Wind Direction (°T)	304	—	154	—	011	—
Barometric Pressure (mb)	1008.5	1003.3	Mol.7	1004.2	1003.1	999.7
Precipitation (cm)	3.0	6.3	7.3	9.6	9.2	9.6
Air Temperature (°C)	3.3	4.2	9.8	8.4	4.9	4.2

*Based on 30 years of data.

Source: NCDC, 1984.

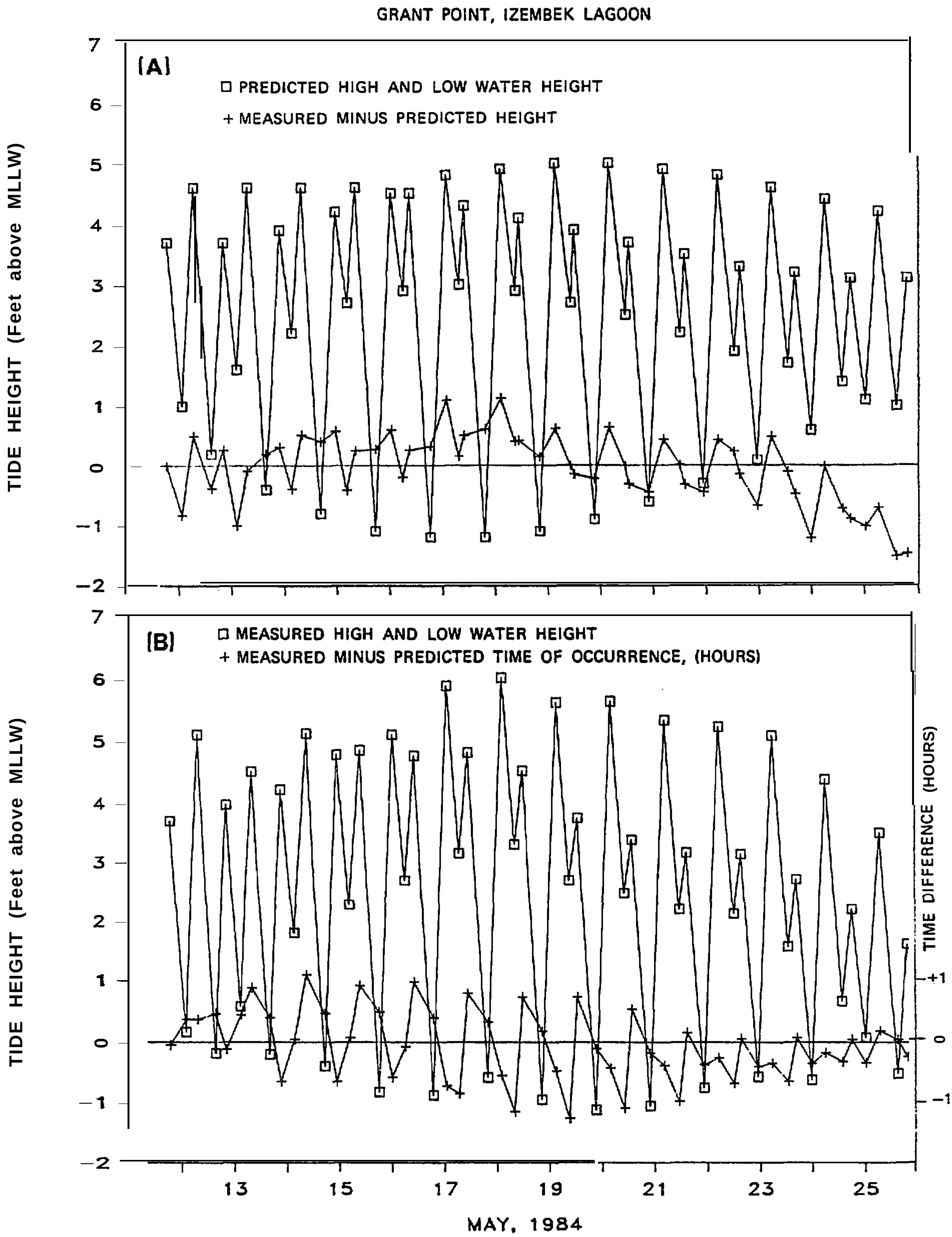


Figure 2.7. Predicted (A) and measured (B) tide heights for Grant Point during May 1984. Difference between measured and predicted tidal heights (A) and time of occurrence (B) are also presented.

2.6.3.1 May 1984 Results

The semidiurnal frequency and *nearly* rectilinear motion of the NAS currents observed in May 1984 corroborate the conclusions of previous investigators (Coachman 1986, Schumacher and Moen 1983, Kinder and Schumacher 1981b) that tidal currents are predominant on the southeastern Bering Sea shelf. The currents generally set to the northeast and southwest (along the shelf and parallel to the depth contours). There was, however, some variability in current direction and speed between the 20-m and 50-m stations and between the near-surface (5 m below the surface) and near-bottom (2 m above the bottom) currents.

The near-surface currents at the 20-m station set 075°T (relative to true north) and 270°T on the flood tide and ebb tide, respectively. The near-surface average speed was 21 cm/s; the near-bottom currents set 55°T and 255°T with an average speed of 16 cm/s. The current speeds at the 20-m station exceeded 60 cm/s at the surface and 45 cm/s at the bottom less than 1% of the time. A small offshore component was evident at both levels.

Progressive vector diagrams (PVDs) of the near-surface currents (Fig. 2.8) confirmed the semidiurnal tidal current motion and revealed a net transport to the north at 2.9 cm/s. This transport suggests that near-surface water on the shelf can have a significant offshore transport component over periods of one to two weeks. Conversely, near-bottom transport was definitely along the shelf toward the southwest at 1.4 cm/s. The calculated net current of 1.4 cm/s is deceptive: during the first two days the net current speed was 3.5 times greater, then decreased to nearly 0 cm/s for the remaining 10 days. The winds during the first two days were from the southeast in excess of 15 m/s eventually decreasing to below 10 m/s from the northwest. This brief record would suggest that local winds have very little direct effect on NAS nearshore currents.

The current speeds were somewhat greater at the 50-m station with average values of 25 cm/s near the surface (setting 55°T and 280°T on the flood and ebb tide, respectively) and 17 cm/s near the bottom (setting 55° and 250°T). The near-surface current speeds exceeded 75 cm/s less than 1% of the time; the near-bottom speeds exceeded 40 cm/s less than 1%. of the

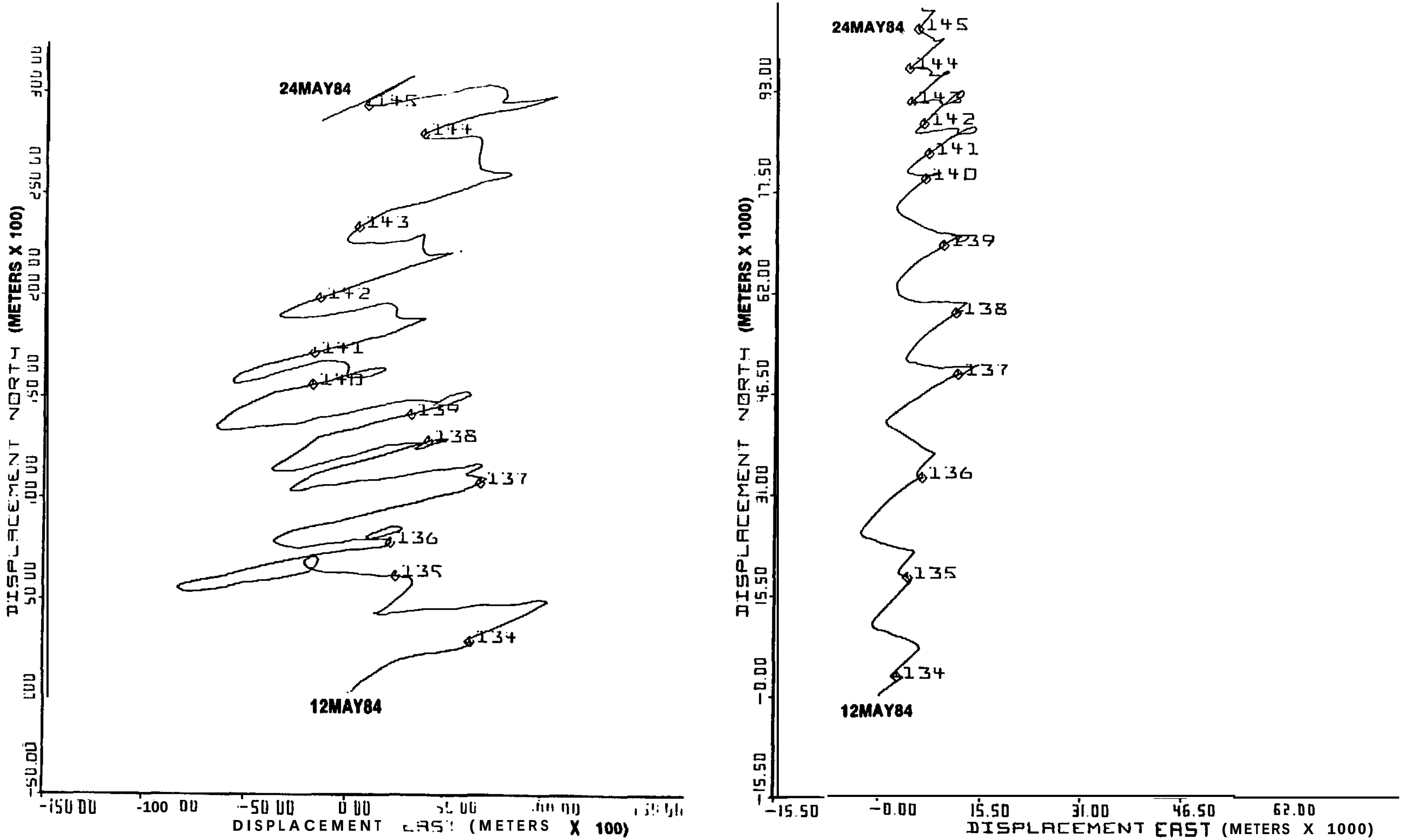


Figure 2.8. Progressive vector plots of current velocity at Station **20S** and **50S (5m** below surface).

time. Like the 20-m station, currents at the 50-m station revealed an offshore component.

Near-surface net transport at the 50-m station was, like the 20-m station, to the north (Fig. 2.8). **The net current** speed, however, was 3.5 times greater at the 50-m station (10.1 cm/s). There was virtually no near-bottom net transport; similar to the 20-m station, except that there was no transport even during the initial two days. The predominance of the tidal currents was apparent and, again, there was no obvious direct correlation of the winds and currents.

2.6.3.2 September-October 1984 Results

No near--bottom current data were recovered for the 20-m station during September and October. The near-surface currents set 55°T and 280°T (with a definite offshore component) at an average speed of 22 cm/s. The current speeds exceeded 70 cm/s less than 1% of the time. These currents were similar to those measured in May 1984 at the 20-m station.

The major difference at the 20-m station between the May and September-October period was revealed in the PVDs (Fig. 2.9). The net transport, although still to the north, was 4.4 times greater in September-October (12.8 cm/s) than in May. This was the highest net current speed measured at any of the locations during this study. This record was also unique in that during the last three days the tidal influence was completely masked and on the second to the last day the net transport increased to 46 cm/s to the north. Winds during this period were from the north at about 13 m/s. Winds with speeds in excess of 15 m/s during September had no measurable effect on the currents. These two facts suggest, once again, that the winds have a minimal direct effect on the NAS currents.

The currents measured during September-October, 1984 at the 50-m station differed from the May currents in that the directions had changed by 10° to 20° and the current speeds were somewhat slower in September-October. The near-surface currents set 65°T and 245°T with an average speed of 20 cm/s; the near-bottom currents set 75°T and 225°T with an average speed of 12 cm/s. Tidal currents were, once again, predominant.

