CHAPTER 7

Physical Oceanography

by

L.E. Hachmeister
and
J.B. Vinelli

Science Applications, Inc.
13400B Northrup Way #36
Bellevue, Washington 98005

ACKNOWLEDGEMENTS

SAI wishes to thank Tom Kozo and Don Schell's group for allowing use of their preliminary data in this analysis program. In addition, thanks are due to NOAA/OCSEAP personnel George Lapine, Mike Meyer and Mike Albertson for their support in coordination of the field work and to all the field staff for their assistance in collecting drifters during the summer program.

SUMMARY AND CONCLUSIONS

This report summarizes the major objectives and findings of a study of the physical oceanographic conditions on the inner shelf of the eastern Beaufort Sea of Alaska. The program was part of an integrated investigation of physical and biological processes active within and between the nearshore and lagoon/barrier island systems of the region. The physical oceanography program was intended to identify the general types of lagoon/barrier island systems found along the eastern Alaskan Beaufort Sea coastline and compare relative flushing and exchange characteristics in relation to potential vulnerability to effects of oil and gas development.

Flushing efficiencies of pulsing and limited exchange lagoons found in the eastern Beaufort Sea are considerably lower than the open lagoons studied farther west (e.g. Simpson Lagoon) and may rely on extreme local wind events to effect rapid exchange of lagoon and nearshore waters. Implications for oil and gas development activities in the eastern Beaufort of Alaska include the lagoon systems' extreme sensitivity to the introduction of surface or subsurface pollutants into the nearshore region, i.e. substances can be rapidly interjected into the lagoon system via tidal pulsing but only very slowly ejected from the system via tidal mixing. For example, if flushing of a lagoon system is such that the lagoon retains only 5% of a tidally input pollutant from the nearshore during one tidal cycle, subsequent tidal cycles acting to remove that pollutant from the lagoon will also be only 5% efficient; 95% of the initial pollutant concentration will remain after each cycle.

The major driving mechanism for water exchange and transport on the inner shelf of the eastern Alaskan Beaufort Sea, including the nearshore and lagoon systems, is derived from atmospheric forcing. The windfield determines both the direction and the intensity of the longshore current, the retention or removal of warm nearshore waters from the coast, the vertical mixing and horizontal exchange of lagoons, and (probably most importantly) the movement of ice and water on and off the nearshore region. In the western Beaufort this implies that year-round mean conditions will be very similar with prevailing winds primarily from the east. In the eastern Beaufort, winds are bimodal with prevailing winds from the west through the fall and winter and from the east in the spring and summer. Storms tend to produce winds from the northwest in both regions and can result in high longshore currents, especially in the fall when a large expanse of open water exists along the Beaufort coast.

Suggested future work includes an effort to obtain simultaneous current measurements on the inner shelf region of the eastern and western Alaskan Beaufort and an investigation into the dependency of flushing properties of pulsing and limited exchange lagoons on lagoon geometry and tidal and wind forcing.

INTRODUCTION

General Nature and Scope of Study

A physical oceanographic program was conducted to study circulation and exchange processes active within and between nearshore and lagoon regimes in the eastern Beaufort Sea. This program was part of an integrated investigation of physical and biological processes operating along the eastern Alaskan Beaufort coast which was intended to (1) describe the general types of lagoon/barrier island systems occurring in this section of the Beaufort Sea, (2) compare the observed lagoon types with the physical and ecological characterization already provided for areas farther west, e.g. the Simpson Lagoon-Jones Island system, (3) describe the overall biological production and processes in the nearshore region, and (4) identify those areas which might be especially sensitive to impact by oil and gas exploration. The goal of the physical oceanography program was to characterize the various types of lagoon/barrier island and nearshore regimes occurring along this part of the Beaufort Sea coastline and to determine the oceanographic processes which control the manner and rates of water exchange within and between these regimes. We conducted both a literature review of previous measurement programs in the region and a field measurement program in the eastern Beaufort Sea.

The general geographic region considered in this study included lagoon and nearshore regimes extending from Pt. Barrow eastward to the Canadian borders with emphasis on eastern areas. New field measurements were collected in a study area between Barter Island and Demarcation Bay (Fig. 7-1).

Specific Objectives

Within the overall task discussed above, specific program objectives of the physical oceanography program were:

1. To obtain field data sufficient to describe the major oceanographic processes occurring in pulsing and other limited exchange lagoons which affect hydrographic properties, flushing, and exchange rates with nearshore waters.
2. To obtain field data sufficient to describe the circulation patterns, hydrographic properties, and exchange rates on the eastern Beaufort nearshore shelf region.
3. To delineate and characterize the various types of lagoon and nearshore systems occurring along the Beaufort Sea coast of Alaska.
4. To compare the relative vulnerability of the various lagoon and nearshore regimes to possible effects of OCS oil and gas development.

Relevance to Problems of Petroleum Development

This study addressed two distinct environmental problems which might accompany OCS oil and gas development: (1) transport of oil products resulting in chronic leakage or catastrophic spills, and (2) adverse modification of the complex physical and biological ecosystems which support biological production and sustain standing populations. Study of the circulation and exchange processes within the region is significant in addressing the first problem since the specific areas affected by spilled petroleum products are dependent on their trajectories, rate of transport, and diffusion en route. This program therefore provided data on water circulation patterns and rates of longshore transport and lagoon/nearshore

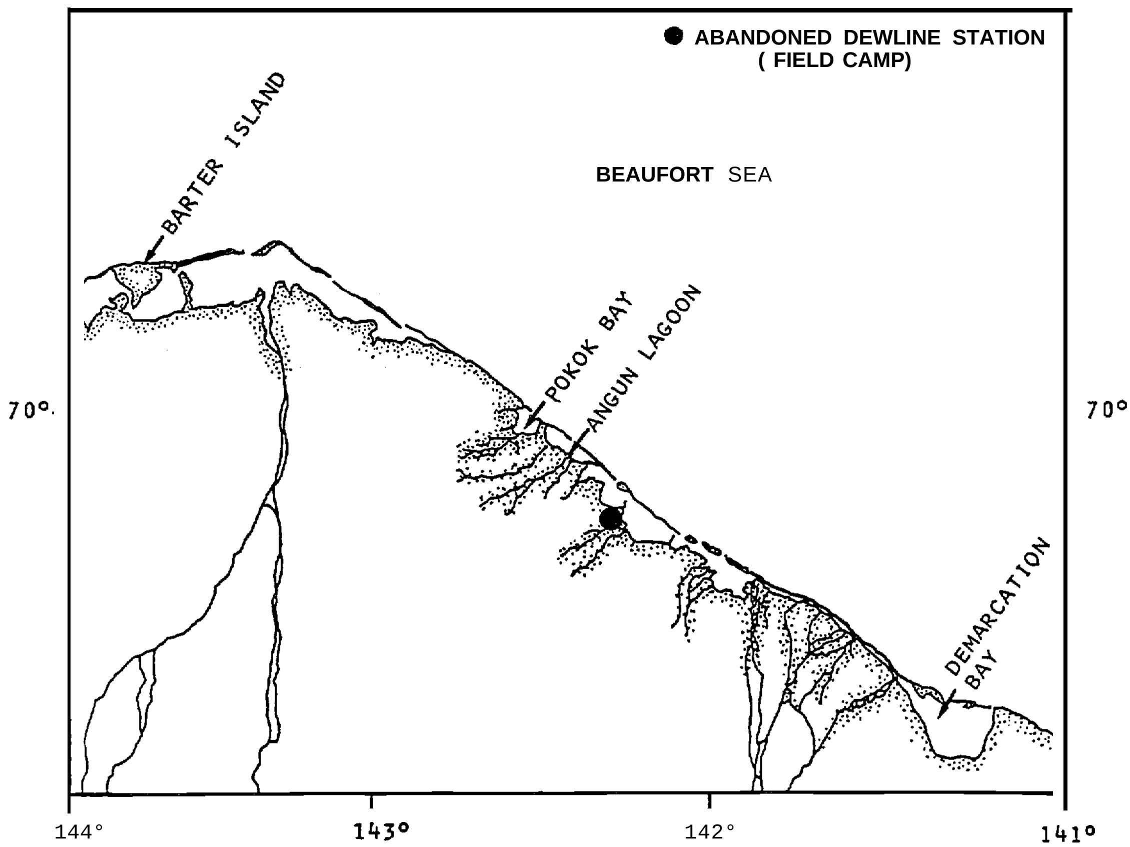


Figure 7-1. Map showing **geographical location of the study area.**

exchange, to be used in assessing the study area's vulnerability to OCS oil and gas development.

In addition, the data provided information relevant to concern over the second potential problem. That is, the physical processes which control the hydrographic properties, coastal circulation and exchange properties are important to the biological communities because they control the physical environments characteristic of the region and can either sustain or limit biological utilization in the region. The data obtained here will be of value in assessing impacts of OCS development.

Addressing both of these potential problem areas requires an understanding of the physical processes characteristic of the study region including the ocean circulation patterns, longshore currents, lagoon/nearshore exchange, flushing rates, and the driving mechanisms which result in the observed physical environment. The objective of this program, therefore, was to obtain the physical data required for this understanding.

