Circulation and Hydrography of Norton Sound

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ABSTRACT

Norton Sound was two-layered vertically in temperature and salinity during summer, the eastern portion being more strongly layered than the western. Weak cyclonic mean flow in the eastern upper layer was not reflected in the lower layer, which was nearly stagnant and contained remnant cold, saline water formed locally during winter. Maintenance of this extreme layering in the eastern sound despite shallow depths (~15 m) was due to buoyancy input as solar heating and fresh water, sufficient to offset vertical mixing generated by tidal currents. In the western sound, coupled northerly upper- and lower-layer flows reflected a northward net flow over the shelf west of the sound. At times a strong baroclinic coastal flow occurred off Nome, and the central western sound was a locus for vertical mixing due to impingement of currents upon a shoal area. During winter, the sound approached vertical homogeneity due to vertical convection consequent to cooling and ice formation. Although it was possible to define mean flows, the currents were dominated by events which reflected regional wind and atmospheric pressure patterns in an as yet uncertain fashion. Such flow events may exert a primary control over such features as the Yukon River plume, which was never observed to enter the eastern sound even though the upper-layer salinity there suggests that Yukon water may have entered the sound prior to our observations.

INTRODUCTION

Observations of temperature, salinity, and currents have been obtained from Norton Sound, Alaska, as part of an investigation of transport processes on the Alaskan continental shelves. The general physical oceanographic conditions within Norton Sound, as deduced from observations made between 1976 and 1978, are addressed in this paper. Since analyses of the observations are still in progress, this should be considered as an interim, working document rather than a set of firm, final conclusions.

Physical setting

Norton Sound is a shallow, high-latitude embayment extending eastward from the northern Bering Sea and forming an indentation in the central west coast of Alaska (Fig. 6-1). Its east-west length is about 220 km, and its width about 150 km. Depths vary from less than 10 m in the southern portion to more than 30 m in a trough-like feature which trends east-west in the nearshore region just south of Nome; average depth in the sound is about 20 m. Two promontories extend into the sound about two-thirds of the way toward its eastern end, Cape Darby from the north and Stuart Island from the south (Fig. 6-1).

Norton Sound is located in a region of extreme seasonal variability. During the approximately June-September summer the sound is ice free and air temperatures are well above freezing. The waters are exposed for 24 hours to daylight, though not necessarily direct sunlight, during part of this period, and generally to light and variable winds. By November, air temperatures drop well below freezing and ice formation has normally begun along the northern shore, with first ice typically forming on the surface in Norton Bay at the northeast corner of the sound.

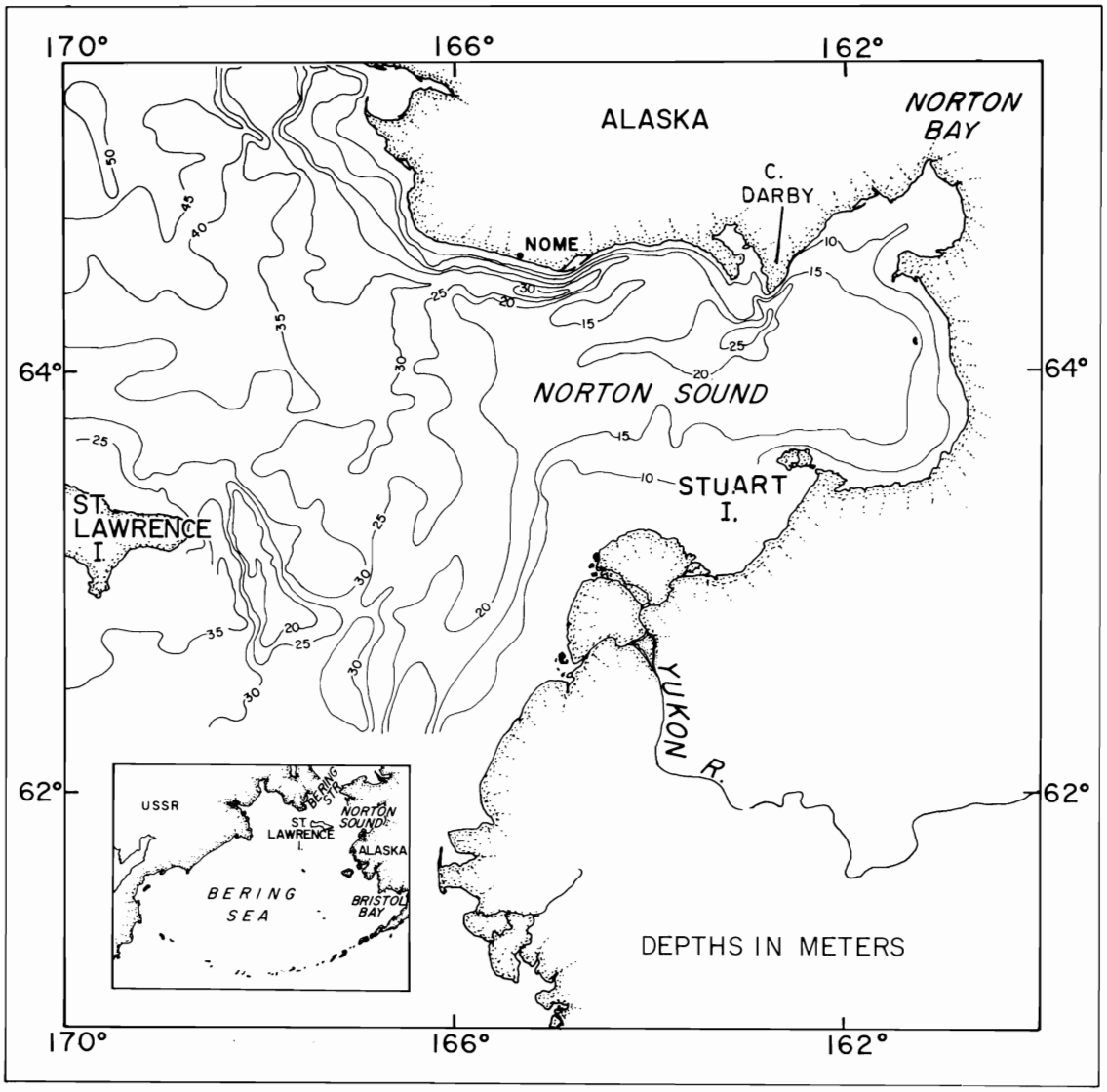

Figure 6-1. Geographical location and bathymetry of the Norton Sound region.

Ice growth continues southward until, by mid-December, the entire sound is more or less covered. This ice cover, which usually persists until April or May, consists primarily of loose pack 0.5-1.0 m thick except for shorefast ice near shore and for some distance offshore in the region of the Yukon River Delta. Direct observations of the ice cover are limited, and much information on its distribution and extent has been obtained through the use of satellite data (Muench and Ahlnäs 1976, Ahlnäs and Wendler 1979).

During winter the ice cover would be expected to markedly reduce air-sea exchange of heat, moisture, and momentum. This would mitigate effects on the water of low air temperatures and winter storms.

Oceanographic background

Our existing knowledge of northern Bering Sea circulation before the present series of studies was summarized by Coachman et al. (1975). The regional circulation is dominated by a northward net water transport of about 1.5×10^6 m^3/sec over the shelf between Norton Sound and Siberia. [Editorial note: this value may be high. See next chapter. D.H.] More recently Muench et al. (1978), on the basis of near-bottom recorded current measurements, have reported northward net flow southeast of St. Lawrence Island and in Bering Strait from October 1975 through April 1977. They also noted that the currents were characterized by north-south flow events having

speeds of 50-100 cm/sec, fast relative to mean flow speed of about 15 cm/sec. These flow events had time scales of several days, or the same duration as meteorological events. Spatial variability of the northward flow and its interaction with the waters of Norton Sound remain uncertain.

Before this study, little oceanographic information was available from Norton Sound itself. Bottom sediment distributions within the sound suggest that mean circulation is cyclonic and penetrates to the easternmost sound (Drake et al. 1980), but flow rates have not been estimated. Cyclonic flow in western Norton Sound was depicted qualitatively in the compilation by Hughes et al. (1974) and mentioned as a probability by Coachman et al. (1975).

The Yukon River enters the Bering Sea in the southwest corner of Norton Sound (Fig. 6-1). A minor portion of its discharge flows directly into the southern sound, while the remainder enters the Bering Sea along the coast farther west. Both the volume and the pathway of Yukon water which enters the sound remain uncertain. River flow can be as high as about 3×10^4 m^3/sec, as gauged at Pilot Station, some 60 km above the river mouth. Most of the annual river influx occurs between about April and November, and flow is an order of magnitude greater in midsummer than in midwinter.

FIELD PROGRAM

Oceanographic data were obtained from Norton Sound during 1976-78. Temperature and salinity data were acquired from vessels in summer 1976, 1977, and 1978 and through the ice from a helicopter in winter 1978. The periods of these cruises are summarized in Table 6-1. Twenty-four-hour time-series current observations were obtained from anchor stations in summer 1976, and instantaneous current profiles were obtained from anchor stations in summer 1977. Ancillary data obtained in summer 1977 included vertical profiles of transmissivity.

In addition to shipboard data, current data were obtained using taut-wire moorings during both winter and summer periods. Statistics for these moorings are summarized in Table 6-2.

Summer temperature and salinity data were obtained using a Plessey conductivity/temperature/depth (CTD) profiling unit with calibration samples on each cast. Winter data were obtained with a Plessey Model 9400 profiling unit operating through the ice from a helicopter. Temperature and salinity data are accurate to within 0.02 C and 0.02°/oo, respectively.