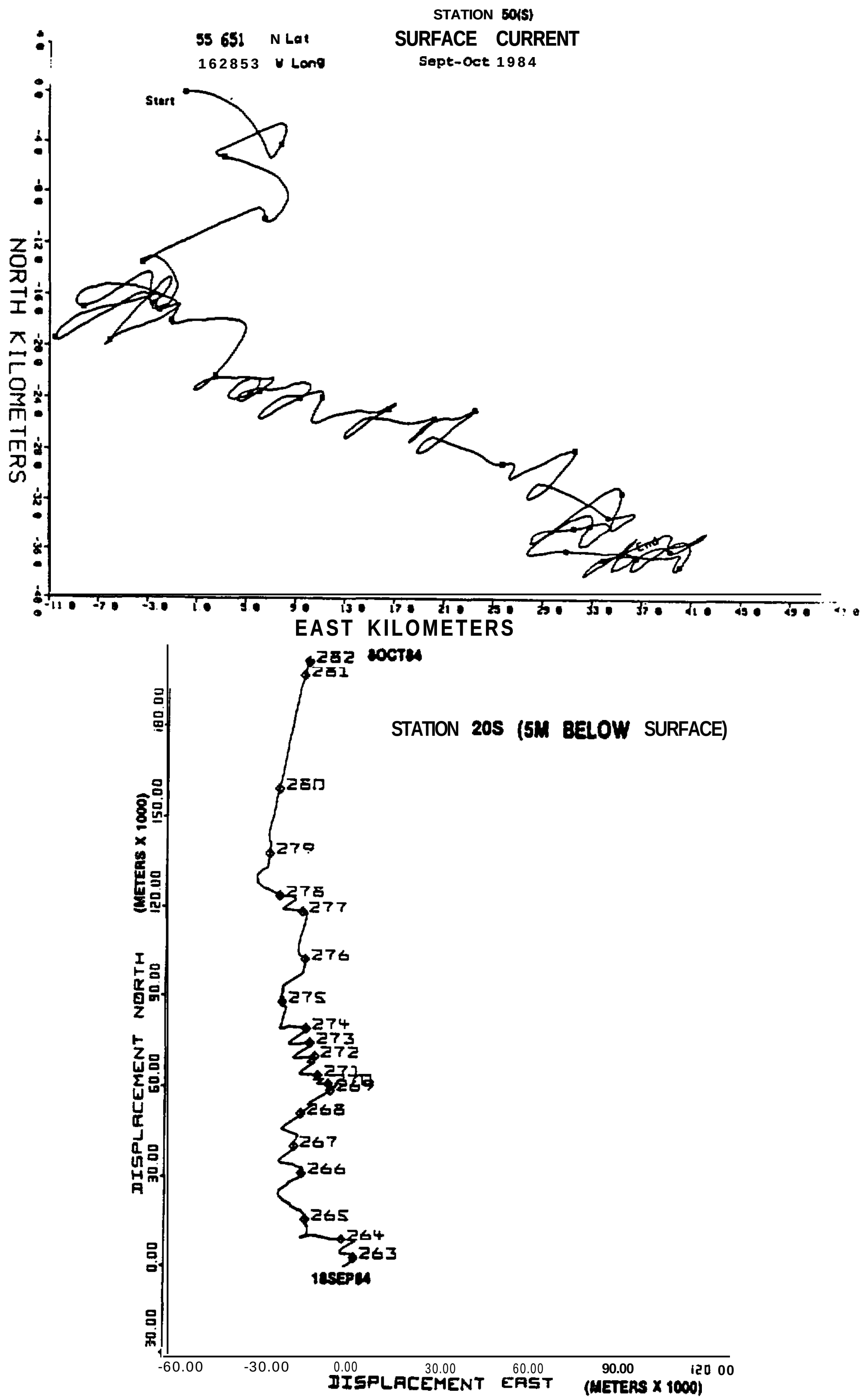


Figure 2.9. Progressive vector plots of Current velocity at Stations 20S and 50S (5m below surface).

Net currents at the 50-m station differed significantly from the 20-m station during September-October and from both the 20- and 50-m stations during May 1984. It has been suggested (Ozturgut 1987, pers. comm.) that the difference in net transport (the PVDs presented in Fig. 2.9) between the 20- and 50-m stations occurs because the 50-m mooring may have been within the inner front during this period. The cross-shelf vertical temperature distribution along Transect 4 (Fig. 2.11) and alongshore vertical temperature distribution (Fig. 2.12) may support this suggestion. It is apparent in vertical temperature distribution that Transect 4 lies in a transition zone between two-layered structure (indicative of the middle domain) and vertically well mixed water (indicative of the coastal domain). The near-surface net currents set to the southeast at 3.0 cm/s (Fig. 2.9); the near-bottom net currents to the east-northeast at 1.0 cm/s. This suggests a slight onshore transport 'at the surface and bottom at the 50-m station. At the other stations and all other times during this study, either offshore or alongshore net transport was observed.

Although both the May and September-October 1984 *net* current data frequently reveal a definite offshore component, this does not necessarily conflict with the findings of previous investigators. Schumacher and Moen (1983) reported that the long-term net transport was alongshore to the northeast, nevertheless, their current records also revealed short--term offshore transport for periods of two to three weeks. Generally, these data are consistent with previous findings that, although there is some cross-shelf transport, the net transport is alongshore toward the northeast in the NAS nearshore coastal zone.

2.6.4 Hydrography

Cruises to collect hydrographic and chemical oceanographic data were conducted during May and September-October, 1984 and January, April, May, and July, 1985. The results from each of these cruises are discussed individually in the following subsections. Additional data, including maps of temperature and salinity distribution, vertical profile plots, and tabulated data are presented in an appendix (see Section 2.11).

2.6.4.1 May 1984

The near-surface temperatures ranged between 2.4° and 4.5°C and generally decreased offshore; however, a minimum did occur at stations located between the 30- and 40-m isobaths suggesting the possible intrusion **and** upwelling of central domain water. Vertical stratification of the water was evident in May 1984 temperature distribution. This stratification occurred in those waters adjacent to Izembek Lagoon and Port Moller where the near-surface temperatures were somewhat warmer. Near-bottom temperatures ranged from 2.0° to 3.9°C and decreased with distance offshore. No warming in the vicinity of the lagoons or cooling near the 30- to 40-m isobaths were evident in these near-bottom temperatures.

The near-surface salinities during May 1984 ranged between 30.4 and 31.8 °/oo and generally increased with distance offshore; the near-bottom salinities also increased with distance offshore and ranged from 31.2 to 31.9 °/oo. As a result of runoff, the lowest near-surface salinity values (and warmest water) were measured near Cape Senlavin, Moffet Point, and those waters adjacent to Izembek Lagoon. These salinity minima were associated with nearshore vertical stratification evident in the salinity distribution (Fig. 2.10) and concomitant with the temperature maxima. This figure also reinforces the evidence for intrusion of central domain water into the coastal domain.

2.6.4.2 September-October 1984

The near-surface temperatures ranged from 9.1° to 10.5°C and decreased with distance off shore. The greatest temperature difference (approximately 1.1°C) was observed offshore of Cape Senlavin, located at the northeast periphery of the study area. Toward the southwest end of the study area the temperature difference was only about 0.4°C. Generally, the near-surface temperature increased toward the northeast. Because the water was well mixed vertically (Fig. 2.11), the same trends described for the near-surface temperatures were also observed in the near-bottom temperature distribution The outermost station located on Transect 7 revealed a two-layered stratification typical of central domain

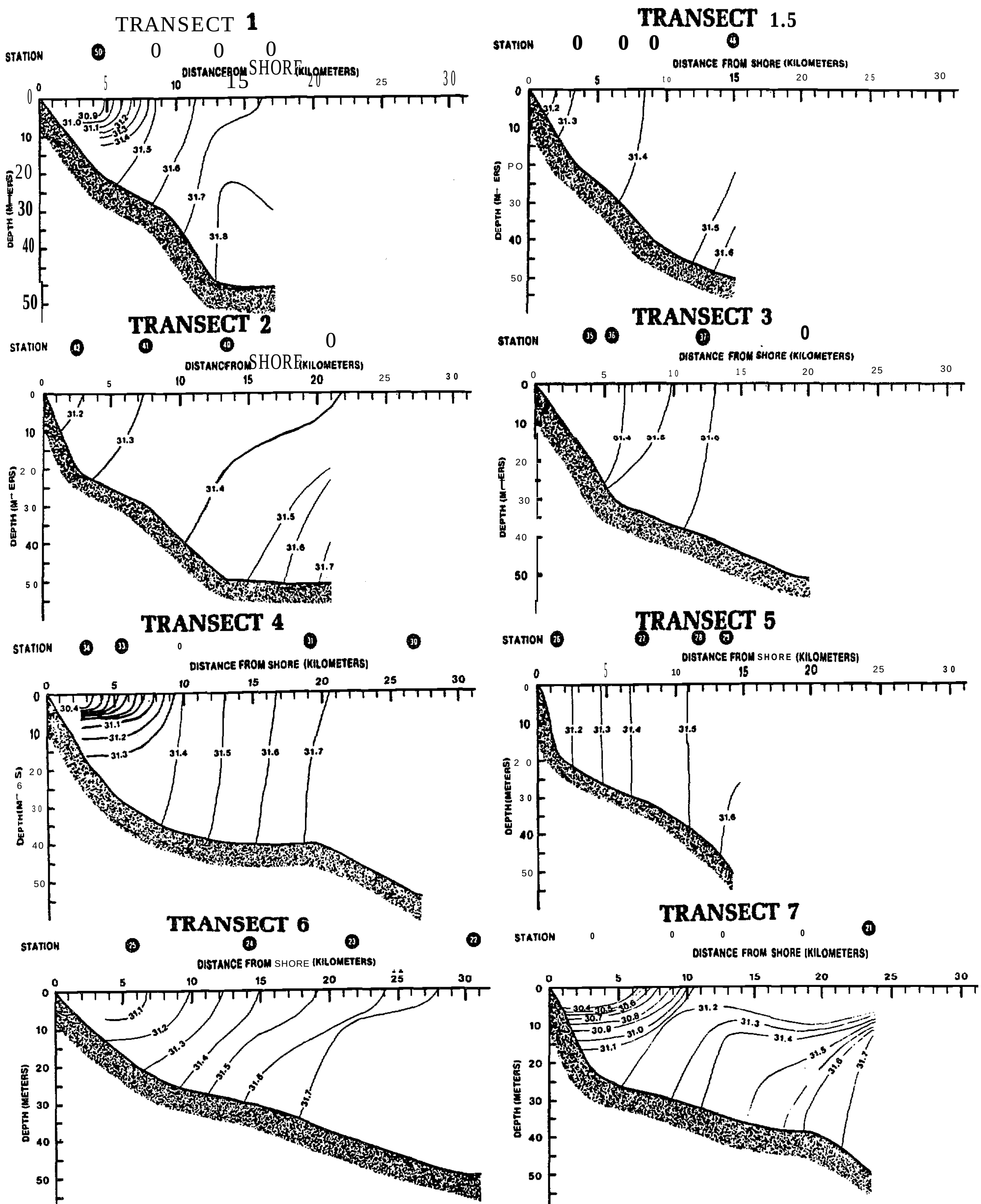


Figure 2.10. Vertical salinity contours for May 1984.