CURRENT STATE OF KNOWLEDGE

Prior to this study, little oceanographic work had been accomplished in the nearshore region east of Barter Island or in limited exchange lagoon systems found in the eastern Beaufort. Considerable work, however, has been done on the shelf, nearshore, and lagoon systems in the central and western Beaufort and many of the characteristics of these areas may be applied in the eastern Beaufort.

Beaufort Shelf Characteristics

The physical setting of the Beaufort Sea is such that the Beaufort shelf is virtually completely covered by ice for all but two to three months of the year. The ice cover tends to insulate the underlying waters from both the atmospheric temperature and wind fields and to provide a source of dense brine in the winter and fresh meltwater in the spring and summer. Spring melting of the sea ice coincides with a massive influx of freshwater run-off from the land, both of which tend to stabilize the upper surface water, retain solar heat, and further enhance sea ice melting. Depending on the wind field for a particular year, the open water lead along the coastline may be as wide as 100-200 km and extend the entire length of the Beaufort Sea. The wind field in the western Beaufort is typically dominated year-round by easterly or northeasterly winds, whereas the eastern Beaufort exhibits dominant easterly and northeasterly winds in the summer and westerly and southwesterly winds in the winter. This wind pattern in the eastern Beaufort tends to move surface waters and ice offshore in the summer and onshore in the winter.

The entire Beaufort coast in general experiences relatively small changes in sea level due to astronomical tides (approximately 10-30 cm); however, meteorologically induced variations may range from as much as +3.0 m to -0.9 m (Schaeffer 1966; Matthews, unpublished data). The largest setup typically occurs in the fall when long stretches of open water are common and the winds have become predominantly westerly, driving water onto the shelf.

The shelf in the central and western Beaufort is relatively narrow with the shelfbreak typically occurring 80-90 km offshore. Lagoon systems which characterize this region of the Beaufort coastline have been termed ‘open” lagoons, open to the wind-driven longshore transport and to onshore/offshore transport due to numerous large openings in their offshore barrier island systems.

In the eastern Beaufort the shelf is slightly more narrow (approximately 40-60 km). The barrier island systems tend to be closer to the coastline, more extensive, and closed to direct flowthrough by the longshore current, thus limiting the exchange of water between the longshore currents and the lagoons to a small number of openings in the barrier island system (limited exchange lagoons). In many of these limited exchange lagoons, the exchange of water is restricted to one or two major entrances. These lagoons, which typically have very narrow entrances, exhibit highly localized current jets at the entrances in response to periodic tidal forcing and have been termed ‘pulsing” lagoons.

Patterns of water movement on the shelf tend to exhibit strong continuity in the longshelf direction (paralleling isobaths) and large zonal variability in the cross-shelf sense (crossing isobaths). Following Aagaard (1981), the region of the shelf landward of the 40-m isobath which exhibits one set of characteristics will be referred to as the ‘inner” shelf; the region seaward of the 40-m isobath will be termed the 'outer" shelf. That area of the inner shelf landward of the 20-m isobath with activity marked by the ice and/or surface waves, and which exhibits higher summer temperatures and lower salinities than the water between 20 and 40 m, will be referred to as 'nearshore" following Truett (1981).

An excellent discussion of hydrographic properties and circulation patterns in the entire Beaufort inner and outer shelf is presented by Aagaard (1981). A general summary of that discussion and the results of other researchers is given here.

Outer Shelf

The most prominent hydrographic feature on the outer Beaufort shelf is the summer subsurface temperature maximum typically observed at or seaward of the 40-m isobath. This temperature maximum is associated with an eastward flowing core of water originating in the Bering Sea as observed by Mountain (1974a,b) and others. The flow is actually composed of two distinct water masses referred to as Alaskan coastal water and Bering Seawater (Mountain 1974a). The Alaskan coastal water is formed along the Bering and Chukchi Sea nearshore region from a combination of warmed Bering Sea water and low salinity coastal runoff. The colder and more saline Bering Sea water moves below the Alaskan coastal waters and at a slightly slower velocity (Mountain 1974b). Alaskan coastal water signatures can typically be seen as far east as 150°W longitude where it mixes with local surface water, whereas the Bering Sea water has been observed as far east as Barter Island. This Bering Sea water follows the 40- to 50-m isobaths throughout the American sector of the Beaufort Sea during the summer months and provides a good demarcation zone for separating the inner and outer shelf regimes.

The mean circulation pattern of subsurface waters on the outer shelf is predominantly eastward paralleling the isobaths. Aagaard (1981) and others have suggested that this mean flow, observed during both summer and winter months, is driven by the difference in sea level between the Atlantic and Pacific oceans and extends across the entire Beaufort shelf, possibly as far east as Baffin Bay. There is some evidence that surface waters above this eastward flow may have mean westward motion although no direct current measurements confirming this hypothesis have been made. Currents in both the surface and subsurface waters can be affected by periodic meteorological forcing with typical periods on the order of 3-10 days and may show reversals in the mean eastward flow which are in turn correlated with deep upwelling events on the outer shelf.

Inner Shelf

Although current measurements on the inner shelf are extremely sparse due to the difficulty of maintaining moorings in the presence of sea ice, recent drifter data reported by Matthews (1982) and current meter measurements made by Aagaard (1981) give some indication of both open water and ice-covered water movements. It has been generally agreed that water movement on the Beaufort inner shelf is wind-driven. This hypothesis is further supported by Matthews' drifter data which suggest that the motion of all recovered drifters resulted from prevailing wind-driven currents, both for open water and under-ice releases. Drifter travel times and computed current speeds were consistent with values of approximately 3-4% of the wind transport for the same periods with under-ice motion being significantly less. Aagaard (1981), in direct winter current measurements on the inner shelf near Narwhal Island, also reports that the under-ice water movement was quite slow but that the observed (0.1-0.3 cm/s) net movement was observed to redirected toward the west consistent with the mean wind direction. Daily current speeds and directions, however, were observed to be as high as 5-10 ends and closely followed the variability of local wind patterns.

If these conditions can be extrapolated to the eastern Beaufort Sea then current patterns on the inner eastern shelf would be expected to show a more even distribution of both easterly and westerly currents. As discussed previously, prevailing winds along the central and western Beaufort are from the ENE during all seasons. However, In the eastern Beaufort the distribution of winds is more bimodal. At Barter Island, for example, the average winds are from the ENE to E for 35% of the time and from the WSW to W for 25% of the time (Searby and Hunter 1971) with winds predominantly from the west during the winter and from the east during the open water season (Brewer et al. 1977). If the inner shelf waters in the eastern Beaufort follow the local wind patterns one could expect to observe mean current patterns to the east in the winter and to the west in the summer following local wind patterns.

Transverse circulation on the inner shelf may result from one of several possible driving mechanisms. Dense brine formation occurs in the winter during the freezing process in the inner shelf. This dense water flows offshore along the bottom under the influence of gravity and is most likely accompanied by an onshore return flow in the upper layers. While this mechanism is probably more important during the early portions of freeze-up, especially in the more shallow nearshore waters, it probably continues throughout the winter months to some degree.

The second effective mechanism for inducing cross-shelf circulation results from the presence of large amounts of warm fresher water in the nearshore during spring and summer months. In this case, the less dense nearshore waters move offshore driven both by the accumulation of runoff in the nearshore and the lateral spreading effect induced by gravity. This offshore surface flow (and most likely accompanying onshore bottom flow) is similar to estuarine flow except that the effect is observed along the entire coastline. Later in the summer, when freshwater input is reduced, the warmer and less dense nearshore water may still respond to the effects of lateral spreading and continue the process although to a lesser degree.

The third mechanism for inducing cross-shelf circulation is wind-driven currents. In the western Beaufort this effect would be predominantly offshore in the upper layers and onshore in the lower layers due to the predominantly ENE winds. However, in the eastern Beaufort the effect would be similar to the western Beaufort pattern during easterly wind events and in the opposite sense (onshore flow in the upper waters and offshore in the lower layers) during westerly wind events. Seasonal variability would therefore show a net offshore transport of surface waters in the summer and onshore transport in the winter. This effect also has implications for the presence of nearshore ice in the eastern Beaufort during the summer months and for nearshore water available for the exchange with local lagoon systems.

Considerable research has been accomplished in the central and western Beaufort nearshore and lagoon regions. Results of one such program are summarized in Matthews (1979). Results of this multi-Year field measurement program in the central Beaufort between Flaxman Island on the east and Oliktok Point are consistent with present understanding of lagoon and nearshore flow. Winter conditions find dense brine (more than 40 ppt) collected in Simpson Lagoon waters deeper than 2 m with temperatures near -20C, moving slowly in response to tidal forcing. Complete flushing of the lagoon occurs during river overflow in early June (6-8 June yearly average). Maximum runoff lasts for approximately 10 days and freshwater conditions persist for perhaps one month, depending on wind conditions. Following this, saline water appears again in the lagoon and high solar radiation heats bottom waters to as high as 10-12°C. Matthews notes that the month of August is marked by the appearance of cold and saline frontal systems moving through Simpson Lagoon and alternating with warmer brackish water. The presence of storms vertically mixes the shallow nearshore and lagoon waters but the frontal systems continually re-establish themselves throughout the summer months.