TABLE 6-1

Summary of cruises to Norton Sound

Vessel	Cruise ID	Dates	No. of Stations
Discoverer	RP4-D1-76B Leg V	26 Sept - 9 Oct 1976	33
Sea Sounder	None	8-12 July 1977	26
Surveyor	RP4-SU-77B Leg IV	11 Aug - 2 Sept 1977	55
Discoverer	RP4-D1-78B Leg I	10 July - 3 Aug 1978	56
Discoverer	RP4-D1-78B Leg III	10-29 Sept 1978	46
NOAA UH-1H	W-29	17 Feb - 5 March 1978	37

Currents were observed on the taut-wire moorings with Aanderaa Model RCM-4 current meters. Our discussion addresses the non-tidal, low-frequency flow components, as tides are treated in Chapter 8 of this volume. In order to remove tidal and higher-frequency components, the records were processed according to Charnell and Krancus (1976) and run through a 35-hour low-pass filter.

Anchored time-series stations were obtained using an Aanderaa current meter modified to operate through a deck readout unit. Speed and direction were measured hourly at 5-m intervals through the water column. Hourly CTD casts were also made at the time-series stations. Instantaneous current profiles were obtained using a Hydro Products current meter. Observations were not taken when the vessel exhibited yawing motions, easily detectable by rapid variations in heading.

In addition to the water column observations, wind speed and direction and air temperature were obtained from shipboard and were also recorded at the nearby weather station at Nome.

OBSERVATIONS

Distribution of density, temperature, and salinity

The waters of Norton Sound are characterized during the summer by two layers separated by a strong pycnocline. The upper layer is warmer and of

TABLE 6-2

Norton Sound taut-wire mooring summary

Mooring	Bottom D (m)	Meter D (m)	Mooring time period	Usable record L (days)	Latitude (°N)	Longitude (°W)	Vector mean speed	Vector mean dir
NC-14	32	22	8/21/76—6/25/77	309	64° 21.6′	165° 21.6′	2.2 cm/sec	073° T
NC-15	19	15	8/21/76—1/30/77	131	64° 06.5′	165° 17.7′	5.9 cm/sec	018° T
NC-20	19	6	7/8/77—8/25/77	48	63° 59.7′	165° 29.4′	7.8 cm/sec	340° T
NC-20	19	14	7/8/77—8/25/77	None	63° 59.7′	165° 29.4′	malfunctioned	
NC-21	25	6	7/9/77—7/22/77	~13	64° 08.2′	163° 15.2′	malfunctioned*	
NC-21	25	20	7/9/77—8/26/77	48	64° 08.2′	163° 15.2′	0.1 cm/sec	198° T
NC-22	16	8	7/9/77—lost	None	63° 41.0′	163° 00.1′	not recovered	
LD-5	27	20	7/25/78—9/4/78	42	64° 08.3′	163° 00.2′	0.8 cm/sec	309° T

*Record became increasingly error-ridden with time, so no mean is presented here, but early part of record was useful for comparison purposes.

lower salinity, and hence is less dense than the lower layer. This layering was more pronounced and consistent in its characteristics in 1976 and 1977 (Figs. 6-2 and 6-3) than in 1978 (University of Washington data not shown). In 1976 and 1977 temperature and density differences between the layers were greater in the eastern than in the western sound. A near-surface lens of warm (>12 C), low-density (<13 σ_t units) water in the southwestern sound was especially pronounced in July 1977 (station 23), and indicated the presence there of Yukon River water which is characterized by low salinity and corresponding low density. Concurrent temperature increases and density decreases with time during July-August 1977 were evident in both layers. The data in summer 1978 were insufficient to define spatial variations, but were adequate to detect higher bottom-layer temperatures in the eastern sound (~7 C, as opposed to 1-2 C during 1976 and 1977) than during the previous two seasons. Bottom-layer salinities were also lower in the eastern sound in 1978 than during 1976 or 1977 (about 32°/oo, as compared to 34°/oo).

The tendency for increased stratification in the eastern as compared to the western sound is exemplified by vertically averaged density gradients for July 1977 (Fig. 6-4). The single isolated high value off the Yukon River was due to elevated near-surface temperatures. A pronounced region of minimum stratification was present in the central western sound. Closely spaced stations obtained through this region in August 1977 defined vertical density structure through the area of minimum stratification (Fig. 6-5). This feature coincided with a shallow rise (depths <20 m) in the bottom southeast of Nome (Fig. 6-1).

Though there was considerable year-to-year variation in detail, several features of the horizontal temperature and salinity distributions persisted. The surface and near-bottom temperature and salinity distributions adequately represent the upper and lower layers, respectively, and are used to depict these features (Figs. 6-6 and 6-7). The upper layer was dominated by an eastward-trending high-salinity, low-temperature tonguelike feature which originated in the northwestern portion of the sound. This feature was best defined in July 1977, and by August it extended east-southeastward the full length of the sound but was patchy in nature. In September 1976 the tongue was restricted to the region just off Nome, and in 1978 the data were inadequate to detect its presence or absence. Generally, lower-salinity, warmer water lay north and south of the tongue. The lowest salinities which were observed occurred off the Yukon River in July 1977. This may have been a

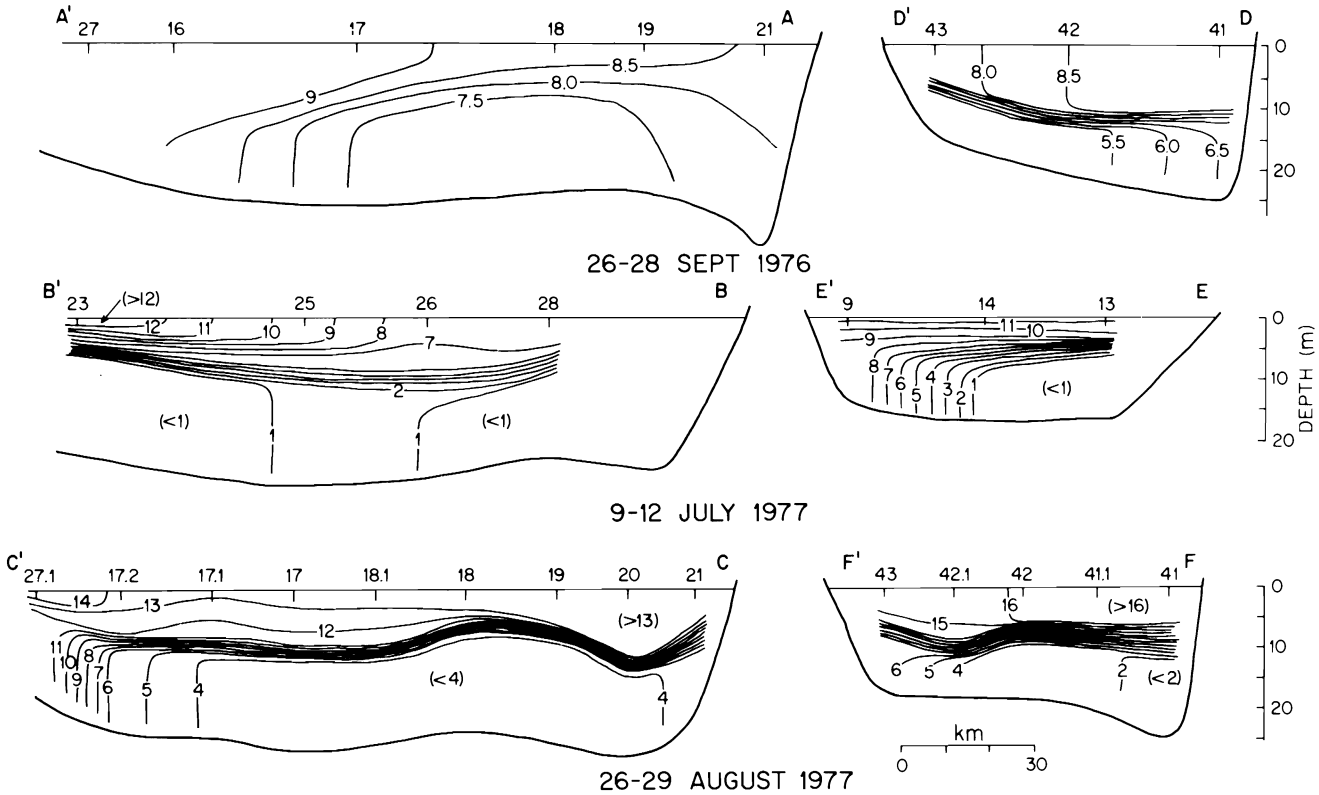

Figure 6-2. Vertical distributions of temperature along selected north-south sections across Norton Sound at three different times. Section locations are shown in Fig. 6-6.