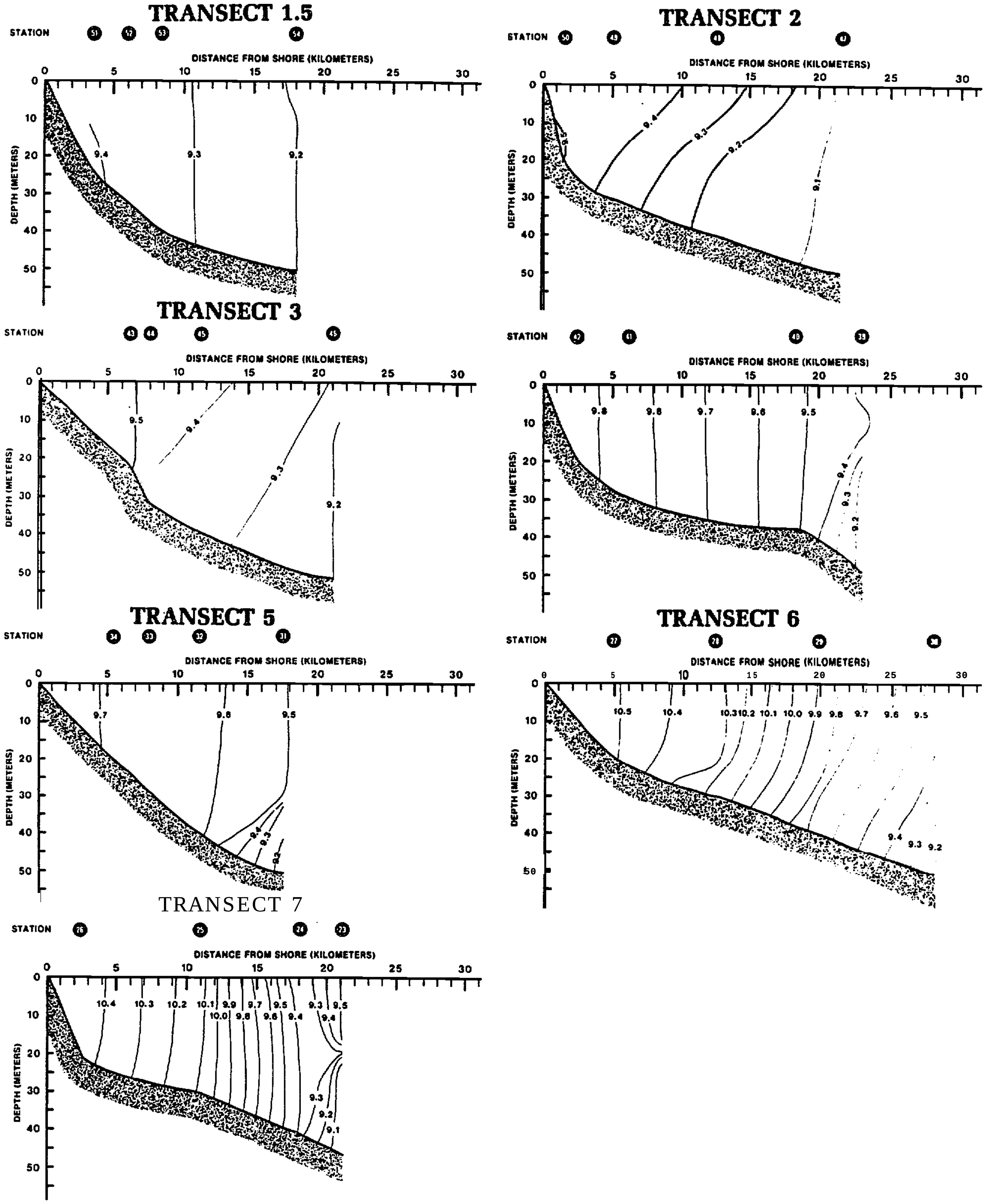


Figure 2.11. Vertical temperature contours for October 1984.

water (Kinder and Schumacher 1981a). This transition from the coastal domain across the inner front to the central domain is obvious in the vertical distribution of temperature along the 50-m isobath (Fig. 2.12). The inner front along Transect 7 was only 5 km wide.

The salinity distribution during September-October, like the temperature distribution, reflected the fact that the water was well mixed. The near-surface and near-bottom salinities ranged from 30.9 to 31.9 $^o/_{oo}$ and increased with distance offshore. The lowest salinities were observed in the waters adjacent to Port Moller. There was no typical two-layered structure indicative of the central domain evident in the vertical salinity distribution along Transect 7 or any other transect. This suggests that the central and coastal domain waters during this time differed only in temperature and structure.

2.6.4.3 January 1985

Surface temperature and bottom temperature generally increased with distance offshore during January. The surface temperature ranged from 2.5° to 5.2°C; bottom temperature from 3.0° to 5.2°C. The warmer temperatures were measured. at the southwest periphery of the study area (Unimak Island). The distribution of temperature indicated that the water was mixed vertically at nearly every transect.

A notable exception to this generalization occurred along Transect 6 where a near-bottom intrusion of central domain water was evident in both the temperature (Fig. 2.13) and salinity distribution. At all other transects the salinity distribution, like the temperature distribution, indicated that the water *was* well mixed vertically. Near-surface and near-bottom salinity increased with distance offshore with ranges of 30.6 to 31.8 $^o/_{oo}$ and 30.9 to 32.4 $^o/_{oo}$, respectively. The salinity decreased *from* southwest to northeast alongshore; the waters adjacent to Port Moller were the freshest (approximately 0.5 $^o/_{oo}$ less than the surrounding water).

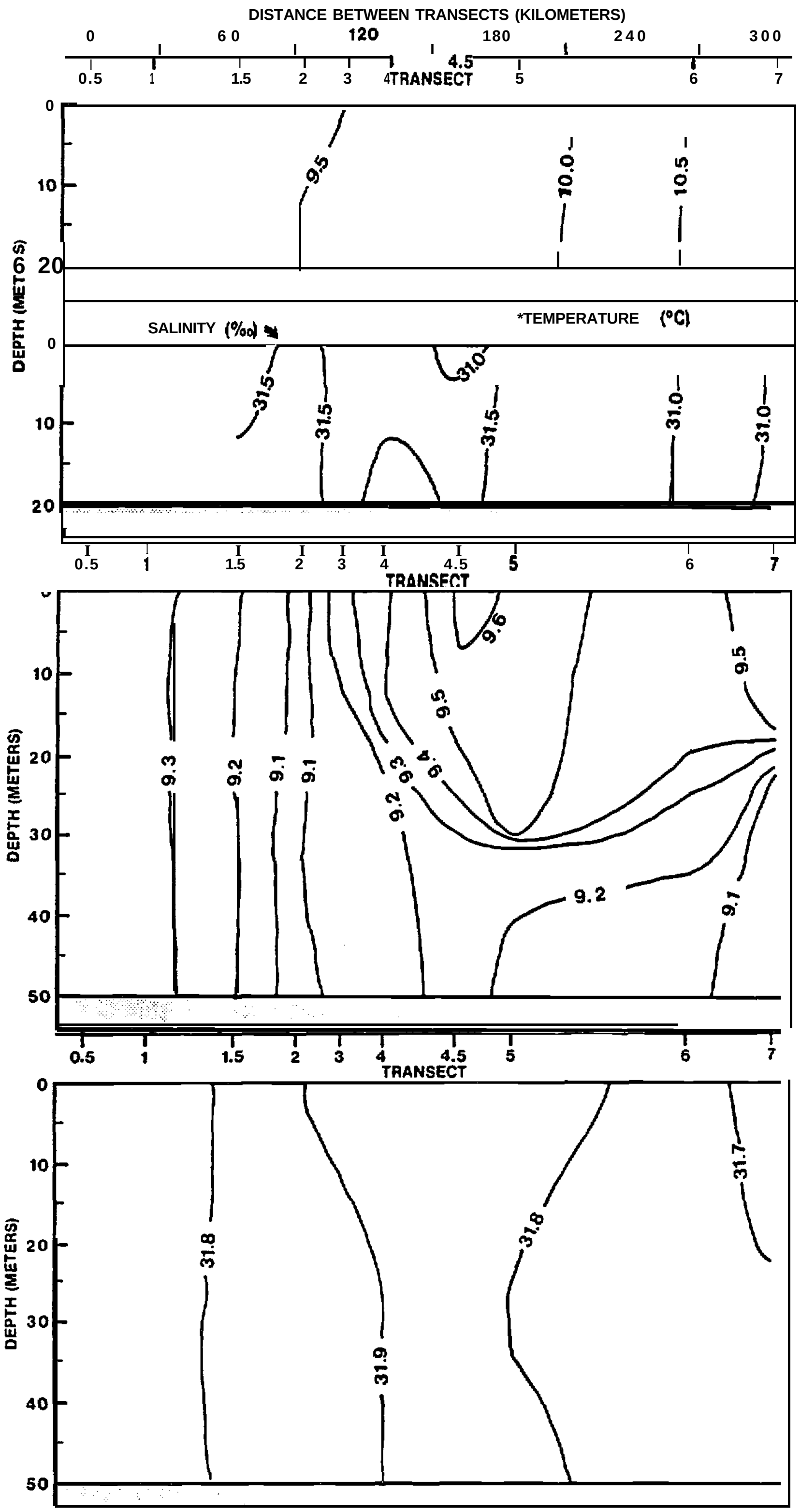


Figure 2.12. Temperature and salinity contours along the 20-m isobath and the 50-m isobath for October 1984.

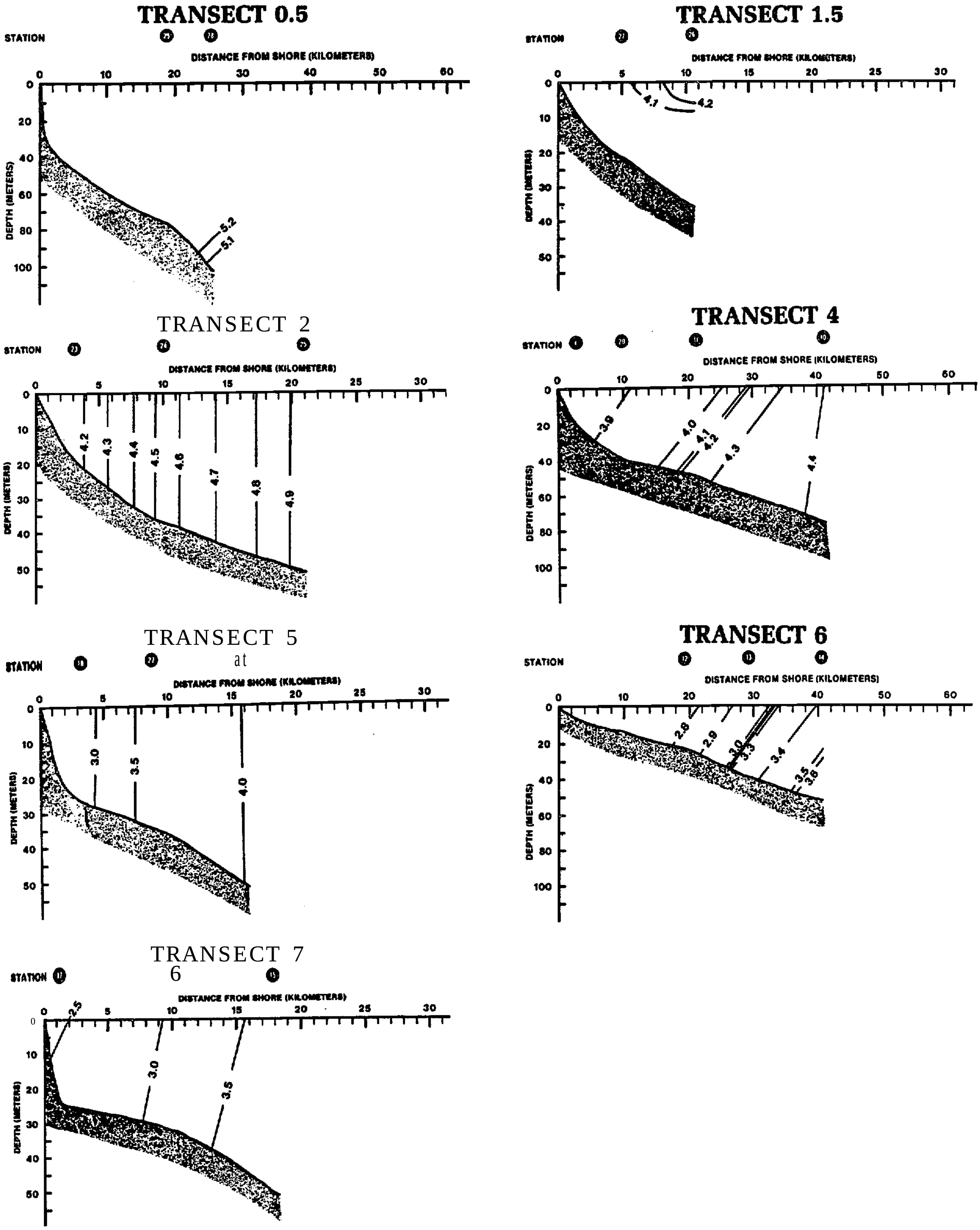


Figure 2.13. Vertical temperature contours for January 1985.