Observed currents in the lagoons and nearshore appear to be predominantly wind-driven with current speeds approximately 3-4% of the wind speed. Superimposed on these mean wind-driven currents are short-term effects of storm passages and tidal. effects which are dominated by diurnal M2 forcing. Current speeds are such that flushing rates in open-type lagoons similar to Simpson Lagoon may be on the order of 3-4 days with mean easterly winds.

STUDY AREA

The "PREFACE" to this volume gives a general description of the overall study area. However, Figures 7-1 to 7-3, Figure 7-5, and Figure 7-17 in this Chapter on 'Physical Oceanography" gives specific locations of field sampling efforts associated with this part of the project.

METHODS AND RATIONALE FOR DATA COLLECTION

A field sampling program to assess the physical processes occurring in pulsing-type lagoons and the nearshore shelf region of the eastern Beaufort Sea (Fig. 7-1) was conducted in two phases intended to coincide with early summer and fall conditions in the Beaufort Sea lagoon systems. Early summer conditions are characterized by an abundance of heat and freshwater input to the nearshore region, whereas fall conditions are characterized by cooling and a lack of freshwater. In addition, the two periods generally have dissimilar meteorological conditions, with easterly winds typically dominating in the early summer and westerly winds dominating in the fall. Nearshore circulation patterns were expected to differ during these times since they are largely driven by the area's meteorology and since storms through the area increase in frequency as fall approaches, therefore increasing the storm-surge-induced movement of offshore water to the nearshore and lagoon regions. The physical oceanography field measurement program was designed to address these differences between the two periods and to characterize the influence of the lagoons on the biological processes in the nearshore shelf regions.

The planned measurement program was based on a series of lagoonal, nearshore and mid-shelf current meter moorings. Measurements from these moorings were to be supplemented by a CTD survey, intended to define the distribution of water types found in the region, and a series of bottom and surface drifter deployments and recoveries intended to indicate the trajectories of the nearshore surface and subsurface waters. Vessel support for the Phase I field program was provided by OCSEAP using the M/V HOOD and NOAA helicopters. The second phase of the field program was conducted by using Zodiac rubber boats.

Phase I: 21 July-8 August 1982

Current meter moorings were planned for the Angun Lagoon entrance and the 20- and 40-m depth contours in a line extending from the Angun Lagoon entrance toward 350 True North. The mooring in the Angun Lagoon entrance consisted of a Neil Brown acoustic current meter and an Aanderaa water level recorder. The two offshore moorings were cancelled due to ice conditions during the first phase of the program, and two current meters with temperature and conductivity sensors were instead deployed in the interior of Angun Lagoon and Pokok Bay to monitor the time rate of change of water properties in the two basins. Another planned mooring in the Pokok Bay entrance was not deployed due to the large ice blocks moving into the lagoon through the entrance at the planned time of deployment.

Sets of surface and bottom drifters were deployed along the lagoon barrier islands and were recovered during the several days following each deployment. The inferred trajectories from this quite successful program were examined in light of concurrent meteorological and current measurements in the area. The planned CTD survey of the offshore area was not conducted due to lack of ship support early in the field program and severe ice conditions which later developed.

Phase 11: 7 September-15 September 1982

Phase II of the field program was intended to observe the properties of the lagoon/nearshore exchange during periods of low or no freshwater input to the system and of decreased surface warming.

The principal activities planned for this phase of the sampling program were recovery of the current meter moorings, CTD surveys, and surface and bottom drifter deployments/recoveries. Current meter moorings deployed in Angun Lagoon and Pokok Bay during Phase I were recovered during this second phase. Because the MV HOOD was not available for Phase II, the CTD survey was conducted from a Zodiac on an A-frame especially constructed to both recover the current meter moorings and perform CTD tasks. The CTD survey was somewhat limited due to lack of navigation equipment on the Zodiac and heavy concentration of nearshore ice; in addition, the CTD batteries could not be recharged after their initial use in the lagoon survey due to power failure at the base camp, thus preventing much of the planned lagoon CTD work. The Phase II surface and bottom drifter deployments/recoveries also were cancelled due to heavy concentrations of sea ice along the outside of the barrier islands in the region.

RESULTS

Results of the field sampling program are presented separately for current and hydrography measurements. Some measurements are also presented from the concurrent meteorological and primary productivity progr ems.

Current Measurement Program

Current measurements were collected in the study area using both Lagrangian and Eulerian techniques. Lagrangian techniques consisted of deployment and recovery of surface and bottom dri.fters in the nearshore region and lagoons; Eulerian techniques consisted of current meter moorings in the entrances and interiors of Angun Lagoon and Pokok Bay.

Drifter Study

During the first phase of the field program, five deployments of seabed drifters and eight deployments of surface drifters were performed between 26-29 July 1982. The seabed drifters consisted of a hemispherical head of 18-cm diameter, attached to a weighted tail-like shaft 50 cm long; the surface drifters were yellow polypropylene 2-1/2" by 3-1/2" in size. The seabed drifters were deployed in groups of 25 and the surface drifters in groups of 50, marked to identify their original deployment site. Scheduled recovery of the drifters by oceanography program personnel were planned at low tide for two days following deployment and on opportunistic helicopter and Zodiac trips in the study area during the remainder of the field program. Table 7-1 lists the times of each of these deployments and the number of drifters deployed. Figure 7--2 indicates the place of deployment for each drifter type. Of 400 surface drifters deployed only 33 were ever recovered; of the 125 seabed drifters which were deployed, 20 were recovered.

Seabed and surface drifters were deployed to estimate the longshore water trajectories and maximum observed current velocities in the study region. The longshore or littoral current is directly linked to the intensity and direction of the wind. During the 24-hour period following

Table 7-1. Drifter deployments.

Type	Group	Deployment Date/Time		No. of Drifters Deployed	Wind Speed	Wind Direction
Seabed	1	7/26/82	12:25	25	7.3 m/s	205 'T
Surface	A	7/26/82	12:25	50	7.3 m/s	205 'T
Surface	B	7/26/83	12:45	50	7.3 m/s	205 'T
Seabed	2	7/26/82	12:55	25	7.3 m/s	205 'T
Surface	C	7/26/82	2:55	50	7.3 m/s	205 'T
Seabed	3	7/26/82	3:15	25	7.3 m/s	205 "T
Surface	D	7/26/82	3:15	50	7.3 m/s	205 'T
Seabed	4	7/29/82	2:45	25	6.3 m/s	65 'T
Surface	E	7/29/82	2:45	50	6.3 m/s	65 'T
Seabed	5	7/29/82	14:00	25	6.6 m/s	69 'T
Surface	F	7/29/82	14:00	50	6.6 m/s	69 'T
Surface	G	7/29/82	14:00	50	6.6 m/s	69 'T
Surface	H	7/29/82	14:00	50	6.6 m/s	69 'T