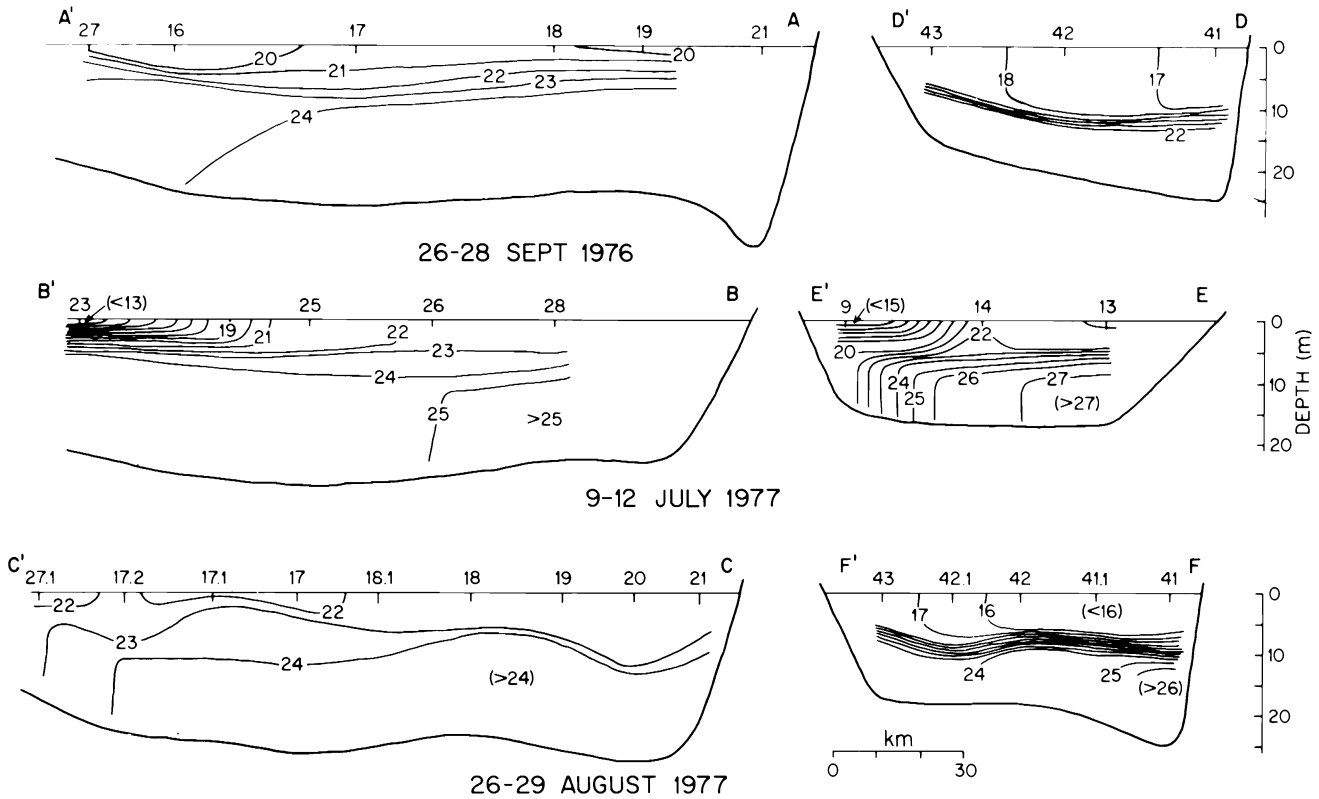

Figure 6-3. Vertical distributions of density (σ_t) along selected north-south sections across Norton Sound at three different times. Section locations are shown in Fig. 6-6.

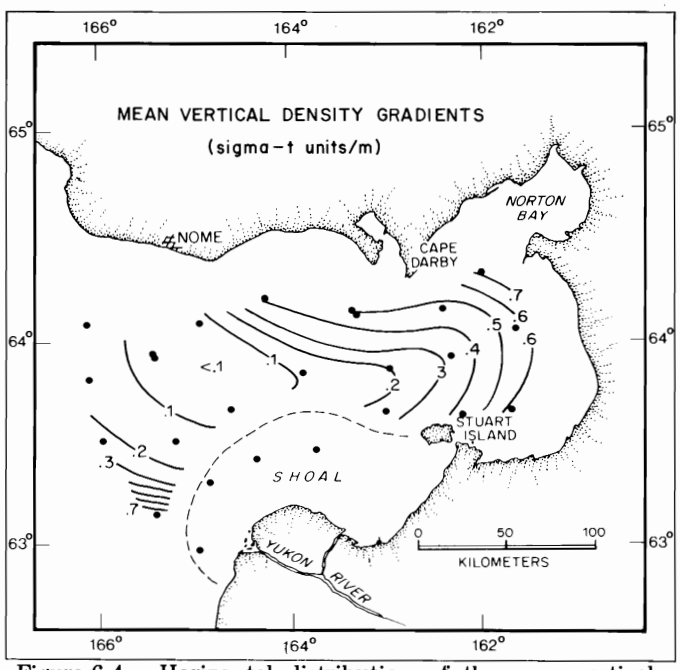

Figure 6-4. Horizontal distribution of the mean vertical density gradient in sigma-t units/m for the upper 15 m of the water column during July 1977, obtained by vertically averaging, from the surface to 15 m, gradients computed for 1-m increments. Dotted line defining shoal area is schematic only.

sampling artifact, as measurements were obtained closer to shore at that time than during other cruises and probably penetrated farther into the Yukon River plume. The maximum observed temperatures (>16 C) occurred in the northeastern sound during August 1977. The horizontal range of temperatures within the upper layer during September 1976 was only about 1 C, in sharp contrast to stronger gradients observed in the 1977 summer data.

The lower layer in the eastern and northeastern sound was characterized during summer 1976 and 1977 by particularly cold, saline water. The coldest (<0 C), most saline (>34°/oo) water observed was present in July 1977, whereas by August temperatures had increased to 2-3 C, salinities had decreased to 32-33°/oo and the locus of maximum salinity had shifted somewhat westward. As for the surface layers, bottom-layer salinities were lowest off the Yukon River mouth.

A band of relatively low-salinity (22-23°/oo) water paralleled the northern coast of the sound in September 1976 and August 1977 and appeared to be a westerly extension of warm, low-salinity water then occupying the upper layer in the northeastern sound.

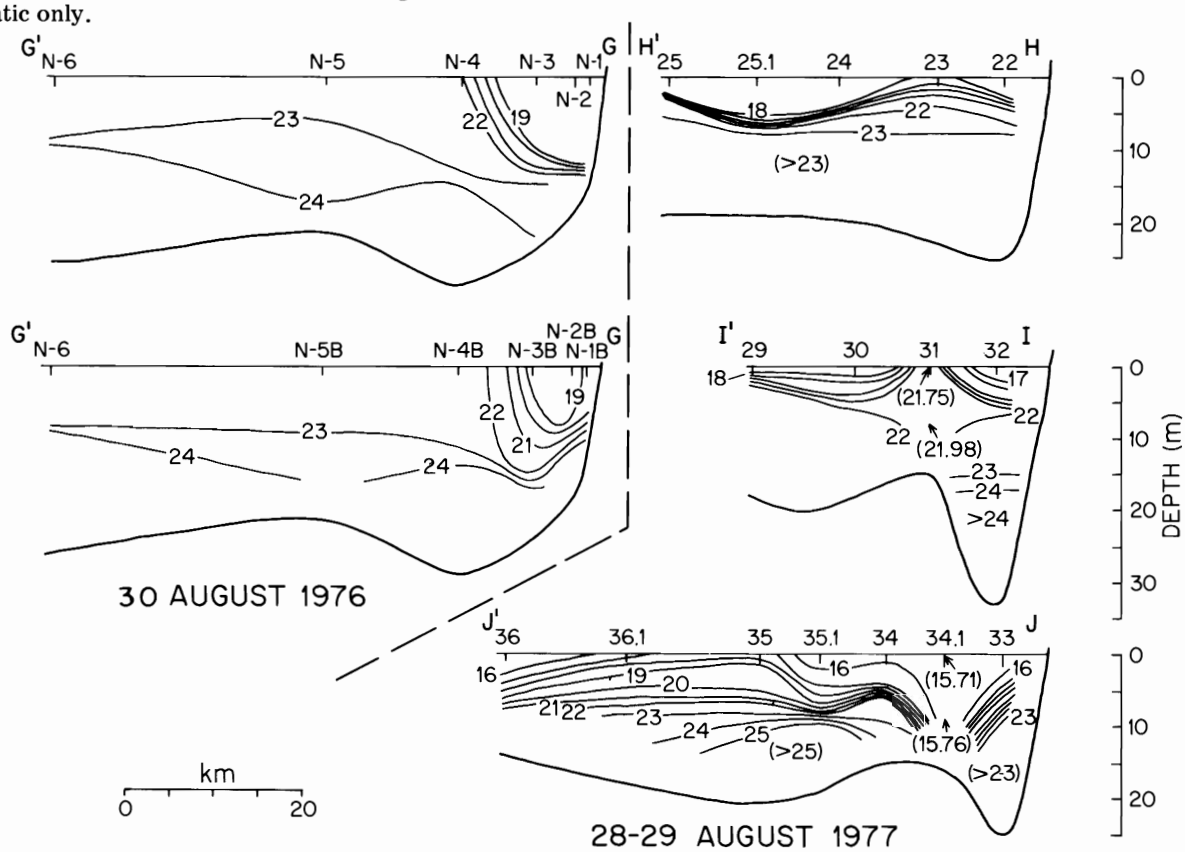

Figure 6-5. Vertical distributions of density (σ_t) along selected sections normal to the coastline of northern Norton Sound at two different times. Section G-G′ was occupied twice in rapid succession on the same day. Locations are shown in Fig. 6-7.