2.6.4.4 April 1985

April near-surface and near-bottom temperatures generally increased with distance off shore. The temperature gradient along Unimak Island northeast of Cape Mordvinof tended to be alongshore and decreased to the northeast. The near-surface temperatures decreased by approximately 2°C from southwest to northeast, ranging between 2.8°C (southwest and offshore) and -0.1°C (northeast and nearshore). This trend was apparent for the near-bottom temperatures as well, with temperatures ranging between 3.0° and -0.2°C. In the vicinity of Izembek Lagoon the cooler temperatures extended further offshore. The distribution of temperature indicated that the water was well-mixed vertically along the entire NAS study area as shown in Figure 2.14.

The vertical distribution of salinity, also shown in Figure 2.14, supports the vertically well-mixed characterization. It is apparent that the coastal domain, as defined by previous investigators, extended to the 50-m isobath. The salinity, like the temperature, generally increased with distance offshore with the near-surface values ranging from 30.7 to 32.1 ‰ and the near-bottom values from 30.9 to 32.3 ‰. The lower salinity values were measured nearshore near the northeast periphery of the study area; the higher values were measured offshore in the southwest.

2.6.4.5 May 1985

The near-surface and near-bottom temperatures generally decreased offshore. This was unlike January and April 1985 but similar to May 1984. The near-surface temperatures ranged from 2.5° to 5.0°C; the near-bottom from 2.0° to 4.5°C. These maximum temperatures were approximately 0.5°C warmer than the maximum temperatures measured in May 1984. The temperature distribution indicated that the water was well mixed vertically from Transect 0.5 up to, but excluding Transect 4 (Moffet Point). From Transect 4 on up to the northeast periphery of the study area and extending at least as far inshore as the 20-m isobath, the water exhibited the two-layered structure typical of the central domain (Fig. 2.15).

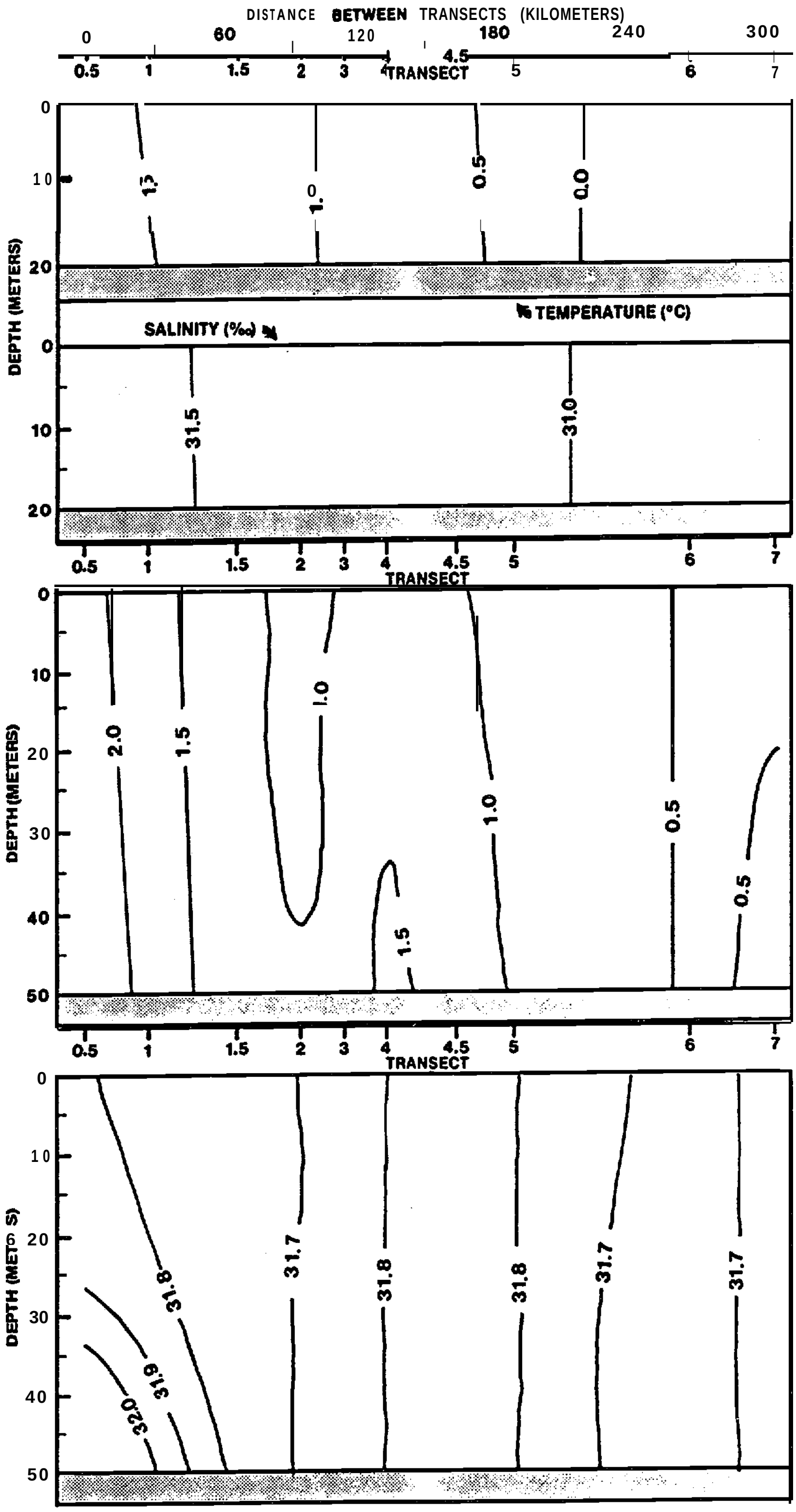


Figure 2.14. Temperature and salinity contours along the 20-m isobath and the 50-m isobath for April 1985.

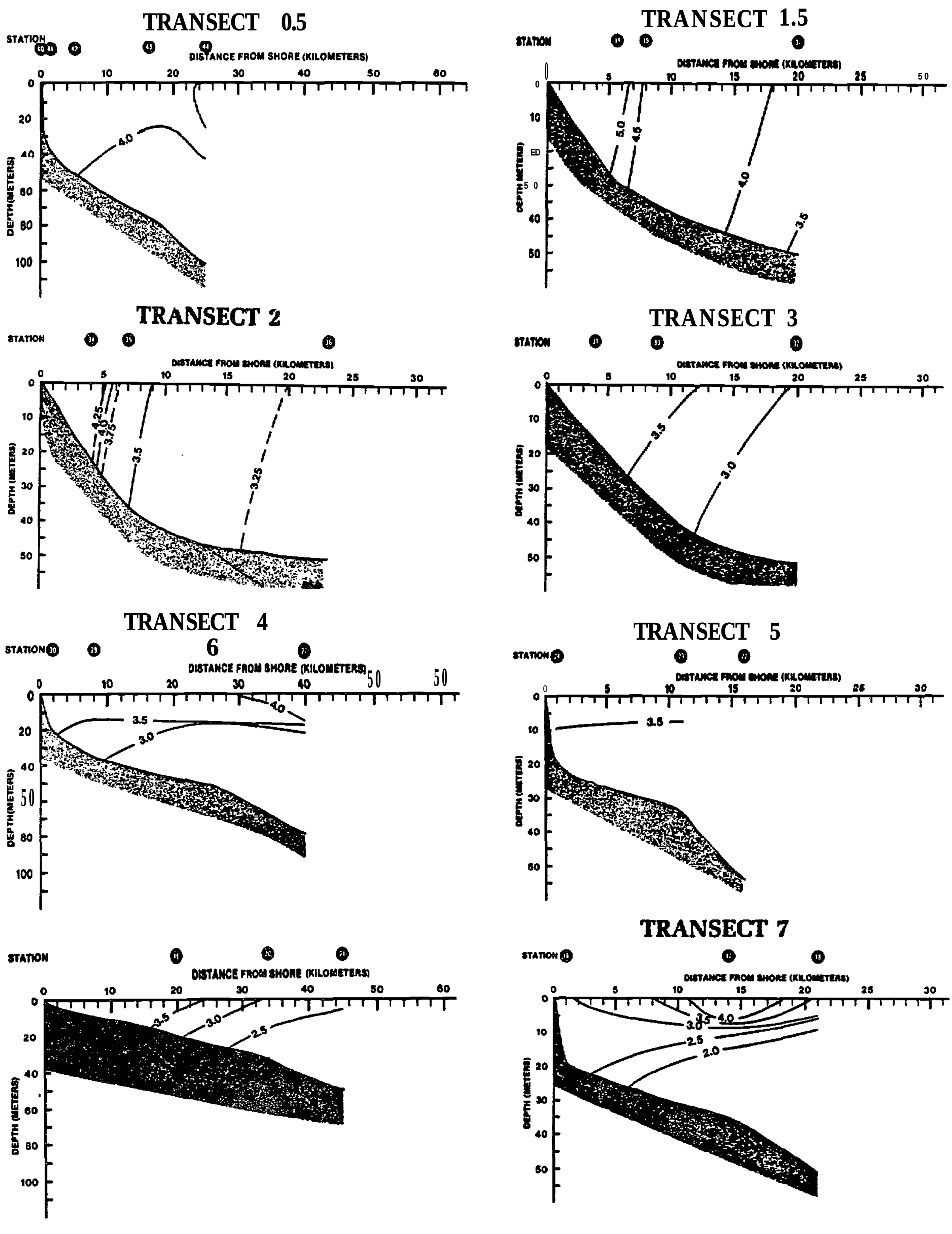


Figure 2.15. Vertical temperature contours for May 1985.

With the exception of Transect 7 (Cape Seniavin), this two-layered structural trend was not reflected in the salinity distribution. Salinity generally increased with distance offshore. The near-surface and near-bottom salinity values ranged from 30.8 to 32.1 $^{o}/_{oo}$ and from 31.0 to 32.6 $^{o}/_{oo}$, respectively. The *lower values* were measured in the nearshore northeastern periphery of the study area; the higher values were in the offshore southwestern periphery of the study area.

2.6.4.6 July 1985

Near-surface and near-bottom temperature trends were dissimilar during the July oruise. The near-surface temperatures, which ranged from 7.0°C in Unimak Pass to 9.0°C near Izembek Lagoon, generally increased with distance offshore. The near-bottom temperatures, however, decreased with distance offshore, ranging from 3.5°C (offshore southwestern periphery of the study area) to 9.0°C (nearshore northeastern periphery of the study area). The near-surface temperature trend did deviate from the above characterization at two locations: a temperature maximum occurred near the 20-m lsobath adjacent to Izembek Lagoon, a temperature minimum was observed near the center of Transect 6. No corresponding temperature maxima or minima were observed near the bottom. In addition, similar to April 1985, the temperature gradient in the vicinity of Unimak Island tended to be alongshore rather than cross-shelf. The vertical temperature distribution (Fig. 2.16) *was* typical of the two-layered structure found in the central domain during the summer. This two-layered structure extended inshore as far as the 20-m isobath.