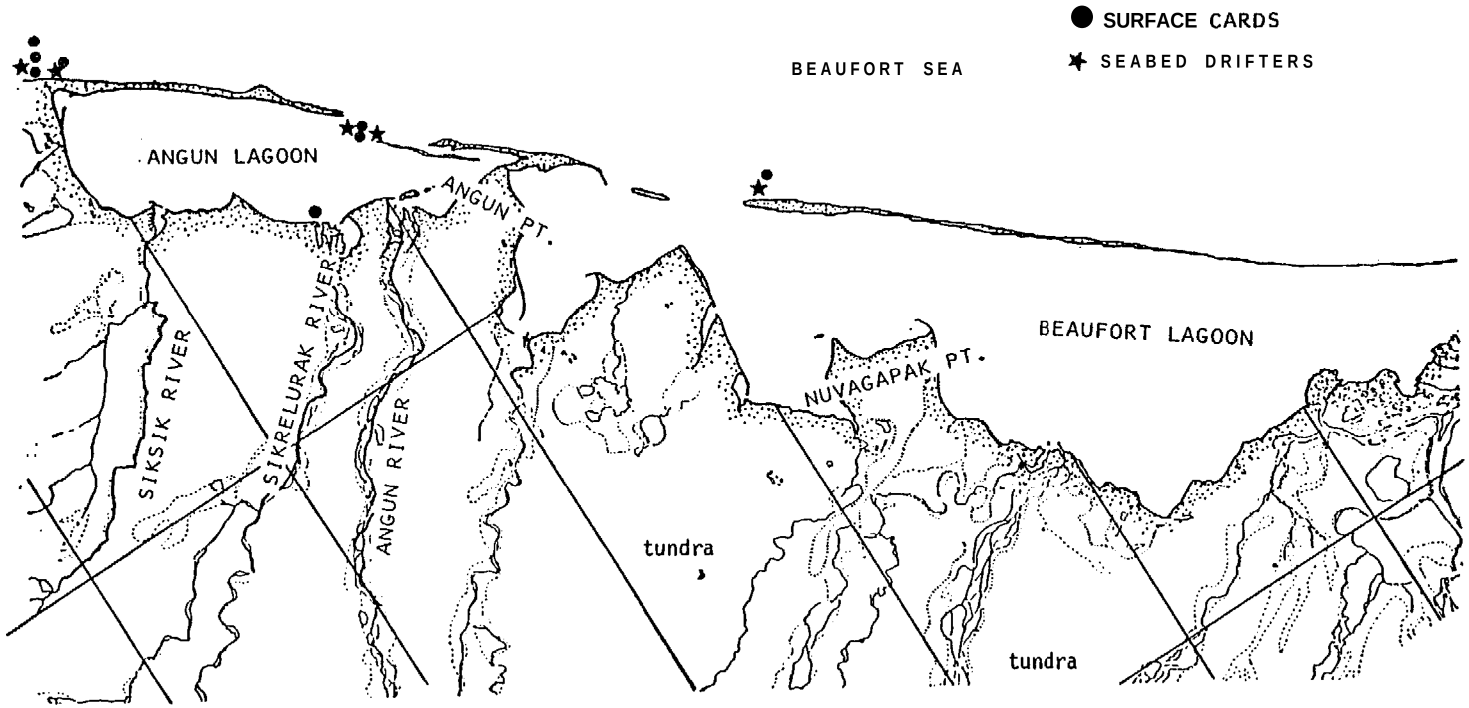


Figure. 7-2. Sites of surface and seabed drifter releases on 26 and 29 July 1982.

the release of the drifters on 26 July, wind speeds and directions varied from 2.7-l 2.7 m/s and 145-295°T with a mean of 7.3 m/s from 205°T. The end of the period, however, was dominated by a storm with 12-hour average winds of 11.4 m/s from the WNW. These winds approximately paralleled the coastline in the study area and to a large extent determined the fate of the drifter motion.

Figure 7-3 shows the sites for the seabed drifters deployed on 26 July during dominant westerly winds. If Matthews' criteria (nearshore transport approximately 3-4% of the wind) is employed, then drifters not beached on the first low tide (approximately 24:00 26 July) should have been swept completely from the study area to the east by the second low tide (approximately 23:00 on 27 July). With these criteria, the highest seabed drifter speeds observed ranged between 0.17-0.22 m/s for four recoveries on 26 July following the low tide. Some further longshore transport also probably occurred after beaching on the subsequent high tide prior to recovery but this amount should be minimal having occurred on the beach. Average wind speeds measured at Beaufort Lagoon during this period were 5.3 m/s. Although this is a very crude approximation, water velocities appear to be a few percent (approximately 3-4%) of the wind speed, which is consistent with Matthews' observations.

Surface drifter recovery from the 26 July deployment was far less successful with only 16 recoveries out of 200 drifters deployed. No recoveries were made from one set of 50 drifters deployed off the barrier island at Nuvagapak Point in Beaufort Lagoon. Figure 7-4 shows the sites of surface drifter recoveries (as stated above, any drifters not recovered prior to the low tide on26 July were probably swept from the area). No attempt to calculate surface drifter velocities was made because all drifter recoveries were made 3-7 days after deployment rather than within 1-2 days following deployment, as was the case of the seabed drifters.

Wind conditions for the second drifter deployments on 29 July were nominally 6.5 m/s from the ENE during the 24-hour period following deployment. These conditions are considerably different from those experienced during the first deployment and more closely characterize summer conditions in the eastern Beaufort Sea. Figures 7-3 and 7-4 show the sites for seabed and surface drifter recoveries for the 29 July

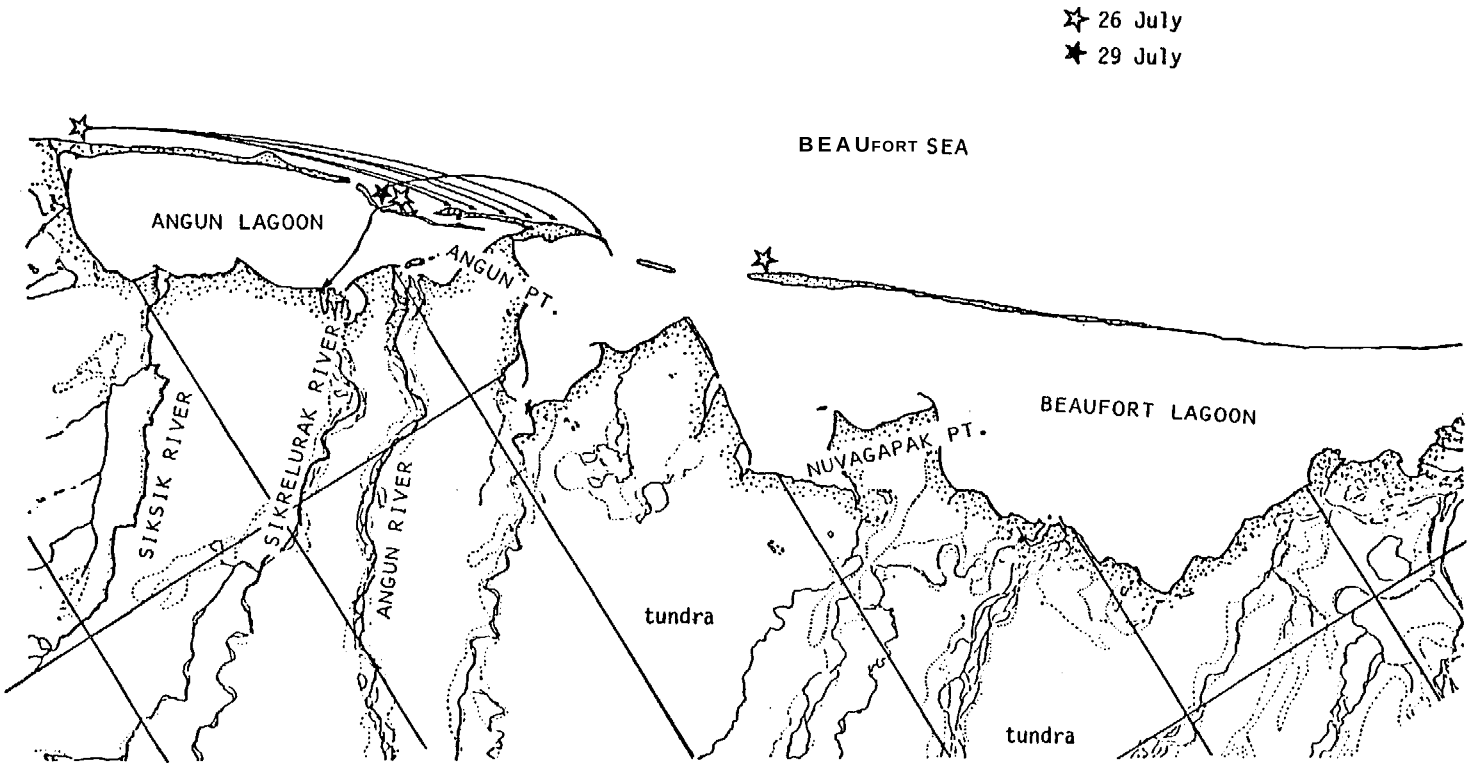


Figure 7-3. Trajectories of seabed drifters deployed 26 and 29 July 1982.