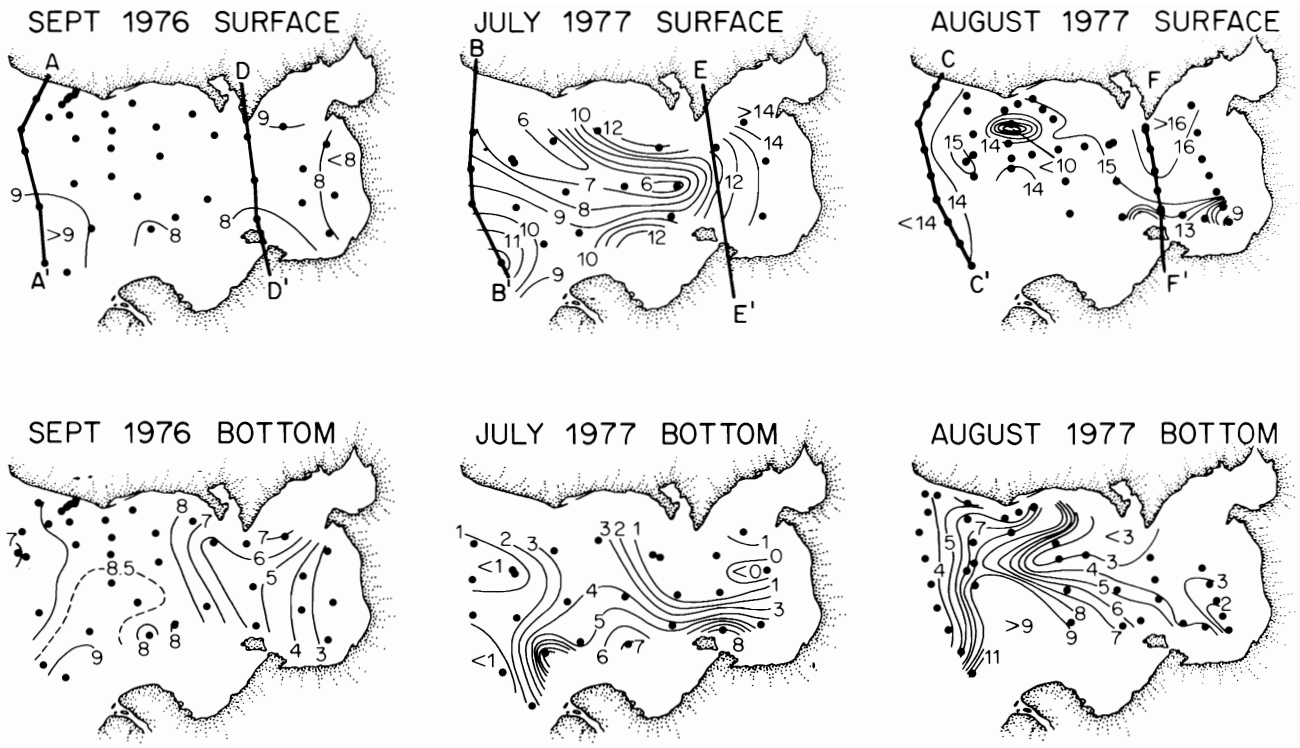

Figure 6-6. Horizontal distribution of upper- and lower-layer temperatures in Norton Sound at three different times. Location of sections in Figs. 6-2 and 6-3 are indicated.

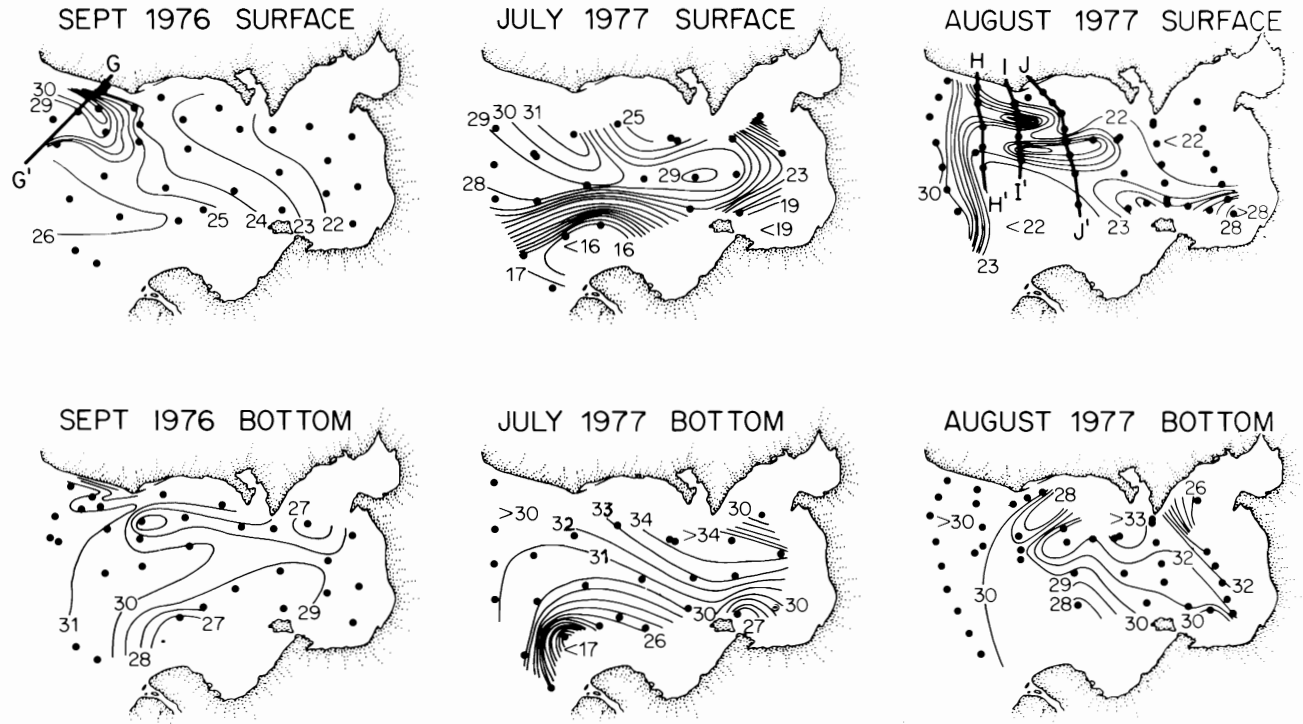

Figure 6-7. Horizontal distribution of upper- and lower-layer salinity in Norton Sound at three different times. Locations of sections in Fig. 6-5 are indicated.

Station coverage during July 1977 and in 1978 was inadequate to determine whether or not the feature was present. Horizontal salinity gradients were stronger in both layers during 1977 than in 1976.

Other temperature-salinity features were evident only part of the time, but nevertheless can contribute to our understanding. In September 1976, temperature on the σ_t = 21 surface showed two tongues (Fig. 6-8): a warm (8.5-9.0 C) easterly-directed tongue in the southern sound and a colder (7.0-8.5 C) tongue extending westward in the northern part, neither of which was evident in summer 1977. Although distributions on isopycnal surfaces in shallow water like this, particularly near the top of the pycnocline, must be interpreted with caution, the distribution shown here agrees generally with the concept of a cyclonic circulation as discussed below. In September 1976 the near-bottom salinity distribution revealed two tongues of relatively high-salinity water (>31°/oo) penetrating the sound from the west, roughly coincident with the two troughs in bottom topography south of Nome (Fig. 6-7). These features were not evident in summer 1977. A westward baroclinic coastal flow was present off Nome during August 1976 (Fig. 6-5), and was also reflected in the time-series current observations at station 22 (Fig. 6-9). The same region during 1977 appeared to be the site of vertical mixing 10-15 km offshore rather than of such a baroclinic current.

Winter observations were obtained in February 1978, and the temperature and salinity distributions at that time are summarized on vertical sections in Fig. 6-10. The entire water column was at the freezing point, or about −1.6 C. Density differences were due to salinity differences, and were small with variations less than one σ_t unit. Since observations did not extend into the eastern portion of the sound because that region was ice free during the field work, conditions there remain uncertain, but they were probably similar to those observed in the western sound. The western sound was characterized by weak horizontal and vertical density gradients. Density was about 0.2-0.3 lower in the eastern than in the western portion, and lower by about the same amount near the bottom than near the surface. The two-layered structure which was present during summer had disappeared, its place having been taken by more or less uniform and weak vertical density stratification. Convective cooling and ice formation had created vertically uniform temperatures at the freezing point, but some vertical salinity, hence density, stratification remained.

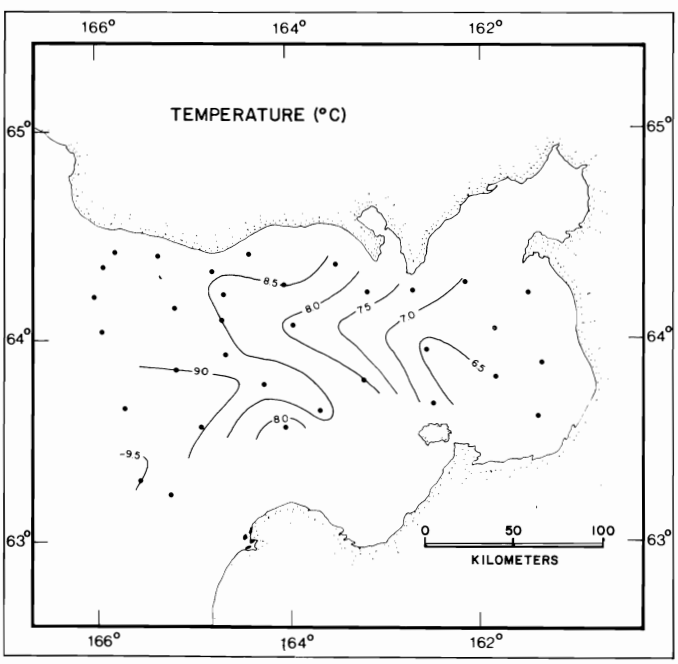

Figure 6-8. Distribution of temperature (°C) on σ_t = 21 in September 1976.

CURRENT OBSERVATIONS

Current measurements were obtained from taut-wire moorings, as time series from anchored vessels and as instantaneous vertical profiles from anchored vessels. Statistics of the taut-wire mooring current measurements are given in Table 6-2.