The two-layered structure was also evident in the salinity distribution. In fact, the distribution of salinity and temperature almost suggests that the coastal domain, as described by previous investigators, existed only out as far as the 20-m isobath in July. The near-surface salinity generally increased with distance offshore and ranged from 30.2 $^{o}/_{oo}$ in the northeast (nearshore) to 32.7 $^{o}/_{oo}$ offshore of Unimak Island. Directly off of Iaembek Lagoon the near-surface salinity contours were normaltothe shore rather than alongshore. The near-bottom salinity revealed a slight bulge In the alongshore salinity contours. Near-bottom salinity increased with distance offshore and

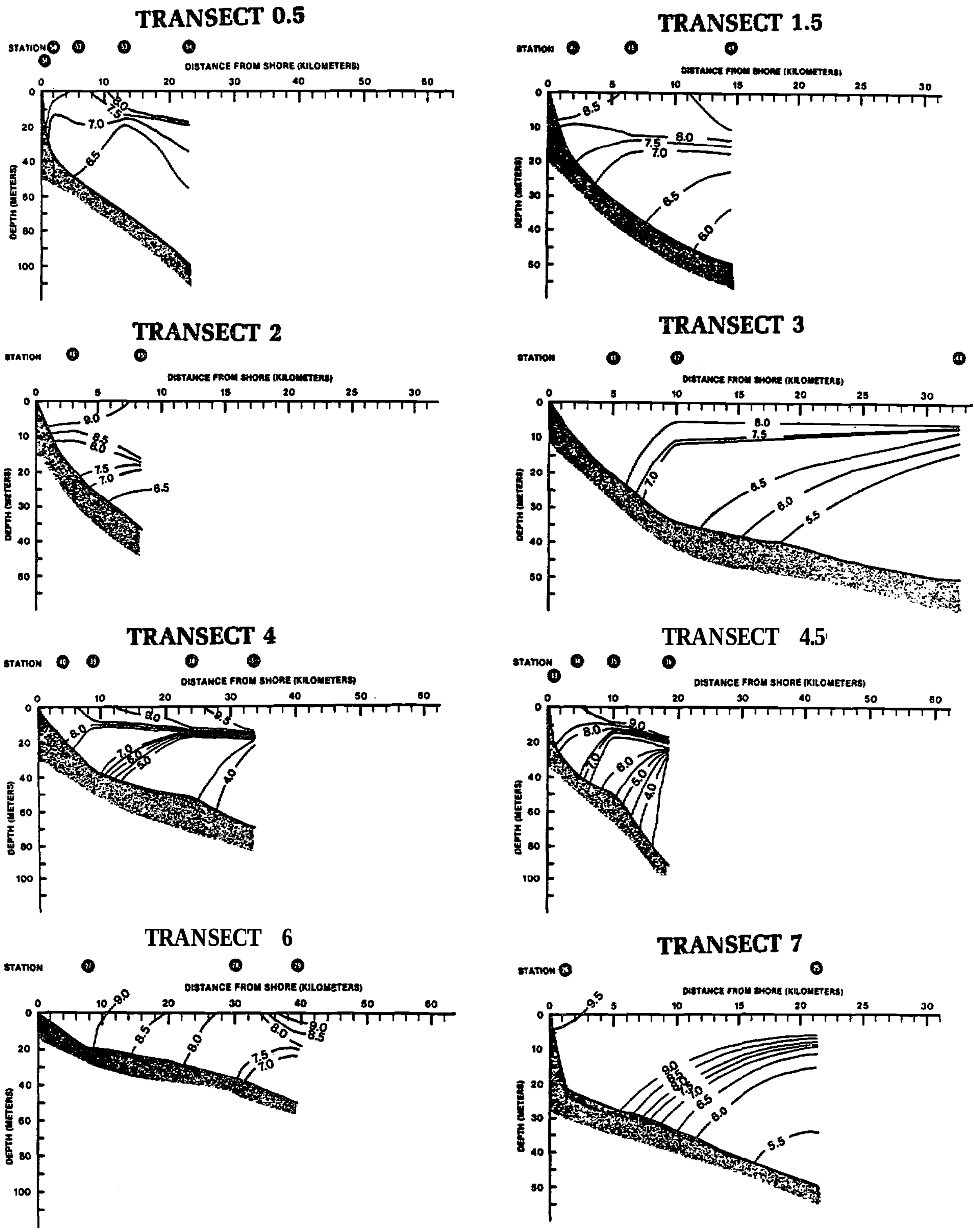


Figure 2.16. Vertical temperature contours for July 1985.

ranged from 30.4 $^o/_{oo}$ in the northeast to 33.3 $^o/_{oo}$ off *of* Unimak Island. The higher salinity values observed near-surface and bottom in the vicinity of Unimak Island suggest that there may have been some oceanic influence in July.

2.6.4.7 Discussion

The horizontal and vertical distribution of salinity and temperature generally agree with previous investigators (Coachman 1986, Schumacher and Moen **1983,** Kinder and Schumacher **1981a,** fngraham **1981).** The coastal domain, characterized by vertically well-mixed water, usually extended out to the 50-m isobath. Nevertheless, there were exceptions to this general characterization. Stratification was observed during **May** 1984 and 1985 and July **1985.** Usually, the nearshore stratification resulted from runoff from the land. The offshore, and most extreme, stratification resulted from intrusion of central domain water into the NAS nearshore zone. During July **1985** this intrusion (and stratification) extended inshore as far as the 20-m isobath along most of the NAS. There were isolated instances of intrusion during other cruises as well, although generally beyond the 40-m isobath.

Within the coastal domain the **near-surface** and near-bottom salinity increased with distance offshore, usually ranging from approximately 31 $^o/_{oo}$ nearshore to 32 $^o/_{oo}$ offshore. The difference between surface and bottom salinities was usually less than 0.5 $^o/_{oo}$. Occasionally, salinity values greater than 33 $^o/_{oo}$ were observed in the vicinity of Unimak Pass and values less than **31** $^o/_{oo}$ *were* observed in the vicinity *of* Cape Seniavin. During any given cruise the salinity rarely varied more than 2 $^o/_{oo}$. The general trend was toward higher salinities in the southwestern periphery of the **NAS** study area. The lower salinity values in the northeastern periphery of the study area resulted from the higher runoff *in* that area of the Alaska Peninsula.

Both surface and bottom temperatures decreased with distance offshore except during January and April **1985** when temperatures increased offshore. The near-surface temperature also increased with distance offshore during July **1985.** During the six cruises surface and bottom temperatures ranged from **-0.1°C** (April **1985)** to **10.5°C** (September-October 1984). Temperature, more than salinity, determined the degree of stratification observed within the WAS nearshore zone. Because the water was usually well mixed, the difference between surface and bottom temperature at any given station was less than 1°C. Only during July 1985, during a period of relatively intense stratification, did the temperature difference approach 5°C. Presumably if the water in July had become rapidly mixed (e.g., as a result of a storm), the bottom temperature could have been warmed by 1° to 2%.

2.6.5 Lagoonal Influence

2.6.5 .1 Bathymetry

Water depths were measured across the three entrances to Izembek Lagoon to determine the cross-sectional area and configuration of each entrance and determine the relative importance of each entrance for transmitting water in and out of the lagoon. The configuration of each entrance is presented in Figure 2.17.

The south entrance, estimated to be 900 m wide, has a relatively simple configuration with a single main channel with a maximum depth of approximately 13 m below MLLW. Of the three, this entrance appears to have changed the least (based on previous charts). The middle entrance is interspersed with many small channels and shoal areas, and over 50% of the entrance would be exposed at MLLW. The width was estimated to be 1600 m, and the deepest channel was looated approximately midway with a maximum depth of 9 m below MLLW. The north entrance is the largest and most complex with many channels. The section profiled was estimated to be 2320 m wide, with a maximum depth measured approximately 13 m below MLLW.

The cross-sectional areas were calculated for a tide range of -0.5 m below MLLW to +1.7 m above MLLW. Within the tide range specified, cross-sectional areas ranged from 4000 to 5940 m^2 for the south entrance, 850 to 3560 m^2 for the middle entrance, and 8400 to 13,330 m^2 for the north entrance. The total inlet cross-sectional area available to water transport ranges from approximately 14,860 m^2 (at a tide stage of 0.0 m) to 20,440 m^2 (tidal stage of 1.2 m). Assuming the fraction of Izembek Lagoon effectively communicating with eaoh tidal entrance is a function of

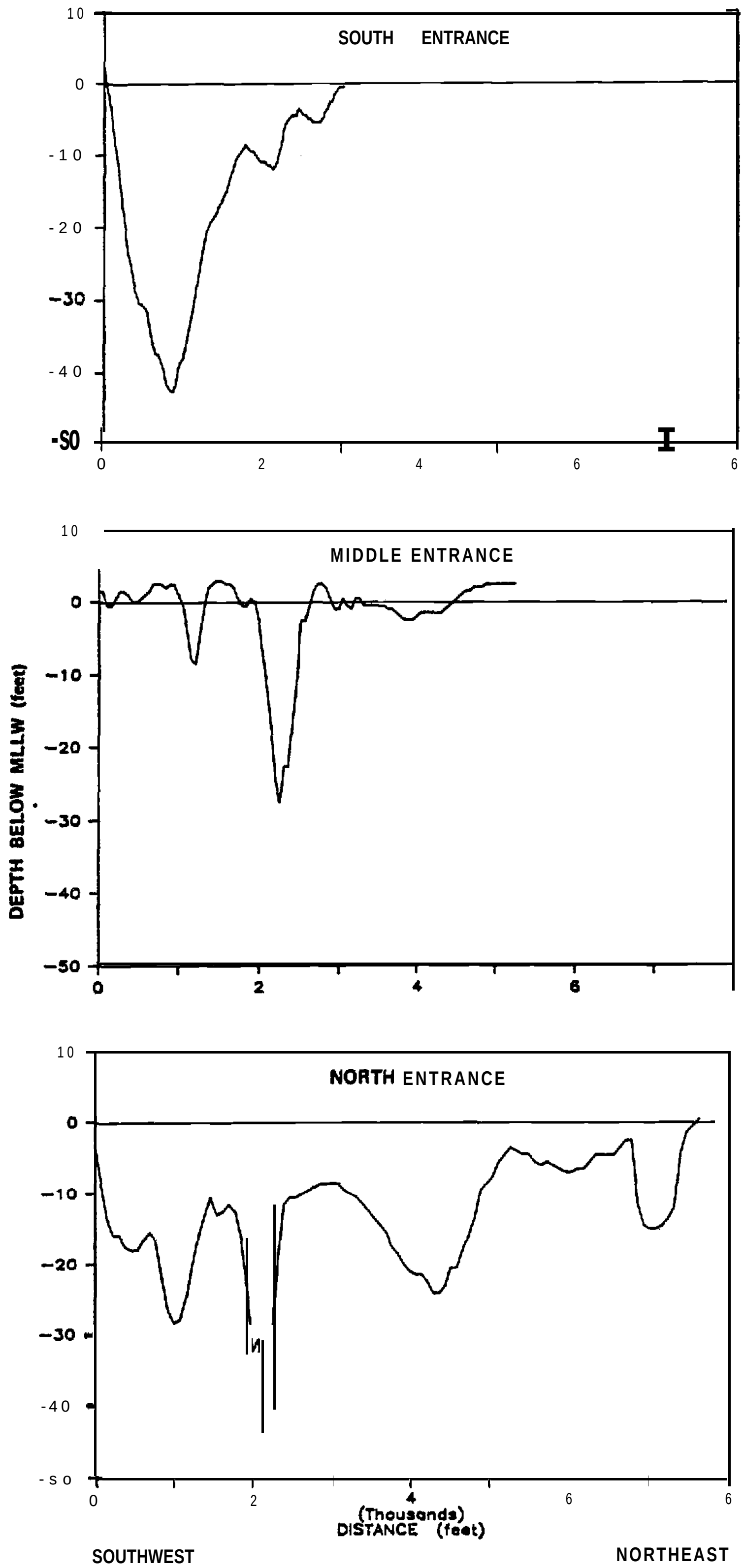


Figure 2.17. Izembek Lagoon entrance cross sections (adjusted to MLLW).

the entrance cross-sectional area in relation to the total available cross-sectional area, then the area of the north, middle, and south entrances, relative to the total area at a tidal elevation of 0.0 m would effectively communicate 62.5%, 7.51, and 30% of the total volumetric flow, respectively.