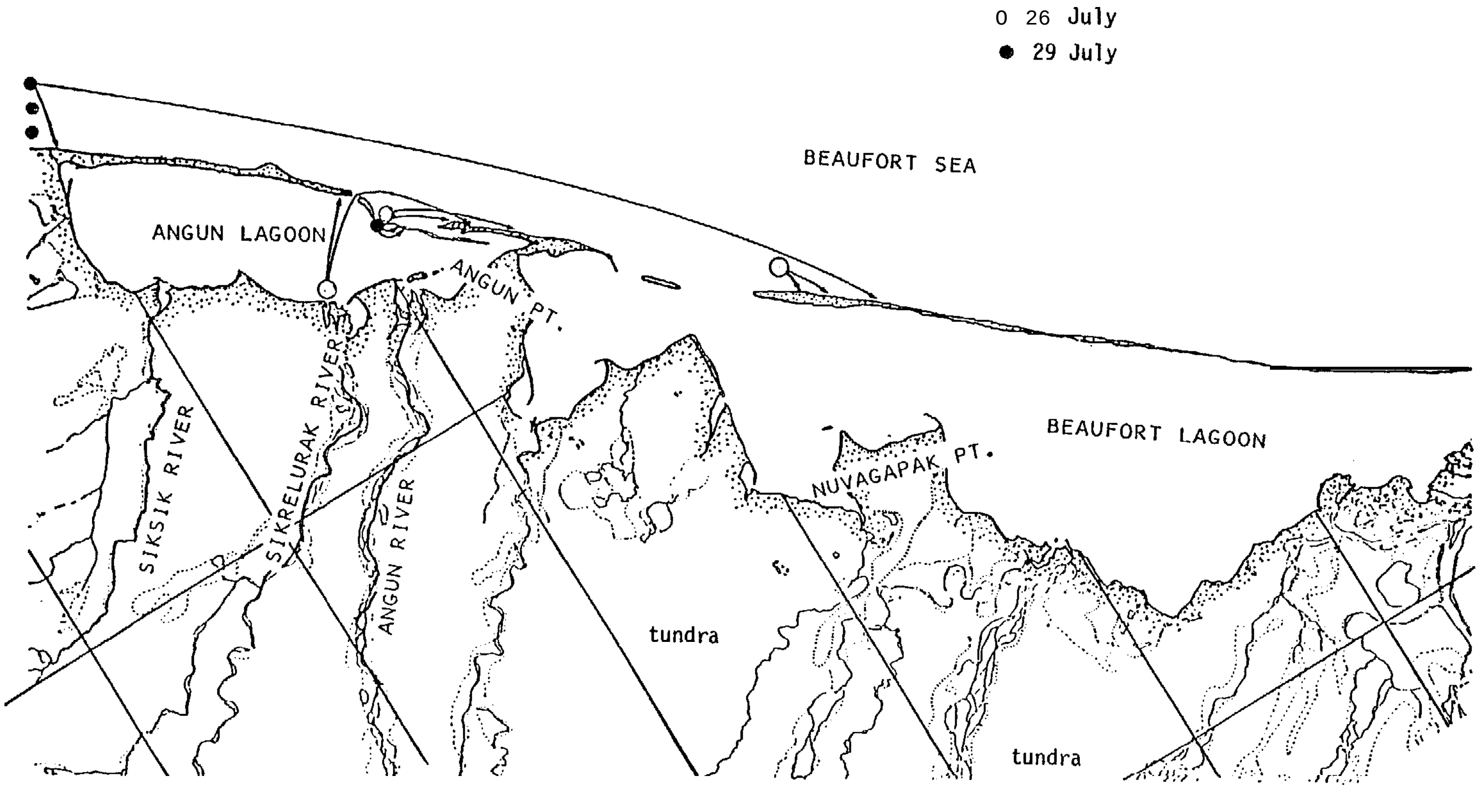


Figure 7-4. Trajectories of surface drifters deployed 26 and 29 July 1982.

deployments. Note that, although the winds were from the east for the 24-hour period following deployment, all motion appears to remain predominantly to the east rather than the west, as would be anticipated given the dominant wind conditions. However, this conclusion is biased by eleven surface drifter recoveries accomplished 1.75 hours after deployment which showed eastward current speeds of 0.32 m/s. This speed was calculated from recoveries made only three hours after the winds had shifted from a three-day period of NW winds and a residual longshore current to the east could have been present when deployment occurred.

It is significant that no seabed drifters were recovered until 12 hours after the winds shifted from the ENE (which would tend to move the drifters offshore) to more than 6.o kt from the WNW (which would tend to move the drifters back onshore) on 31 July. These WNW wind conditions then persisted for six days during which time all of the seabed drifters which were eventually recovered were found. Of the 200 surface drifters deployed during the ENE winds, only six were recovered after the first 11 deployed at Angun Entrance were picked up two hours after deployment. Results of the surface and bottom drifter studies substantiate the belief that westerly winds trap warm coastal water in the nearshore region and transport this water along the coast at from 3-4% of the wind speed. Conversely, easterly winds move the warm nearshore waters offshore to be replaced by cooler water from the midshelf region.

Figures 7-3 and 7-4 also show the bottom drifters which were deployed outside of Angun Lagoon and were recovered on the far side of the lagoon interior, and the surface drifters which were deployed on the far side of the lagoon interior and were recovered outside the lagoon, thus substantiating hydrographic results, which indicate net bottom transport into the lagoon and net surface transport out of the lagoon (these results will be further discussed in the Hydrographic Data section).

Current Meter Moorings

As part of the physical oceanography sampling program for this project, three current meter moorings consisting of one current meter per mooring were deployed in Angun Lagoon and Pokok Bay (locations are indicated on Fig. 7-5). These moorings included two Aanderaa current

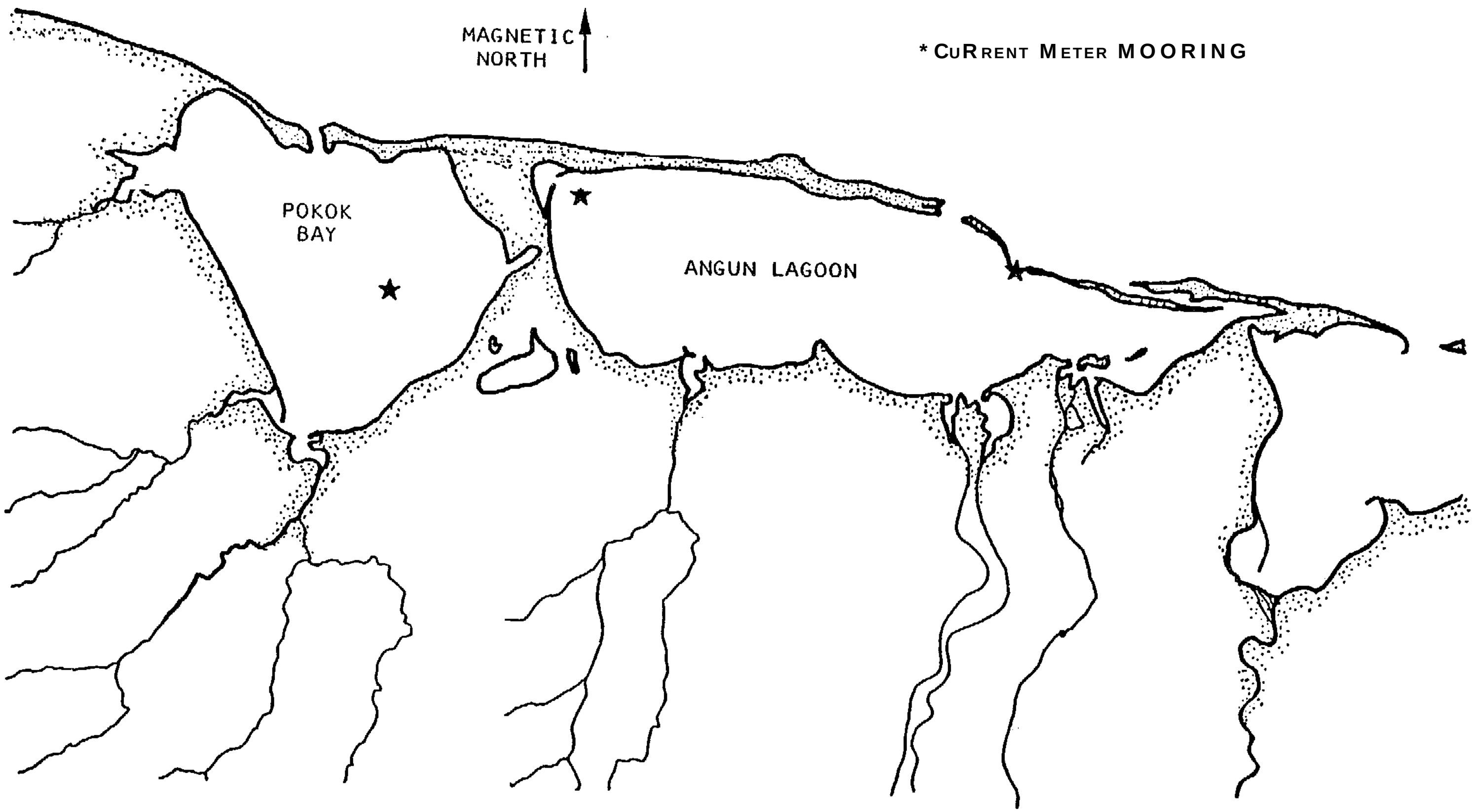


Figure 7-5. Location of current meter moorings in Angun Lagoon and Pokok Bay,

meters, one Neil Brown (NBIS) acoustic current meter, and one Aanderaa pressure and temperature meter. The Aanderaa current meters were deployed in Pokok Bay and the western end of Angun Lagoon. The NBIS current meter was moored in the main channel of Angun Lagoon. The Aanderaa pressure sensor was attached to the NBIS current meter for 11 days until it was detached by an ice floe; it was then redeployed adjacent to the Aanderaa current meter in the western end of Angun Lagoon.

As a sample of the data collected in Angun Lagoon and Pokok Bay, Figure 7-6 shows the output from the NBIS current meter and the Aanderaa pressure meter while both were located in the Angun Lagoon channel. The variables plotted are depth, temperature recorded by the NBIS current meter, temperature recorded by the Aanderaa pressure meter, and estimated long- and cross-channel current speeds. The long- and cross-channel speeds were estimated by rotating the north and east current components in the direction parallel and normal to the Angun Lagoon entrance (35°T; positive values indicate flow out of the lagoon). A one-hour filter was applied to the current and water level measurements.

The measured data confirm visual observations of high tidally-driven currents through Angun Lagoon entrance (12-hour M2 tidal component predominates the records). Despite the high current speeds, tidal height variations are only on the order of 20 cm superimposed on meteorologically-induced driven events (approximately 50-100 cm) occurring on scales of several days.