Five time-series current profiles were obtained at anchor stations along a transect south of Nome during summer 1976 (Fig. 6-14). While these were of too short duration to use in estimating mean flow, four of the five (22, 24, 25, and 26) were long enough to allow averaging out of the tidal signal. Moreover, they provide the only vertical distributions of current obtained in the region south of Nome. They are summarized as vector-averaged currents at each depth and presented along with vector-averaged winds observed from the anchored vessel (Fig. 6-9). The highest speeds observed were about 50 cm/sec and occurred near the surface at Station 22. Speeds decreased with increasing depth at that location to about 10 cm/sec near the bottom, and the direction rotated from northwesterly near the surface to west-southwesterly near the bottom. Mean speeds at stations 24, 25, and 26 were highest—12-18 cm/sec near the surface—and decreased to about 5 cm/sec near the bottom. Flow directions at these locations were in the northwest quadrant throughout the water column. Short-term fluctuations, having time scales of a few hours, were superposed upon the mean flow at each location (Fig. 6-11). The surface wind was considerably steadier with time than the currents.

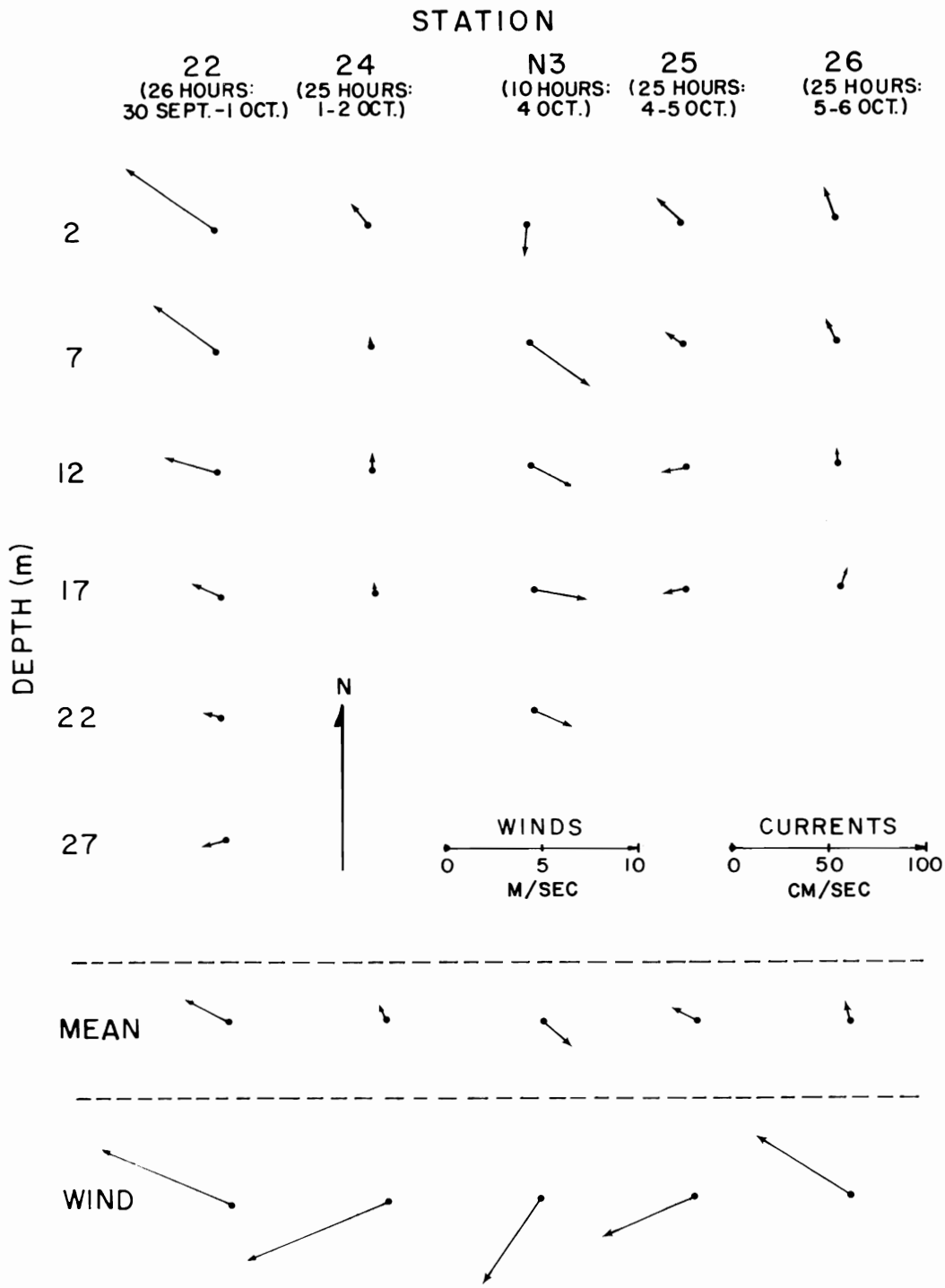

Figure 6-9. Vector-averaged currents and surface winds at the five time-series stations in western Norton Sound during September and October 1976. Mean current vectors are depth averaged. Station locations are shown in Fig. 6-14.

Two 44-day and one 14-day record were obtained from taut-wire moorings in summer 1977 (Table 6-2 and Fig. 6-12). An additional 45-day record, LD-5, was obtained during summer 1978 from nearly the same location as NC-21 off Cape Darby. Near-bottom records from this location during both summers indicated flows of order 1 cm/sec or less. The summer 1977 near-surface record at the same location was cut short due to instrument malfunction, but indicated northwesterly flows of 10-15

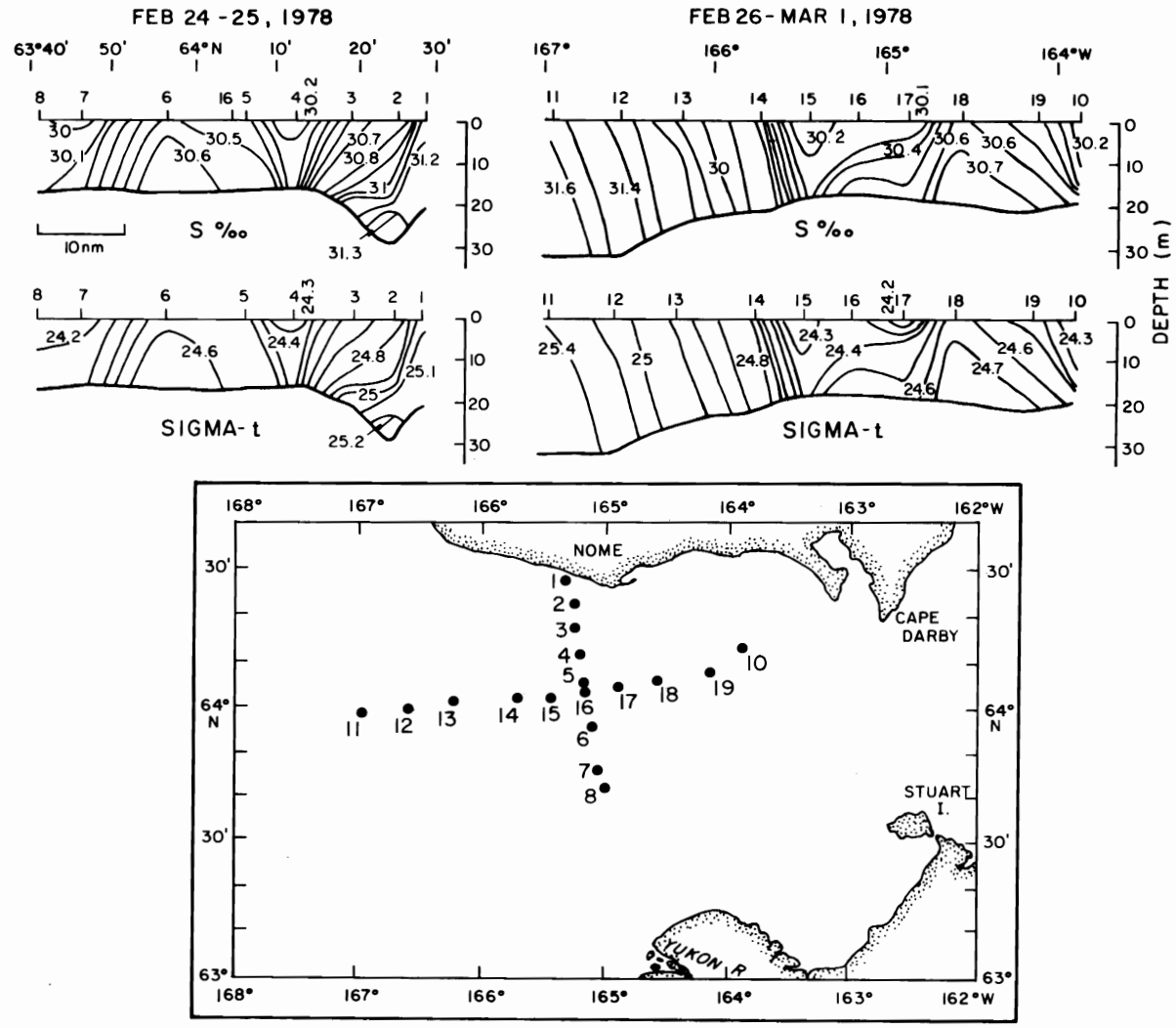

Figure 6-10. Vertical distribution of salinity and density (σ_t) along two sections during winter 1978.

cm/sec. The summer 1977 near-surface record from NC-20 in the central western sound indicated north-northwesterly flow at 10-15 cm/sec.

Overwinter records were obtained from moorings NC-14 and NC-15 in the western sound. These were both near bottom and bracketed the period from late summer to mid or late winter 1977. They indicate a mean current which was northerly in the central sound and northwesterly along the northern shore, with speeds of about 5 cm/sec.