Izembek Lagoon, with a surface area of 218 km^2, is comprised largely of tidal flats (78%) and, to a lesser extent (22%), tidal ohannels (Barsdate et al. 1974). During a typical semidiurnal tidal cycle the mean tidal excursion is 1.6 m with a second average tidal excursion equal to 23% of the principal tidal range. These values result in a tidal prism of approximately 4.29 x 10^8 m^3.

2.6.5.2 Drogue Studies

Plots of drogue motion for the south entrance revealed that flood and ebb flow is concentrated along the west bank of the inlet. Drogues released from the south entrance remained within 5.5 km of shore (i.e., out to the 20- to 25-m isobath) during the four days of tracking. The net direction of travel was upcoast to the northeast, although drogues traveled as far as 9.5 km southwest of Cape Glazenap in the first one or two days following release. The northeasterly maximum range was 25 km from Cape Glazenap. Two of the drogues reentered Izembek Lagoon through the south entrance and one drogue entered the middle entrance.

Much of the offshore movement of the drogues occurred within the immediate area of the south entrance. For example, one of the drogues traveled 5 km directly offshore within six hours after release. The maximum average speed during ebb tides observed (excluding speeds within the entrance) was 38 cm/s. The maximum average speed observed for the south entrance drogues during flood tide was 65 cm/s. The overall net flow upcoast after 75 to 80 hours of tracking ranged from 3 to 8 cm/s.

The drogue release location at the north entrance was approximately 2.5 km from shore north of the actual entrance. This was necessary because of foggy conditions at the time of release. These drogues exhibited a stronger offshore movement than those released at the south entrance. Whereas the drogues released at the south entrance tended to remain a relatively constant distance from shore, most of those at the north entrance continued to move offshore. During the first two days following release, all the drogues except one remained downcoast of the north entrance.

The maximum current speed measured by drogues released from the north entrance was 35 cm/s during flood tide. During ebb tide the maximum current speed was 30 cm/s.

The results suggest that water is being pushed offshore of the north entrance in a type of tidal pumping effect. This effect apparently does not extend offshore beyond the 25-m isobath. This transport may be an important mechanism for mixing organic matter discharged from Izembek Lagoon with adjacent waters which are subsequently transported northeast. During periods of cross-shelf transport this material could migrate into the central domain.

The trajectories of drogues in the nearshore zone reflect a complex interaction of regional currents, tidal currents, winds, and water exchange from Izembek Lagoon. Trajectories confirm upcoast flow (to the northeast) during flood, and downcoast flow (to the southwest) during ebb. Nevertheless, distinct differences existed in the trajectories between the south and the north entrance releases (Fig. 2.18). Additional plots of drogue trajectories and wind and tide data are presented in an appendix (see Section 2.11).

2.6.5.3 Twenty-four Hour Inlet Survey

The results of the single 24-hour inlet survey, conducted at the south entrance of Izembek Lagoon are presented in Figure 2.19. The semi-diurnal tidal influence was very evident during the survey period. Current speeds ranged from 0 to 216 cm/s (one-minute-averaged) with the highest speeds observed during the flood tide. The currents set 240°T on the ebb tide and 080°T on the flood tide. Some vertical shear was evident as the tides began to change as shown in Figure 2.19 (0300 19 May 84). The temperature fluctuations observed were probably the result of lagoonal heating due to insolation during this late spring observation period.

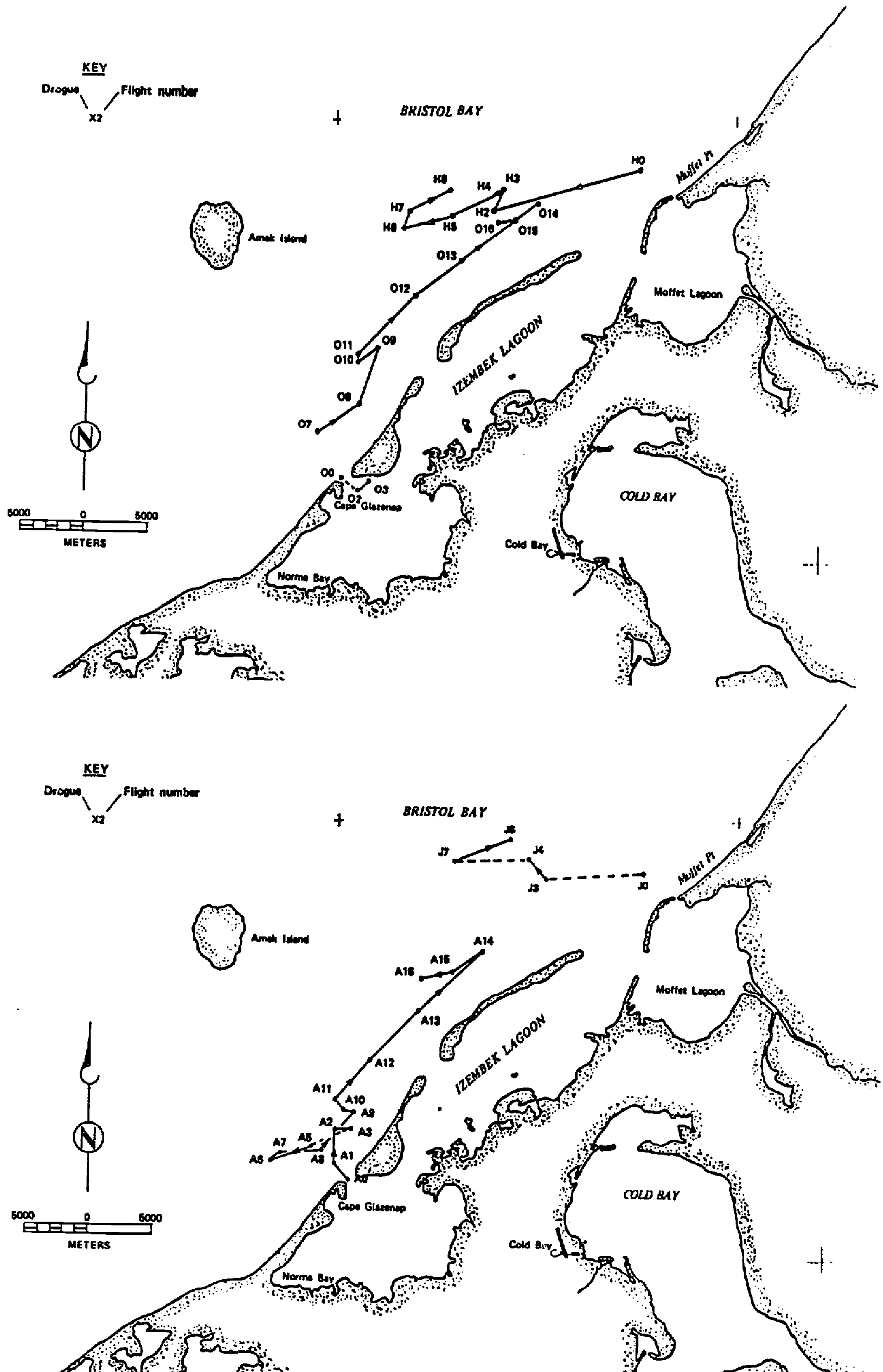


Figure 2.18. Trajectories for the first (A) and second **(B)** drogue releases.

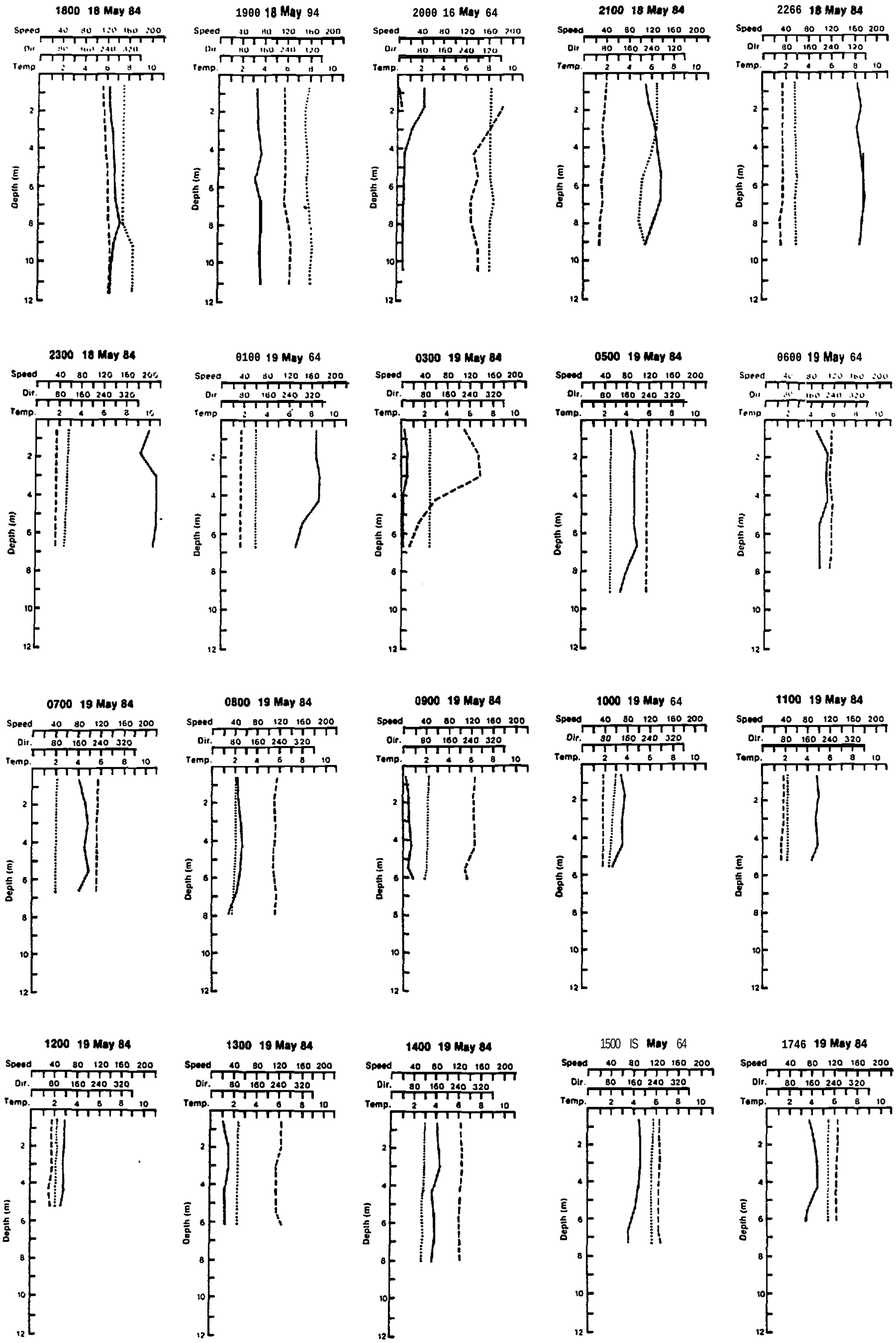


Figure 2.19. Vertical profiles of current speed (——), direction (- - -), and temperature (……) during the diurnal survey at the south inlet of Izembek Lagoon.