A rough estimate of the volume transport in and out of the main Angun Lagoon channel was made using the data gathered by a current reeker in the channel. The channel profile was estimated from depth sounding data collected during the field program and a logarithmic velocity profile was assumed. This calculation indicated that flow through the instrumented entrance can account for over 60% of the level variations observed in the lagoon. Two other entrances were less than a meter in depth although one is almost 60 m in width. The main entrance to Angun Lagoon is approximately 25 m wide and 5 m deep with very steep sides. As observed in Figure '7-6, current speeds were in excess of 1 kt during peak ebb and flood periods at a distance of approximately 1 m from the bottom. Maximum observed surface currents during these periods were visually estimated at greater than 2 kt.

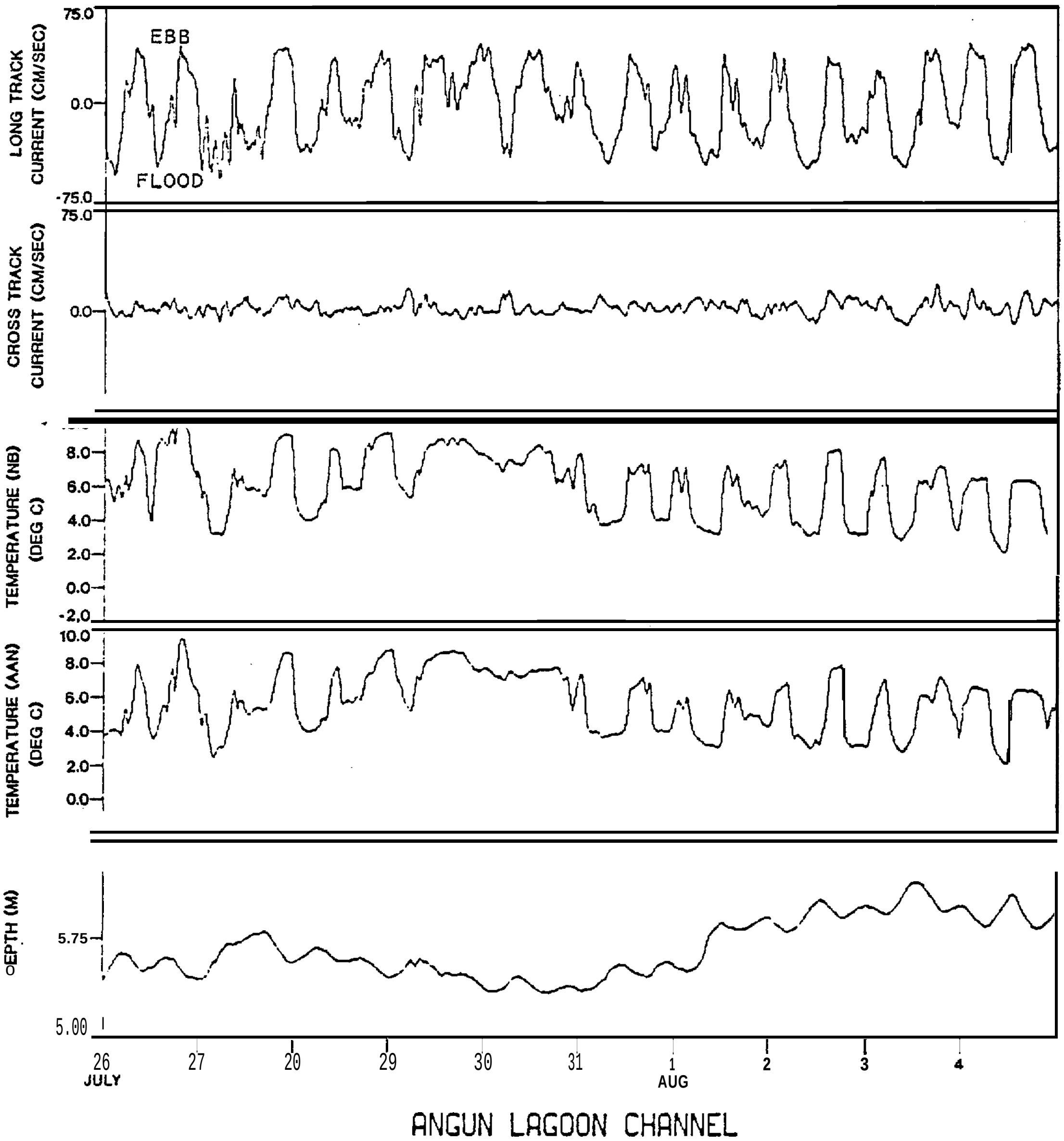


Figure 7-6. Time series plot of one hour lowpass-filtered current and temperature data recorded by a NBIS current meter (top three plots) and by an Aanderaa pressure meter (bottom two plots) located in Angun Lagoon channel.

Related to the high peak-to-peak current maxima observed in the Angun channel flow is similarity in the two temperature records measured in the entrance. Although some slight vertical temperature gradient can be seen over the approximately 1 m vertical separation between the two meters, the temperatures track one another quite well, indicating that when an influx of water is experienced during the flood tide, the flow is inward at all depths (visual observations detected both large flood and ebb surface currents in addition to the measured subsurface currents). Therefore, the temperature of water coming into the lagoon at these two sensor depths (4 and 5 m) during flood tide indicates nearshore water characteristics, and temperatures of water exiting the lagoon during ebb tide indicate characteristics of lagoon water. It is apparent from these records that there is typically a 4-10°C difference between nearshore and lagoon temperatures.

Referring again to Figure 7-6, the absence of this temperature difference during 29-31 July indicates that the nearshore and lagoon waters are at the same temperature and that it is the nearshore waters which have been warmed. It is also interesting that the flood tidal currents are quite small for two of the three cycles in this time interval. The driving mechanism associated wfth this event is the wind. The relationship between the wind and Angun Lagoon channel flow is most easily visualized in Figures 7-15 and 7-16 (pages 392 and 393) where the wind and current data are displayed as stick plots. As discussed in the drifter study, winds were predominantly from the west for several days prior to 29 July at which time they shifted to ENE until 30 July when they again became SW. During this two-day period considerable warm lagoon water was driven from the lagoon systems lining the coast and flooding the nearshore environment with fresher [approximately 17 ppt, Schell (this volume)], warm (approximately 8oc) water. Because this transport was more alongshore than offshore due to the ENE winds, this water was transported along the coastline and was available for exchange with neighboring lagoon systems. The opposite effect is observed during a westerly wind event occurring on the morning of 27 July (discussed in the previous section and displayed in Figure 7-15, upper two traces).

Figures 7-7 and 7-8 show 10 days of data from all the moorings deployed beginning 5 August. As before, the upper trace in Figure 7-7 shows that the currents in Angun entrance are highly bimodal with speeds up to ±1 kt at the 4-m depth. The temperature record (Fig. 7-7, panel 2) indicates nearshore waters from about 1.8 to 2.0°C and lagoon waters slowly varying from 4 to 7°C. The Aanderaa current meter mooring at the far west end of Angun Lagoon also shows considerable structure (Fig. 7-7, panels 3-5). Note that the large event observed in salinity at the Angun interior mooring (Fig. 7-7, panel 4) has no apparent counterpart at the Angun entrance mooring. This rapid decrease in salinity can be attributed to the wind field which at 15:00 on 6 August changed from predominantly NW to predominantly SW, allowing the fresher surface water coming from the rivers to move into the western end of Angun Lagoon. As the winds slowly decreased In intensity and shifted in direction, eventually coming from the NW at 21:00 on 7 August, the freshwater was moved to the east and replaced by more saline water from the eastern end of the lagoon. Note thata corresponding eventis not observed at observed at corresponding times in Pokok Bay (Fig. 7-8).

A second event is observed in Figure 7-7 beginning on 10 August. Unlike the first event, this event shows a 2°C change in the temperature trace at the western end of Angun Lagoon, indicating fresher water at about approximately 15.3 ppt and 4°C. The change in the wind pattern . which induces this event was from NW to E winds and begins at approximately 18:00 on 9 August, lasting for several days. Prior to this period northwesterly winds were observed in excess of 5 m/s and vertical mixing of the lagoon may have occurred in the eastern end. In any *case,* the less saline waters and prolonged easterly winds maintained the fresher water in the western end of the lagoon.

Pokok Bay responded quite differently to the observed meteorological forcing than did Angun Lagoon. Figure 7-8 (lower 3 traces) shows that, with the exception of a slight cooling trend during 7-9 August, not much structure was maintained in the lagoon. Referring back to Figure 7-7 (second trace), the water leaving Angun entrance also showed 3°C cooling between 8-10 August; however, the western end of the lagoon (third trace) showed no such cooling until the major wind reversal late on 9 August.