All of the moored current records revealed non-tidal speed fluctuations which were large relative to mean flow speeds and had time scales of several days (Fig. 6-12), including occasional flow reversals.

DISCUSSION

Winter hydrographic observations made through the ice have established that Norton Sound becomes vertically well mixed during winter. This is common in high-latitude regions, as a consequence of vertical thermohaline convection due to surface cooling and ice formation. Observations during three summers reveal that well-mixed structure gives way to a regime which is strongly two-layered in temperature and salinity and hence also in density. Such a layered structure is generally typical of shallow oceanic regimes subject to tidal and wind mixing and buoyancy input. The upper layer is a consequence of the combined effects of wind mixing, freshwater influx, and solar warming, while the lower layer acquires vertical homogeneity through turbulence generated by currents at the bottom. The persistence of this structure in Norton Sound for several months each summer suggests that the time rate of change is small and that a small horizontal advection is balanced by other processes. The strong pycnocline between upper and lower layers inhibits vertical exchange of heat and salt. Our discussion examines these premises.

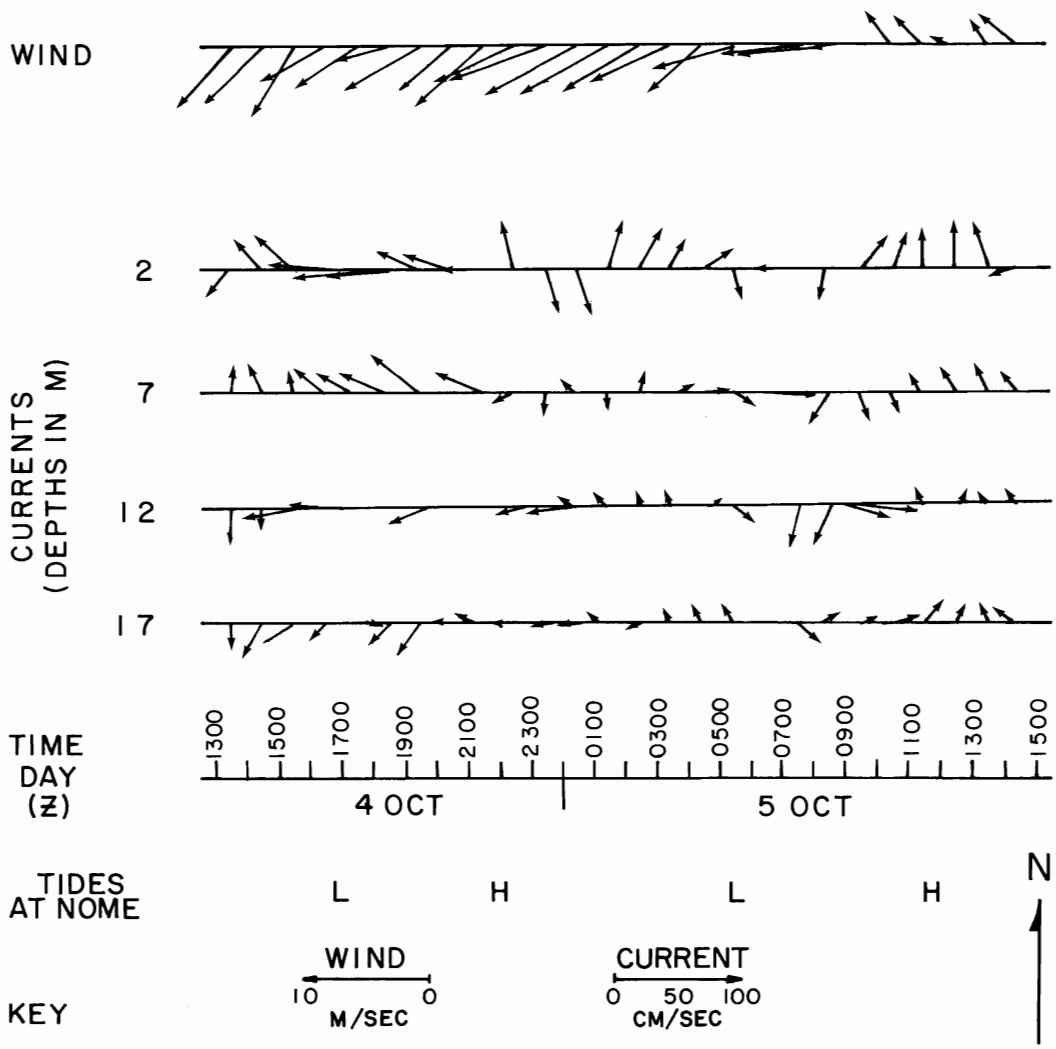

Figure 6-11. Hourly surface winds and currents at time-series station 25 in western Norton Sound during October 1976, illustrating short-term fluctuations.

Circulation

Horizontal property distributions tend to reflect circulation processes. During winter there was little horizontal variability; in summer the lowest temperatures and highest salinities in the upper layer occurred in the central western part of the sound. Elsewhere in the upper layer, temperature and salinity distributions, particularly in September-October 1976 and August 1977, indicate water mass continuity between the easternmost sound and a near-coastal band farther west along the northern coast. This structure suggests that a baroclinic coastal flow was transporting water from the eastern sound westward along the northern coast. The existence of this flow was substantiated both by subsurface density observations (Fig. 6-5) and current observations from station 22 (Fig. 6-9). The baroclinic feature was not present off Nome in August 1977, and hydrographic data obtained during July 1977 were inadequate to detect its presence or absence. Upper-layer current observations farther east off Cape Darby during July 1977 indicate that a westerly mean flow paralleled the coastline but was superposed upon a highly variable flow which included reversals. We conclude that westerly flow along the northern coast is a usual feature but may vary in intensity and extent. It was more pronounced and uniform during October 1976 than during August 1977.

Lower-layer temperature and salinity distributions differed from those in the upper layer, which suggests that advective processes were different in the two layers (Fig. 6-13). Temperature was lower and salinity higher in the eastern lower layer than in its

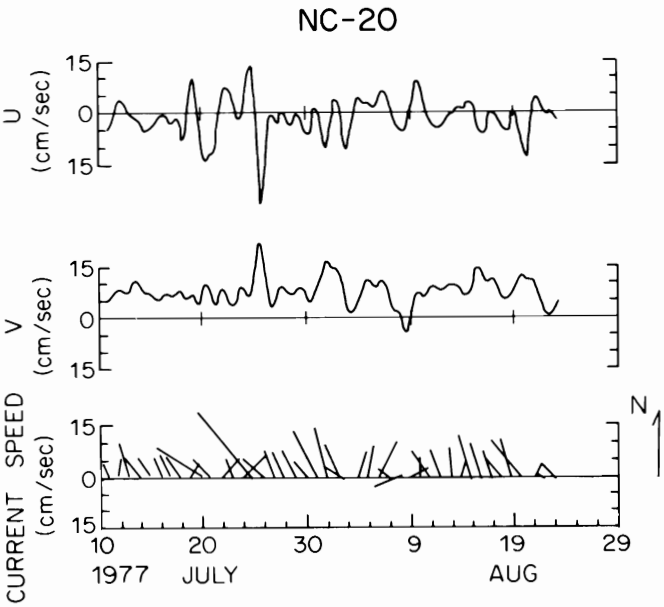

Figure 6-12. Low-pass filtered currents at 5 m depth at station NC-20 in Norton Sound, summer 1977; u and v are east and north components, respectively. Mooring locations are indicated in Fig. 6-14.

western part. This was most apparent in July 1977, less so in August 1977, and least obvious in September-October 1976. Deep temperatures in the eastern sound increased during summer, while salinity decreased; during July-August 1977 the record from a current meter (NC-21) moored in the eastern lower layer indicated that these changes were nearly linear with time. The cold (<0 C), saline (>34°/oo) deep water present in the eastern sound during summer 1976 and 1977 cannot have originated on the shelf to the west because water there was too warm and of too low salinity except in September 1976. This deep water can only have been a remnant of the preceding winter's convective layer, with elevated salinities resulting from salt exclusion as ice was formed. Observations during summer 1978 were sufficient to establish that this was not the case at that time as temperatures and salinities were similar in the eastern and western lower layers.

Sluggish circulation in the lower layer of the eastern sound was substantiated by observations. An advection rate along the lower boundary of the upper-lower layer interface can be estimated for September 1976 using temperature and salinity observations if we assume that the tonguelike low-temperature protrusion from the eastern sound (Fig. 6-8) reflected a steady-state balance between horizontal advection and lateral diffusion. A horizontal length scale of 100 km, applied to the empirical findings of Okubo and Ozmidov (1970), yields a lateral eddy conductivity of order 10^6 cm^2/sec.