2.6.5.4 Discussion

Based on historical data as well as the data presented above, Izembek Lagoon may be characterized as a shallow lagoon with an area of 218 km^2. At low tide much of the surface area (approximately 78%) of the lagoon is a mudflat. Izembek Lagoon has three entrances or inlets--a southern, middle, and northern inlet with cross-sectional areas that ranged from 850 to 8400 m^2 at -0.5 m (referenced to MLLW) and from 3560 to 13,300 m^2 at 1.7 m above MLLW.

The northern or Moffet Point inlet could communicate as much as 62.5% of the total tidal volumetric flow. Therefore, the water adjacent to the northern inlet would most likely be influenced by the lagoon. This was evident in the vertical stratification of water adjacent to the northern inlet as delineated by temperature and/or salinity, particularly during the months of January 1985 (appendix), May 1984 (Fig. 2.10 - Transect 4) and 1985 (Fig. 2.15 - Transect 4), and October 1984 (appendix). Nevertheless, this same degree of stratification was seen at transects located off of Unimak Island and Cape Senfavin suggesting that the influence of the numerous unnamed streams discharging to the NAS is equally important in affecting the distribution of nearshore salinity and temperature. The influence of the lagoons and the streams of the Alaska Peninsula within the study area, however, is limited only to those areas directly adjacent to the lagoon or stream, and probably extend offshore no further than the 20-m isobath.

2.7 CONCEPTUAL PHYSICAL MODEL AND CONCLUSIONS

A conceptual model of the hydrographic charaoteristlcs of the NAS coastal zone has been developed to support interpretation of the data collected in this and numerous previous studies, and to provide a hydrographic basis to support interpretation of ecosystem dynamios. The conceptual model is highly simplified, but illustrates some important factors controlling materials transport and temperature distribution along the NAS. The conceptual model has been based primarily on previous investigations and publications, and is consistent with the findings of this study.

The model considers **water,** salt, and thermal fluxes through the NAS coastal zone. It could be used to support estimates of nutrient and carbon fluxes as well, if integrated with appropriate databases, The modeled domain (illustrated in Fig. 220) is the coastal zone, shoreward of the 50-m isobath and extending from Urilia Bay (Unimak Island) to Cape Seniavin. The alongshore length is approximately 280 km. Looking alongshore, the average cross-sectional area of the domain is 440,000 m^2 (0.44 km^2), so the total volume of seawater is 123 km^3 (1.23×10^{11} m^3).

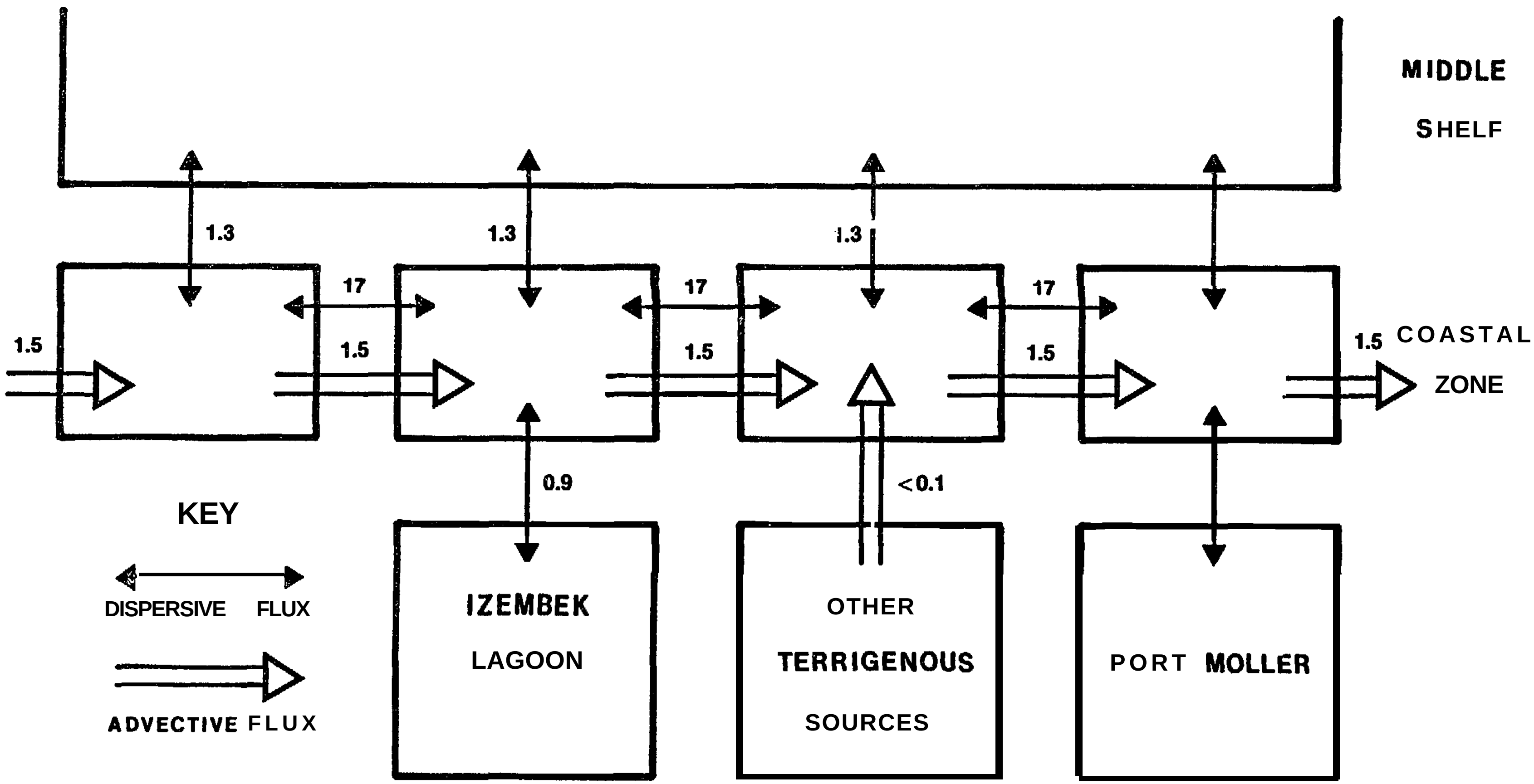
Within the modeled domain the net drift is alongshore toward the northeast. Coachman (1986) presents estimates of mean circulation (adapted from Kinder and Schumacher 1981b) in the model domain at 2 to 5 cm/s. Schumacher and Moen (1983) present mean circulation estimates based on dynamic topography of 2 to 7 cm/s, and a similar range in moored current meter observations (Mooring TP8) from January to May 1981.

Our investigation deployed both shallow and deep moored current meters for approximately two weeks in the spring and three weeks in the autumn of 1984 at the 20- and 50-m isobaths off the north inlet of Izembek Lagoon. The net drift observed during these relatively brief deployments generally deviated from the long-term mean circulation reported by the previously referenced investigators. These results do not contradict the earlier findings. The time series current data collected by Schumacher and Moen (1983) include frequent 2- to 3-week periods of cross-shelf and southwest currents. The data sets collected in our investigation were simply too limited in duration to reveal the long-term mean circulation.

Drogues were also released from Izembek Lagoon inlets on ebb tide during May 1984. Net drifts observed were alongshore to the northeast for 7 of the 11 drogues released and net drift ranged from 2 to 10 cm/s over 2 to 3.5-day tracking times.

Thus, it is assumed that net circulation within the NAS coastal zone is alongshoretothe northeast at2 to 7 cm/s (2 to 6 km/day). Since the alongshore length of the modeled domain is approximately 280 km, the length of time required for a parcel of water to travel through the domain is 50 to 140 days.

It is useful to compare different mechanisms resulting in mass transport in terms of characteristic time scales. A simple and readily applicable basis for development of such time scales is the half-life



NOTE: Volumes of water exchanged in km^3/day

Figure 2.20. Approximate quantification of conceptual model of NAS coastal zone.

related to the pseudo-first-order rate constant. A first order process is one in which the loss rate of a constituent is proportional to the concentration of the constituent. In a well-mixed reactor the concentration of a constituent is the amount or mass of the constituent divided by the volume of the reactor. Thus the ***rate*** of loss is also proportional to the amount ***or*** mass in the reactor. In a first order, ***or linear, reactor,*** the mass of constituent is reduced over time as $M = M_0 e^{-kt}$. If several first order processes affect the constituent, then $M = M_0 e^{-(k1 + k2 + \dots)t}$. In systems that are not truly linear, it is always possible to define a pseudo-first-order rate constant which approximates the first order behavior by defining as the rate of loss of the constituent divided by the total amount remaining. Then a characteristic time scale for the process is estimated by the "half-life" $t_{1/2} = \ln 2/k$. In this simple conceptual model, the NAS coastal zone is treated conceptually as a well mixed linear reactor. Individual processes resulting in losses from the system can readily be compared by comparing their pseudo-first-order rate constants or their characteristic time scales. **For** loss of water by the advective mean circulation, the pseudo-first-order rate constant is given by:

$$k_{advection} = \frac{\text{flow past Cape Seniavin/day}}{\text{total volume of water in domain}}$$

$$= \frac{0.8 \text{ to } 2.7\ \text{km}^3/\text{day}}{123\ \text{km}^3}$$

$$= 6.5 \times 10^{-3} \text{ to } 2.2 \times 10^{-2}\ (\text{day})$$

where the flow is calculated as the cross-sectional area times the current speed, and the indicated range is based on the probable range of 2 to 7 cm/s.

A half-life can be calculated as:

$$t_{1/2} = \frac{\ln 2}{k}$$

$$t_{1/2}\ (\text{advection}) = \frac{0.693}{6.5 \times 10^{-3} \text{ to } 20 \times 10^{-2}/\text{day}}$$

$$= 30 \text{ to } 110 \text{ day}$$

It is seen that these half-lives, or characteristic time scales for advection are similar in magnitude to the transit time across the domain.

For water parcels entering the model domain at Unimak Island the only other significant process that could result in loss from the coastal zone is dispersive exchange across the 50-m isobath and onto the central shelf. In our investigation, significant cross-shelf transport was observed at the 50-m isobath over periods of two to three weeks duration. In May, mean surface net drift at the 50-m isobath was due north at 11 cm/s, indicating a cross-shelf component of 8 cm/s. Bottom currents at the 50-m isobath did not exhibit a significant cross-shelf component during this period. During September the near-surface current meter measured a net onshore drift of 3 cm/s over 19 days while bottom currents continued to indicate no significant cross-shelf transport.

As illustrated by the time series data of Schumacher and Moen (1983), such bursts of cross-shelf transport are not uncommon in longer duration current records (Sohumaoher, pers. comm.). In the context of *longer* time scales, for example the approximately 100 days required for transit through the study area, it is appropriate to conceptualize these bursts of cross-shelf transport as turbulence contributing to a dispersive cross-shelf material flux. Clearly net transport across the shelf is minimal on the basis of both hydrodynamic and water balance considerations.

A characteristic time scale, i.e., dispersive half-life, for this process may be defined as:

$$t_{1/2} \text{ (cross-shelf dispersion)} = \frac{\ln 2}{k \text{ (cross-shelf dispersion)}}$$

$$\text{where } k = \frac{\text{dispersive flux} \times 280 \text{ km} \times 50 \text{ m}}{\text{volume of water in coastal zone}}$$

$$\text{and the dispersive flux} = \frac{K_y}{W}$$

Ky is the cross-shelf dispersivity [5.6 km^2/day (Coachman 1986)] and W is the width of the inner front [20 km (Coachman 1986)]. Applying these values for K_y and W:

$$\text{dispersive flux} = 0.28 \text{ km/day}$$

$$k = \frac{0.28 \text{ km/day} \times 280 \text{ km} \times 0.05 \text{ km}}{123 \text{ km3}}$$

$$= 3.2 \times 10^{-2} \text{ day}^{-1}$$

$$t_{1/2} = \frac{0.693}{3.2 \times 10^{-2} \text{ day}^{-1}} = 22 \text{ days}$$

Comparison of the half-lives for dispersive flux (approximately 20 days) with the half-life for the alongshore advection process (30 to 110 days) reveals that a water parcel in the coastal zone is more likely to be dispersively exchanged with central shelf water than to pass to Cape Seniavin. The pseudo-first-order rate constants can be linearly combined to indicate that the typical half-life or residence time of a water parcel in the coastal domain is 10 to 20 days.