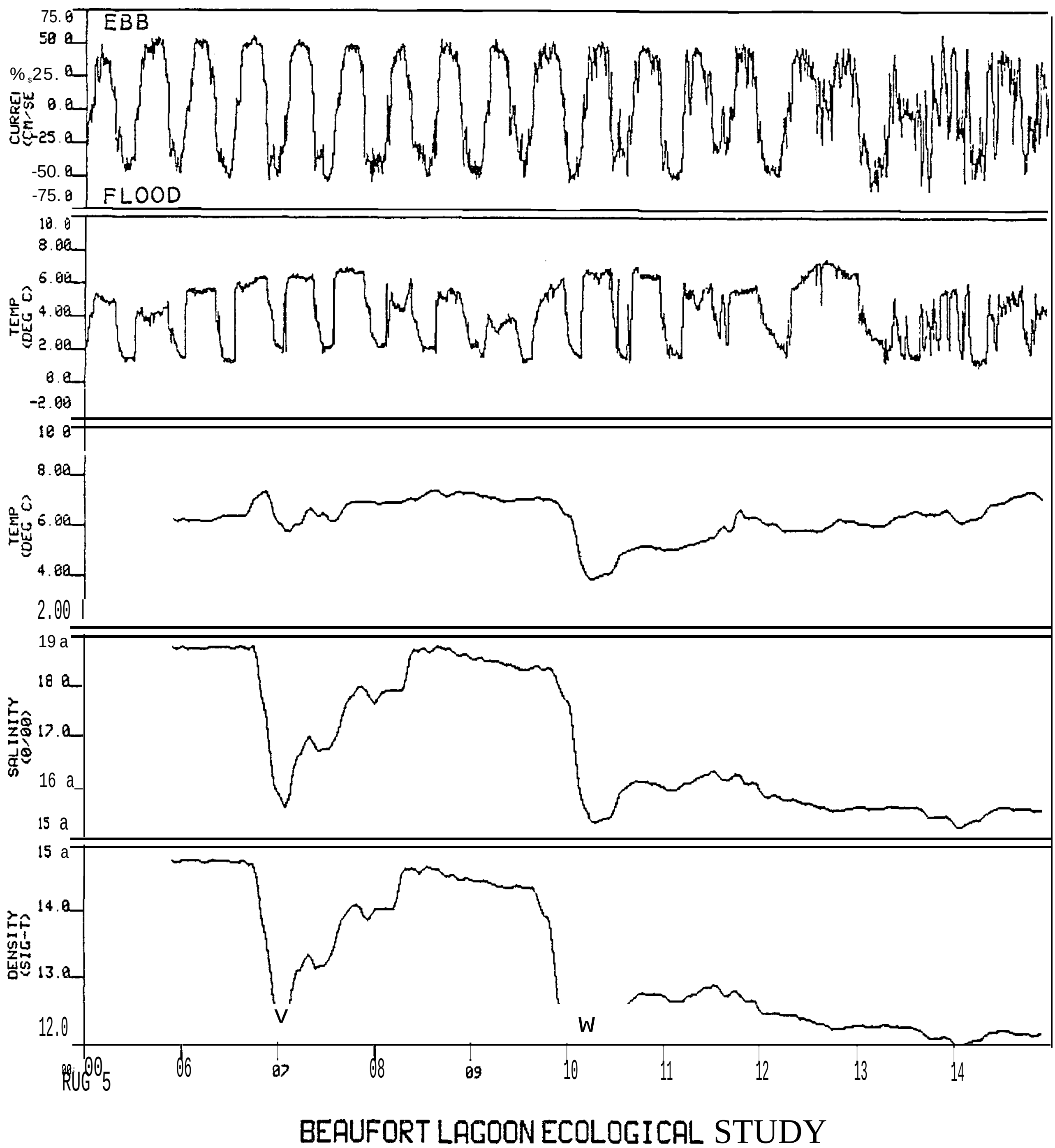
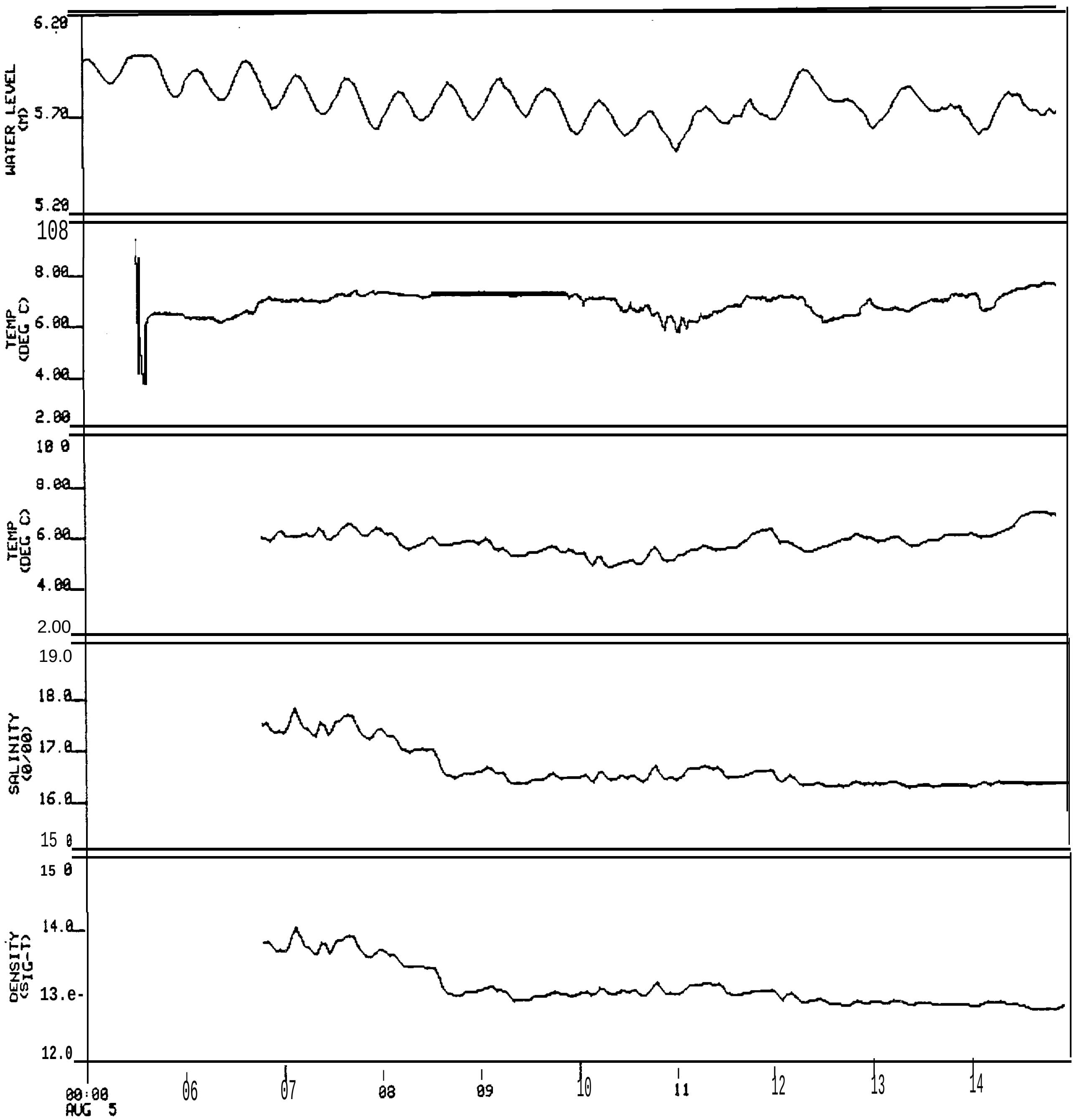


Figure 7-7. Mooring data for Angun Lagoon entrance (top two traces) and Angun Lagoon interior (botton three traces) for ten days beginning 5 August.