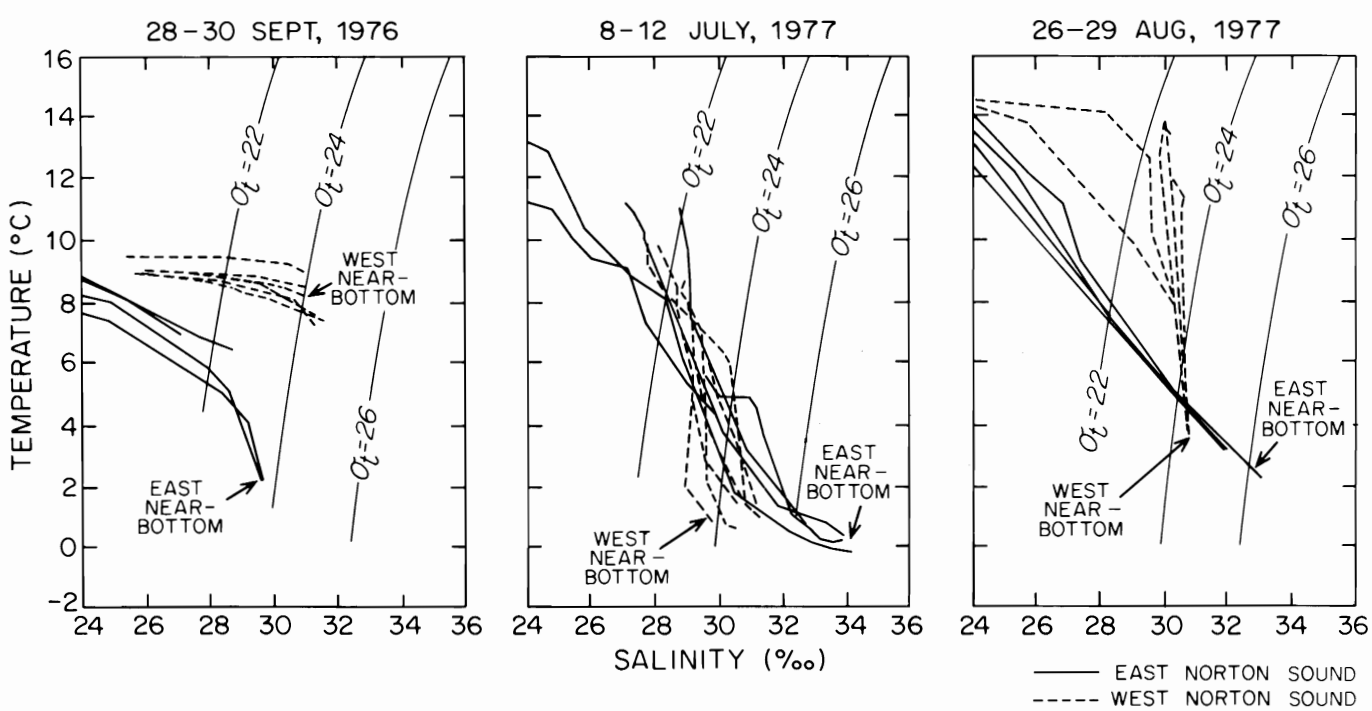

Figure 6-13. Temperature-salinity curves from selected stations in eastern and western Norton Sound during the summers of 1976 and 1977. Temperature and salinities were in fact continuous from east to west across the sound, but stations from the central sound have been omitted in the interest of clarity.

Application of the graphical method described by Proudman (1953) to the geometry of the tongue leads then to estimates of a westward advection rate of less than 1 cm/sec along its axis. During July-August 1977 the observed lower-layer current speed at NC-21 off Cape Darby was 0.13 cm/sec, a comparable value. During summer 1978 a near-bottom mooring at the same location (LD-5) showed a net flow of less than 1 cm/sec to the northwest—again in agreement. The cause of this sluggish circulation in the eastern lower layer is uncertain, but it is probably the extreme layering which could decouple the lower layer from upper layer motions. It does not appear that basin configuration plays a major role, although the promontory extending from the southern shore formed by Stuart Island may be sufficient to deflect to the north whatever easterly flow exists along that shore, preventing it from entering the eastern sound. There exists, however, no sill between these promontories which might prevent interchange of deeper waters, and there are no observations to support this hypothesis. The case for decoupling of motions at the horizontal interface between upper and lower layers will be examined in more detail below.

While upper- and lower-layer circulation appeared decoupled in the eastern sound, time-series observations obtained from the vessel during September and October 1976 did not reveal such decoupling in the western sound. Rather, there was a monotonic decrease in current speed, along with a slight rotation of flow direction, with increasing depth (Fig. 6-9). The four stations with long enough records to allow at least a crude attempt at averaging out the tidal signal (stations 22, 24, 25, and 26) all indicated northwesterly surface flow which became westerly near the bottom. This was in rough agreement with the moored current record from July-August 1977 (NC-20) which indicated a northwesterly near-surface flow in the same region, with an overwinter record at NC-15 which showed northerly flow, and with a near-bottom record off Nome which indicated a weaker westerly flow during September 1976-March 1977. These current observations suggest that western sound circulation was dominated by flow which penetrated only slightly eastward into the sound and was driven primarily by the northward flow over the shelf between Norton Sound and St. Lawrence Island (Fig. 6-14). Low-frequency (of order two days and longer) current fluctuations observed at all of the moorings NC-14, NC-15, NC-20, NC-21, and LD-5 were a major characteristic of the flow; they suggest that the cyclonic circulation driven by northward regional flow may penetrate eastward into the sound to varying extents and may at times

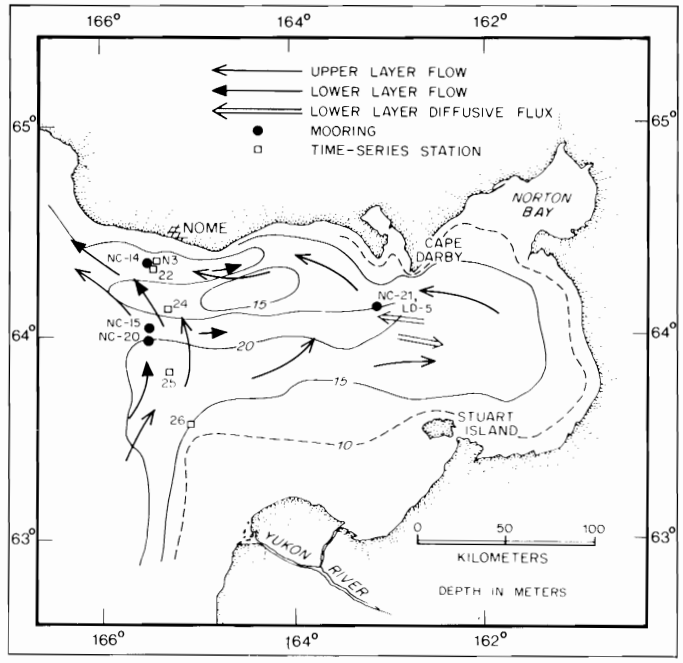

Figure 6-14. Schematic representation of circulation and mixing in Norton Sound based on the summer 1976 and 1977 hydrographic and current data. Locations of time-series current and CTD stations occupied in September and October 1976 and taut-wire current moorings are shown.

form a cyclonic loop within the western sound. The occurrence of northwesterly flow fluctuations at NC-21 off Cape Darby suggests that at least the upper layer of the eastern sound responds to fluctuations in the western portion, although a coherency analysis of near-surface current records from stations NC-20 and NC-21 did not reveal a significant coherency between currents at the two locations. Penetration of flow eastward to Stuart Island would require, by continuity, increased westward flow off Cape Darby. That remnant water was not present in the lower layer in summer 1978 suggests also that advection had occurred in the eastern lower layer prior to our observations. Therefore, it appears that at times eastward flow may penetrate into the eastern sound.

The role of northward flow on the Bering Sea shelf in inducing a circulation within Norton Sound is uncertain. A probable mechanism invokes the high-latitude tendency for conservation of potential vorticity to constrain streamlines to parallel isobaths. The northward regional flow would tend to follow bottom contours into the sound and contribute to a cyclonic circulation there. The potential vorticity argument requires, however, that friction be neglected, an assumption of debatable validity in view of the shallow depths in the sound. Regardless of cause, easterly flow entering the sound along its southern

shore, curving cyclonically to the north, would then be deflected to the west at the northern coast to satisfy volume continuity constraints.

Subtidal flow pulses observed in the time-series current records are a dominant feature of regional flow. Their cause is uncertain, but the shallow depths and broad horizontal extent of the regional shelf suggest that winds and atmospheric pressure events may play major roles. Coachman et al. (1975) have suggested that flow through Bering Strait is characterized by pulsations that depend upon north-south atmospheric pressure differences across the strait. A detailed analysis of this problem is beyond the scope of this chapter, and is treated elsewhere in this volume (Chapter 7).

Maintenance of layering

The extremely sluggish circulation and consequent isolation of the lower layer in the eastern sound in the summers of 1976 and 1977 are of particular interest because of their basic scientific implications and because similar conditions may also exist in other high-latitude bodies of water subject to similar conditions—for example, Kotzebue Sound (Kinder et al. 1977). Retention of temperature and salinity characteristics by this water for four to five months in a total water depth of about 20 m, despite wind and tidal mixing and insolation, suggests: (1) horizontal advection of bottom water into the eastern sound was negligible; (2) insolation, particularly significant during early summer because of long daylight hours, had been unable to penetrate the bottom layer sufficiently to cause appreciable warming; and (3) vertical mixing through the pycnocline was extremely slight through the summer. Of these possibilities, the first has been shown by temperature, salinity, and current observations to be the case. The second may be examined summarily in the light of observations of transmissivity made by using a beam transmissometer in the eastern sound during summer 1977. In the northeastern sound off Norton Bay, transmissivity was of order 10 percent. Transmissivities were somewhat higher farther south, but were still too low to allow appreciable penetration of solar radiation below the upper layer. Transmissivities in the lower layer were uniformly of order 10 percent throughout the eastern sound. The net result was to effectively prevent solar radiation from penetrating to the lower layer.