The water balance for the coastal domain is completed by considering direct precipitation (P), evaporation (E), and runoff (R). Net precipitation (P-E) in the region is approximately 20 cm/year (Neumann and Pierson 1966), the surface oftheatudy area is 5800 km^2, therefore, net precipitation contributes an estimated 0.003 km^3/day or less than 0.49% of the advective transport, and less than 0.1% of the dispersive exchange. In other words, the contribution of net precipitation is negligible.

Freshwater input to the NAS by runoff from the Alaska Peninsula and Unimak Island has been estimated. The estimate is based on the assumption that the streams of the peninsula yield the same amount of runoff *per* unit area as nearby gaged basins. For example, the Kvichak River at Igiugig yields 96 cm/year (511 m^3/s from a drainage area of 16,800 km^2), while Eskimo Creek at King Salmon yields 27 cm/year (0.4 m^3/s from a drainage area of 41.7 km^2). These observed yields are widely disparate and do not provide the basis for a reliable estimate of the yield of the Alaska Peninsula. Nonetheless the yield is probably between these two extreme values, and leas than or approximately equal to 96 cm/year.

The portion of the Alaska Peninsula draining to the NAS coastal zone is approximately 8200 km^2. Therefore, the freshwater runoff from the area is less than, or approximately equal to, 0.02 km^3/year, it is apparent that runoff is an insignificant source of water to the coastal zone. This finding is intuitively reasonable in consideration of the fact that salinity is not markedlylowerinthe coastal zone than in the offshore regions of the shelf, nor is there a large reduction in salinity toward the northeast. This calculation should not be construed to imply that freshwater inputs are unimportant *in* the dynamics of the coastal zone, which may be influenced more by the buoyancy of the freshwater input than by the volumetric flow of the water.

To summarize this discussion, then, two major processes affect the residence time of water in the NAS coastal zone; cross-shelf exchange with central domain water and alongshore transport toward the northeast. Simple calculations suggest that water transported alongshore past Unimak Island is slightly more likely to *cross* the inner front into the central domain than to 'be transported in the coastal domain to Cape Seniavin. The necessary corollary to this conclusion is that most (60 to 80%) of the water moving alongshoreat Cape Seniavin entered the coastal domain by dispersive exchange across the inner front between Unimak Island and Cape Seniavin. A secondary contributor to water passing Cape Seniavin in the coastal domain is water that came into the model domain by transport in the coastal zone past Unimak Island. Freshwater input by rain and runoff are minor contributors to this water mass.

The temperature of water in the coastal zone is thus determined by the temperature of these water masses, modified by thermal exchange with the atmosphere. Significant warming in summer and cooling in winter as one proceeds up the coast from the southwest has been observed in this, as well as earlier, studies. Schumacher and Moen (1983) present contour maps indicating that both the coastal zone waters off Unimak Island and the central domain water adjacent to the coastal zone had similar summer temperatures of about 8°C in 1980. In 1984, a slightly higher temperature of 8.5°C was observed in the coastal zone off Unimak Island, while the vertically averaged temperature at the 50-m isobath was somewhat lower than observed by Schumacher and Moen in 1980; at about 7.5°C. In either case, however, the average temperatures for the water masses contributing to flow at Cape Seniavin was approximately 8°C. The coastal zone waters at Cape Seniavin are significantly warmer in summer, between 9° and 10°C, implying a 1° to 2°C warming in summer during flow through the domain. Considering the flow and surface area of the domain, net surface heat flux of 30 to 60 calories per square centimeter per day ($cal/cm^2/day$) is inferred from observed warming, and the value is consistent with the regional climatology of Budyko (1956).

The temperature of coastal zone water entering the study area was approximately 3.2°C in February, 1981 (Schumacher and Moen 1983) and 4.0°C in January of 1985. Adjacent *central* shelf water appeared to be about 2°C in February of 1981, while 4.0°C *was* observed at the 50-m isobath in January, 4 984. Water exiting the domain *at* Cape Seniavin in January of 1985 averaged about 3°C implying a cooling of about 1°C during transit for a loss to the atmosphere of about 30 $cal/cm^2/day$, which is somewhat less than would be expected. This result, in 1985 when offshore water was relatively warm, may be explained by the cross-shelf exchange process highlighted in the water mass balance discussion earlier in this section. The temperature of the oentral domain waters is less sensitive to surface cooling in winter since this heat loss is distributed through greater depths.

Observations from the Izembek Lagoon inlet and hydrographic transects in the coastal zone indioate that solar heating in the shallow water of the lagoon may be a significant process affecting the coastal zone, at least out to about the 20-m isobath. During the inlet survey the inlet temperature on the flood tide was about 3°C, while on the ebb the temperature rose to about 8°C. Air temperature averaged about 5°C at this time, so insolation was the predominant cause for this warming as the water resided in Izembek Lagoon. Considering the volume of the tidal prism, this net thermal input to the coastal zone could nearly account for the total warming observed at Cape Seniavin. Of course, a significant fraction of this heat is undoubtedly dissipated to the atmosphere rapidly since the tidal discharge from Izembek Lagoon during spring is stratified and stays near the surface, and the warmer-than-air temperatures promote heat losses to the atmosphere.

An important seasonal factor affecting temperature and salinity of the coastal zone, and the Bering Sea as a whole, is the winter ice sheet. These effects have been studied by several investigators. The extent and duration of ice cover is especially important in its effect on springtime temperatures, a critical period for the eoosystem of the coastal zone. Temperature variability and the effects of ice cover on that variability have been investigated for May and June. From 1953 to 1982, the temperature in the study area during May averaged 4.3°C and in June, 6.3°C (Ingraham 1981). The standard deviation in May was 1.8°C and in June 1.1%. In other words, in one year out of ten one would expect the May temperature to exceed 6.6°C and the June temperature to exceed 7.7°C.

A significant factor affecting the variability in temperature is the extent and duration of ice cover. Ice extent statistics for the period 1973-74 to 1978-79 were reported by Niebauer (1983). During these six ice seasons, the observed May and June temperatures (Ingraham 1981) were inversely correlated with maximum extent of the ice sheet ($r = -0.54$ and -0.59, respectively). Regression equations were derived as follows:

$$T\ (\text{May}) = 7.3^\circ C - 0.053\ (\%\ \text{cover})$$
$$T\ (\text{June}) = 9.3^\circ C - 0.055\ (\%\ \text{cover})$$

where % cover is the percentage of the eastern Bering Sea (as defined by Niebauer) covered by ice at the maximum seasonal extent.

The percentage cover ranged from 42 to 76% during the 1973 to 1979 period. The regression equations reproduced observed May and June temperatures to within 1.3°C (standard error of prediction = 0.8°C). This represents a slight improvement over predicting that the observed temperature will be the long term average temperature. Such a prediction would have been accurate to within 1.6% during 1974-79 (standard error of prediction = 1.3°C).

Although it has been demonstrated that runoff is insignificant to the overall water and salt balances of the NAS coastal zone, there are localized and seasonal effects of this runoff. The May 1984 hydrographic data clearly show a warm, low salinity water mass directly offshore of Izembek Lagoon out to the 20-m isobath. The average salinity in the study *area* at the *20-m* isobath *was* approximately 31.2 $^{o}/_{oo}$ compared with 31.7 $^{o}/_{oo}$ at the 50-m isobath. Drogues released from Izembek Lagoon inlets rather consistently moved approximately 3 km offshore (near the 20-n isobath) soon after deployment. The effect of the lagoon, however, is not noticeable at the 50-m isobath and apparently does not result in transport across the inner front. The significance of runoff from the Alaska Peninsula suggests that the severity of the previous winter may affect nearshore temperature and salinity not only through the effect of the sea ice cover, but also through the amount of snowfall and timing of snowmelt in the mountains of the peninsula. This is illustrated by the more obvious effect of freshwater nearshore in 1984 (this study) than *in* 1981 (Schumacher and Moen 1983). Snowfall at Cold Bay in 1983-84 was nearly double the *amount* recorded in 1980-81.

The coastal domain has generally been characterized as homogeneous. The preceding discussion of the localized effects of runoff, however, suggests that there are some deviations to this, as well as other, characterizations. Schumacher and Moen (1983) clearly demonstrated the influence of the Kvichak River on inner Bristol Bay and suggested the numerous rivers along the Alaska Peninsula nay contribute freshwater in quantities equal to those of the Kviohak River. Our 1984 findings, In particular, support this suggestion. This “line source” (so called by Schumacher and Moen 1983) of freshwater definitely influenced the hydrographic structure of nearshore water off Unimak Island, Moffet Point, and Cape Seniavin.

In addition to localized stratification resulting from runoff, large scale (i.e., covering the entire NAS study area as far landward as the 20-m isobath) vertical stratification was observed during July 1985. This non-local phenomenon could have resulted from an intrusion of the central domain into the NAS nearshore zone. This stratification was atypical for the summer season in the eastern Bering Sea when the coastal domain, with its well-mixed water, should extend to the 50-m isobath.

2.8 RECOMMENDED FURTHER RESEARCH

The first recommendation is to modify and expand the CTD hydrographic sampling grid and sample on at least a seasonal basis. Ideally the transects should extend from Unimak Pass up into Bristol Bay. One of the endpoints of these transects should be as close to shore as practical; the other endpoint should extend out beyond the 50-m isobath. This modification to the sampling grid would increase sensitivity to detecting the effects of the passage of water through Unimak Pass and confirm the limit of influence of the Kvichak River. Information on the effects of nearshore stratification and the location of the inner front will be enhanced by extending the transects shoreward and seaward. The location of this front and the processes occurring in and about the front are important not only to physical and chemical oceanographers, but to biologists as well. As an example, Hunt et al. (1981) discusses the importance of fronts on the pelagic distribution of marine birds, which in turn suggests the importance of these fronts to productivity.

The second recommendation is to establish year-round gaging and water quality stations at selected representative rivers along the Alaska Peninsula. Ideally, precipitation should also be measured at some point within each river's drainage basin. A minimum of four stations would be required to begin quantifying the effects of runoff on the NAS nearshore environment. Additional streams that remain ungaged should still be monitored sporadically for water quality. Total discharge for these streams may be estimated using drainage basin areas and precipitation data from nearby rain gages. The minimum water quality parameters to be measured should include: conductivity, temperature, pH, color turbidity, nitrates, nitrites, phosphates (total and dissolved), silicates, and total organic carbon.

Because meteorological length scales are short, the third recommendation would be the installation of several remote meteorological stations along the Alaska Peninsula and, if none exists, one on Amak Island. These stations as a minimum should record wind speed and direction, air temperature, and precipitation. Barometric pressure, although not as variable over tens of kilometers, should be measured at selected stations. These meteorological stations would be augmented by the rain gages discussed previously.

Finally, the fourth recommendation would be to conduct additional current studies using multi-depth current meter arrays and, given the poor visibility in the Bering Sea, telemetering drogues. These studies, concentrating on either side of and in the inner front zone, would contribute significantly to our understanding of cross-front transport of water, nutrients, and plankton. Armstrong (1986) in a personal communication indicated that the fate of king crab larvae (and, hence, the fishery1 may hinge on the movement of larvae into or out of the NAS nearshore zone. More detailed current studies would also provide valuable information for numerical modeling should it be required.

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2.11 APPENDIX

The appendix material for this section was too extensive for publication as part of this volume. It is retained as unpublished information by NOS/OMA/OAD, Alaska Off ice. It is filed under the authorship, title, and date for this report. It contains the following sections:

Meteorology	- 27 pages
Tides	- 2 pages
Currents	- 26 pages
Lagoonal. Influence	- 9 pages
Hydrography	- 367 pages