The extreme layering in the eastern sound can be examined in terms of maintenance of the horizontal interface between layers. This interface is characterized by high vertical gradients; as high as 4 C/m in temperature and 1.5^{o}/oo/m in salinity, with a corresponding Väisälä frequency of about 0.1/sec. Using the upper- and lower-layer current observations obtained from mooring NC-21 off Cape Darby, in conjunction with estimated mean vertical density distributions obtained at the beginning and end of the mooring period, a bulk interfacial Froude Number of about 10^{-1} can be estimated. This value suggests that little exchange due to turbulent mixing occurs across the interface. We may estimate a vertical mixing coefficient through the interface using a simple conservation of heat argument. Assume (1) that bottom water temperature at the end of each winter was near freezing (~1.7 C), as borne out by the winter 1978 observations, (2) that upper-layer temperature had reached 8 C by early August following a linear increase with time from early May when the ice first melted, and (3) that advective sources and sinks of heat can be neglected so that heat entering the lower layer all passes through the interface. The computed vertical mixing coefficient through the pycnocline was of order 10^{-2} cm^2/sec for both summer 1976 and 1977. These values are small compared with those computed for other oceanic regions, but are reasonable for the extremely strong stratification observed.

Buoyancy input into the eastern sound appears to be critical to maintenance of the two-layered structure there. Comparison of our data with those presented by Coachman et al. (1975) from the Bering Strait suggests that the vertical density structure in the western sound is continuous with that on the Bering Sea shelf to the west. The enhanced summer 1976 and 1977 layering in the eastern sound can be accounted for by additional dilution of the upper layer by local freshwater influx and solar insolation. Assuming an initial salinity of 30°/oo (see Fig. 6-10), about 10^6 m^3 of fresh water are required for the observed dilution. This can be roughly accounted for by using a mean annual runoff of 30 cm extrapolated from Nome over a watershed area of about 2.5×10^5 km^2. The Yukon River is a second source of freshwater influx and during midsummer runoff of order 10^4 m^3/sec could supply water sufficient to effect the observed dilution in about 10 days if the water were all to flow into the eastern sound. This amount of freshwater influx is equivalent to a buoyancy input of about 10^{-4} W m^{-2}. Assuming that solar insolation of 0.2 ly/min yields a buoyancy input to the upper layer of the same order, both insolation and freshwater influx are important to the buoyancy input. This compares with a bottom tidal dissipation of about 200×10^{-4} W m^{-2} computed using the same method as Schumacher et al. (1979). In other shallow shelf regions, 1-2 percent of the tidal dissipa-

tion is sufficient to vertically mix the water column. Our estimates suggest that buoyancy input to eastern Norton Sound is sufficiently high that tidal dissipation is inadequate to vertically mix the water column. We conclude that the persistence of this extreme layering in the eastern sound is due to the roles of freshwater influx and solar insolation in generating sufficient buoyancy to overcome tidal mixing. Low net advection in the lower layer is then due to decoupling from the upper layer across the sharp interface maintained by buoyant forces.

Hydrocarbon observations

September 1976 observations of dissolved hydrocarbons provide additional evidence in support of our proposed general horizontal circulation scheme for Norton Sound. Although the observations included other hydrocarbons, we consider here distributions only of methane, ethane, and propane. Most methane found in shallow shelf waters arises from biochemical reactions occurring in anoxic near-surface sediments. A prominent local source of methane may be used as a short-term water mass tracer, since it appears to be quasi-conservative over time and space scales such as we are dealing with in Norton Sound.

The near-bottom methane distribution in Norton Sound suggests a dominant source (2,242 nl/l) at the eastern end of the basin, with a sluggish, ill-defined northwesterly drift (Fig. 6-15). Methane-deficient water (250 nl/l) was apparently entering from the south near the Yukon River Delta with relatively little transport eastward along the southern coast. The high methane concentration in the southeast corner of the sound suggests either an increased source at that location or an extremely sluggish circulation, or a combination of these.

Coincident with the methane observations, a near-bottom plume of ethane- and propane-rich water was detected about 40 km south of Nome near station 24 (Cline and Holmes 1977). The hydrocarbons appeared to originate from a point source and drift northward toward Nome, then northwest along the coast, in agreement with the circulation scheme deduced above.

The Yukon River plume

The fate of Yukon River water remains problematic, though it seems likely that it is dominated by flow events rather than mean flow. The temperature-salinity and hydrocarbon observations obtained during the summers of 1976 and 1977 yielded no evidence that Yukon River water was advected eastward into the eastern sound. Rather, it appeared that Stuart Island might have contributed to blocking the easterly flow along the southern coast (Figs. 6-5 and

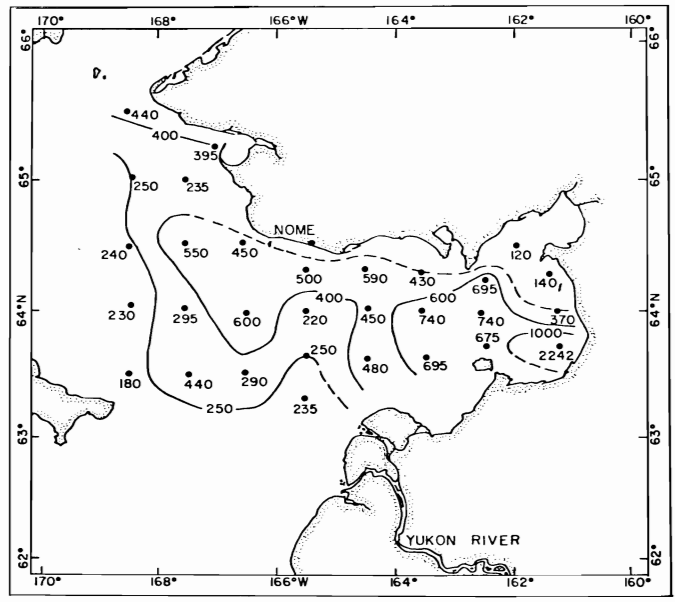

Figure 6-15. Distribution of dissolved methane 5 m above the bottom, September 1976, in nl/l.

6-6). It is of course feasible that sporadic flow of Yukon water had occurred earlier during either or both seasons, and that the observed upper-layer dilution was due in part to remnants of past Yukon water inflows. This may have been true before July 1977, when particularly low (<19°/oo) near-surface salinities were observed in the eastern sound (Fig. 6-7). The limited observations which indicated that the eastern basin had flushed out in summer 1978, resulting in deep-layer temperatures and salinities similar to those in the outer part of the sound, strengthen the supposition that appreciable eastward flow events may occur. The summer 1978 data were not however adequate to determine whether or not Yukon-diluted waters were in fact continuous between the eastern and western sound. A Yukon River origin for bottom sediments in the eastern sound suggests that Yukon water can enter there (Drake et al. 1980). The pulse-like events observed in the current records suggest, moreover, that water motion in the sound, particularly in the form of easterly migrations in the cyclonic flow, may be adequate to cause such additions. We have, however, no direct supporting evidence of such flow. R. Feely (PMEL unpublished data) has observed in data from summer 1979 a narrow coastal band of low-salinity surface water along the southern coast, which may be eastward-flowing Yukon water. However, no flow rates are available.

SUMMARY

Observations obtained from Norton Sound indicate

that in summer the regime was strongly two-layered in both temperature and salinity. The eastern and western sound were effectively separated into two distinct flow regimes at a line roughly coincident with the constriction formed by Cape Darby on the north and Stuart Island on the south. The eastern sound was more strongly layered than the western, and upper- and lower-layer flows were decoupled. The surface layer exhibited a weak tendency toward cyclonic flow, which was reflected both in the hydrographic observations and in moored current records. The eastern lower layer exhibited a near-zero mean flow allowing remnant cold, saline water from the previous winters' convective regimes to retain its identity in both 1976 and 1977 despite the shallow depth of the eastern basin. Sluggish lower-layer circulation was borne out by near-bottom moored measurements south of Cape Darby. Absence of the remnant water in summer 1978 suggested either that a flow event had flushed out the eastern basin or that less cold, saline water was produced in 1977-78.

Short-term time-series measurements in the western sound suggest that the upper and lower layers were not decoupled as in the eastern sound. These observations, in conjunction with moored current records and dissolved hydrocarbon distributions, support the concept of a northerly flow in the westernmost sound. The extent of this flow eastward into the sound may vary; it was apparently more intense in 1976, as evidenced by a strong westerly coastal current off Nome, than during 1977, when such a coastal feature was not observed. Large fluctuations relative to the mean flows, with time scales of several days, were observed at all moorings and suggest that instantaneous flow patterns in the sound may vary considerably.

The central western sound was a locus for vertical mixing as currents, primarily tidal, impinged upon a relatively shallow area. This was the only area where a breakdown in vertical layering was observed. We hypothesize that the relatively deep channels bracketing the shoal allowed occasional eastward flow of deeper, saline water that was then mixed upward leading to the observed higher local surface salinities.

At no time did we see flow of the Yukon River plume into eastern Norton Sound. It remains uncertain where the Yukon water goes: it appears likely that pulse-like flow events such as those observed at the current mooring sites may intermittently transport Yukon water into the eastern sound, or conversely, westward completely out of the sound. It may be entrained into the general northward flow west of the sound. Disposition of the Yukon River plume must be considered an appreciable regional problem.

The near-bottom water in the eastern sound presents an interesting case. It is highly unusual for water at these depths (about 15 m) to retain its temperature-salinity identity for several months without undergoing vertical mixing due to winds or tides or sufficient lateral advection or diffusion to alter its heat or salt content appreciably. Maintenance of this regime is due to a large buoyancy input, in the form of insolation and fresh water, to the upper layer.

ACKNOWLEDGMENTS

This study was supported in part by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multiyear program responding to needs of petroleum development of the Alaskan continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office. We are indebted to Dr. L. K. Coachman for suggestions in preparation of the manuscript, and to the anonymous reviewers who provided suggestions for improving it. The work could not have been carried out without the cooperation of officers and crew of R/Vs *Discoverer*, *Surveyor*, and *Sea Sounder*.

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