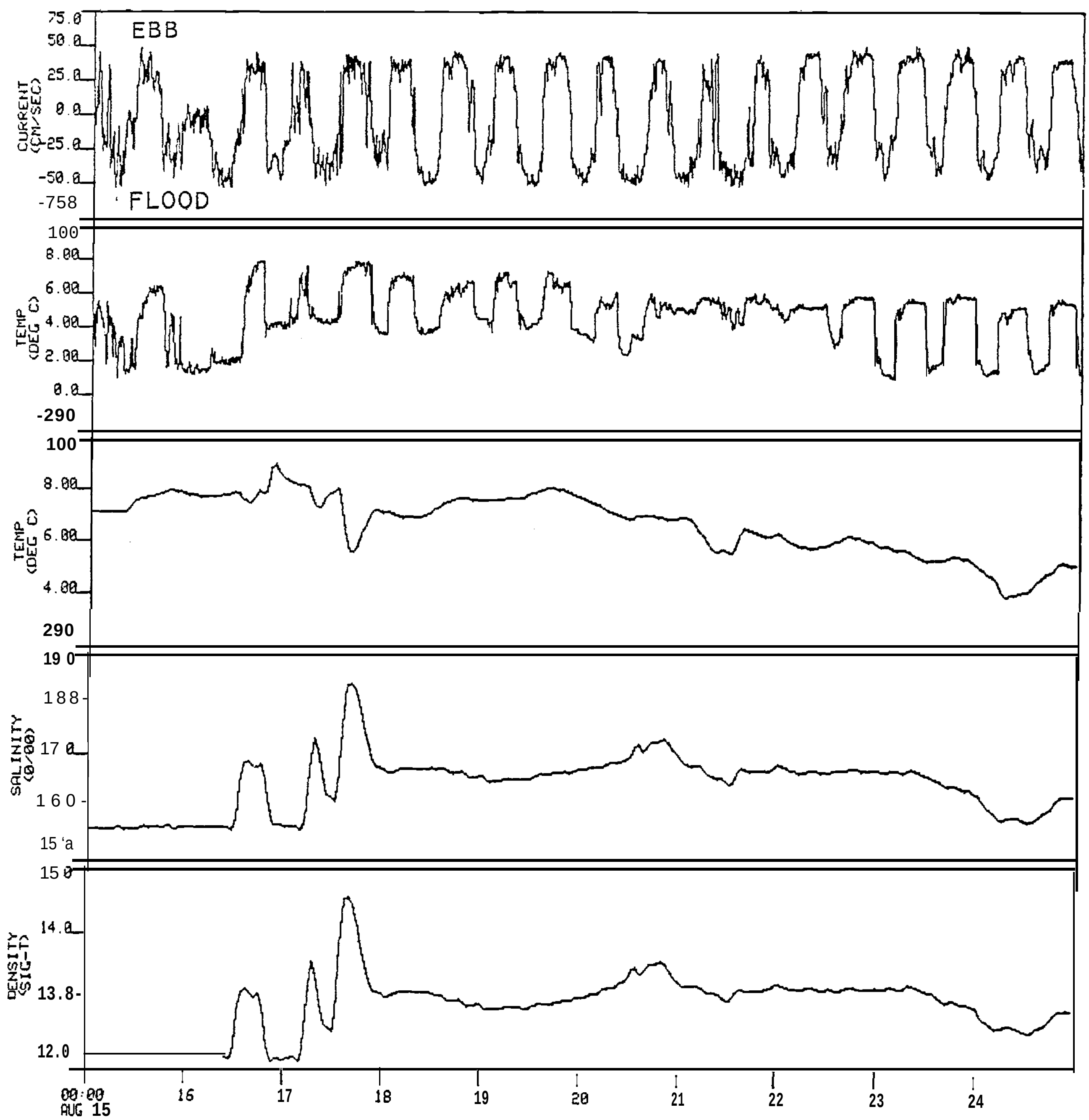
BEAUFORT LAGOON ECOLOGICAL STUDY

Figure 7-8. Mooring data from Angun Lagoon interior (top two traces) and Pokok Bay interior (bottom three traces) for ten days beginning 5 August.

Figure 7.8 (upper 2 traces) indicates that sea level response to the two wind events was minimal (approximately 25 cm decrease) and water level variations were predominantly driven by the astronomical tides. Water in the interior of both Angun Lagoon and Pokok Bay showed a gradual 2 to 3°C warming trend between 10.15 August with no comparable warming trend 'indicated in the nearshore water flowing into Angun Lagoon.

Figures 7-9 and 7-10 show data from the next consecutive 10-day period. A third major event is observed in these data beginning on 16 August. The onset of this event began, as has been observed in the two previous events, by a change in the wind field (Figs. 7-15 and 7-16,. pages 392 and 393). Beginning at approximately 6:00 on 16 August, the dominant winds shifted from very light and variable to coming from the southwest. Nearshore waters increased in temperature by 3°C in one tidal cycle (Fig. 7-9, trace 2) and remained at this temperature almost continuously until 23 August when the wind pattern again shifted to easterly winds. On 17 August winds reached 18 knots, and mean sea level increased over 0.3 m (Fig. 7-10, trace 1). By 22 August nearshore waters and lagoon waters are almost identical in both Angun Lagoon (Fig. 7-9, traces 3-5) and Pokok Bay (Fig. 7-10, traces 3-5) as a result of probable vertical mixing which occurred over an 18-hour period on 17 August (average winds approximately 12 kt). Mixing continued with strong westerly winds (greater than 20 kt) on 20-21 August. *On* 22 August the winds again shifted to easterly and the 4°C difference was again observed between inflow and outflow water in the Angun entrance.

Figures 7-11 to 7-14 show the next two 10-day segments of data. Most noteworthy is the lack of events in the observed data (with the exception of the observed rapid decrease in salinity at the Pokok Bay mooring on 26 August which may have been equipment malfunction). The observed temperature differences between nearshore and lagoon water were observed to slowly decrease from 4 to 2°C with a mean decreasing from approximately 3 to almost 0°C by 12 September. During this period, the salinity in Angun Lagoon maintained an almost constant value of 16 ppt whereas in Pokok Bay salinity increased steadily from 16 to over 17 ppt by 11 September. Also during this time, the temperature in Pokok Bay decreased from 4 to 2°C whereas Angun maintained a 4°C average until 8 September when it rapidly cooled from 4°C to 3°C over a four day period. Nearshore



BEAUFORT LAGOON ECOLOGICAL STUDY

Figure 7-9. Mooring data for Angun Lagoon entrance (top two traces) and Angun Lagoon interior (bottom three traces) for ten days beginning 15 August.

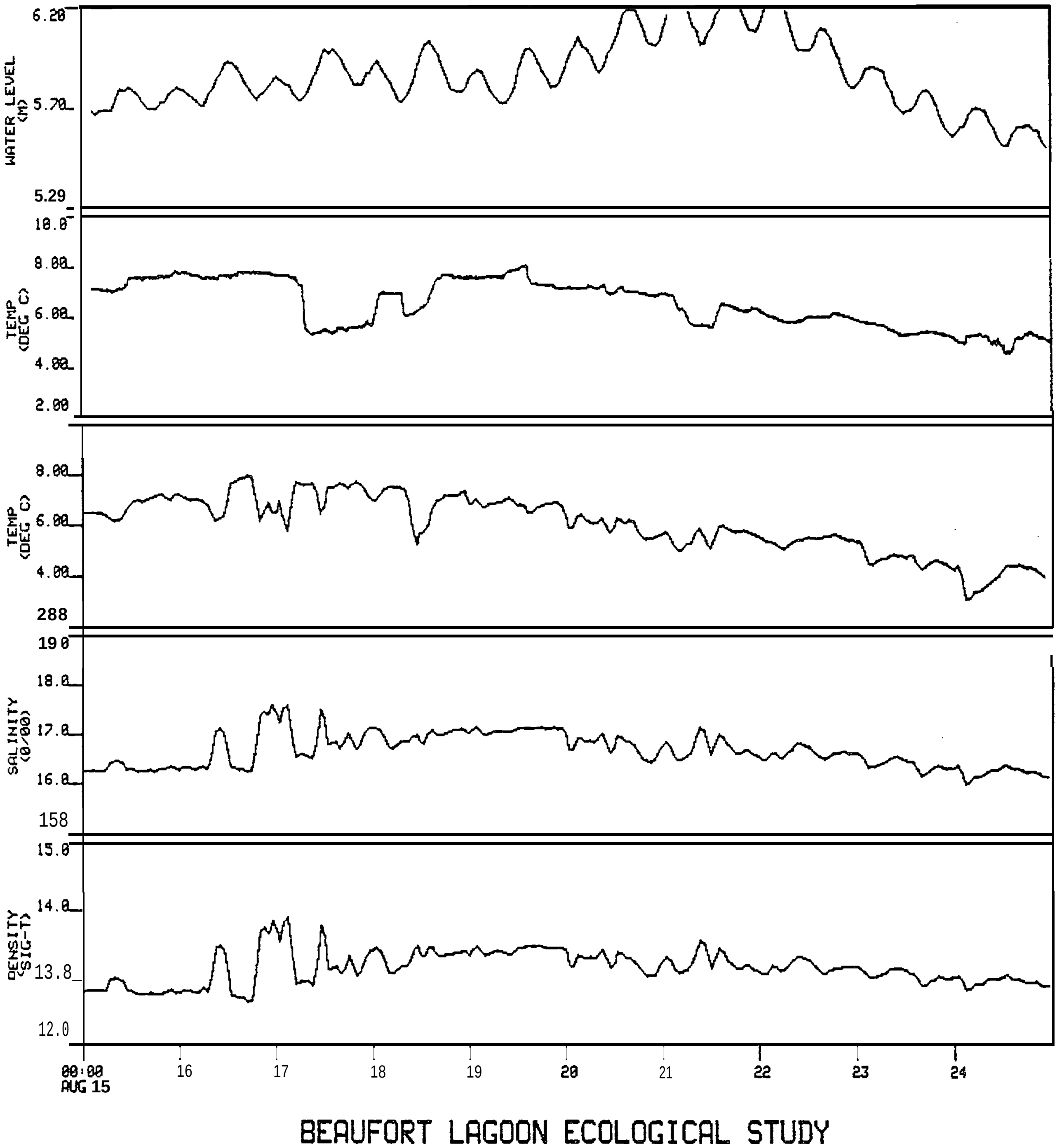
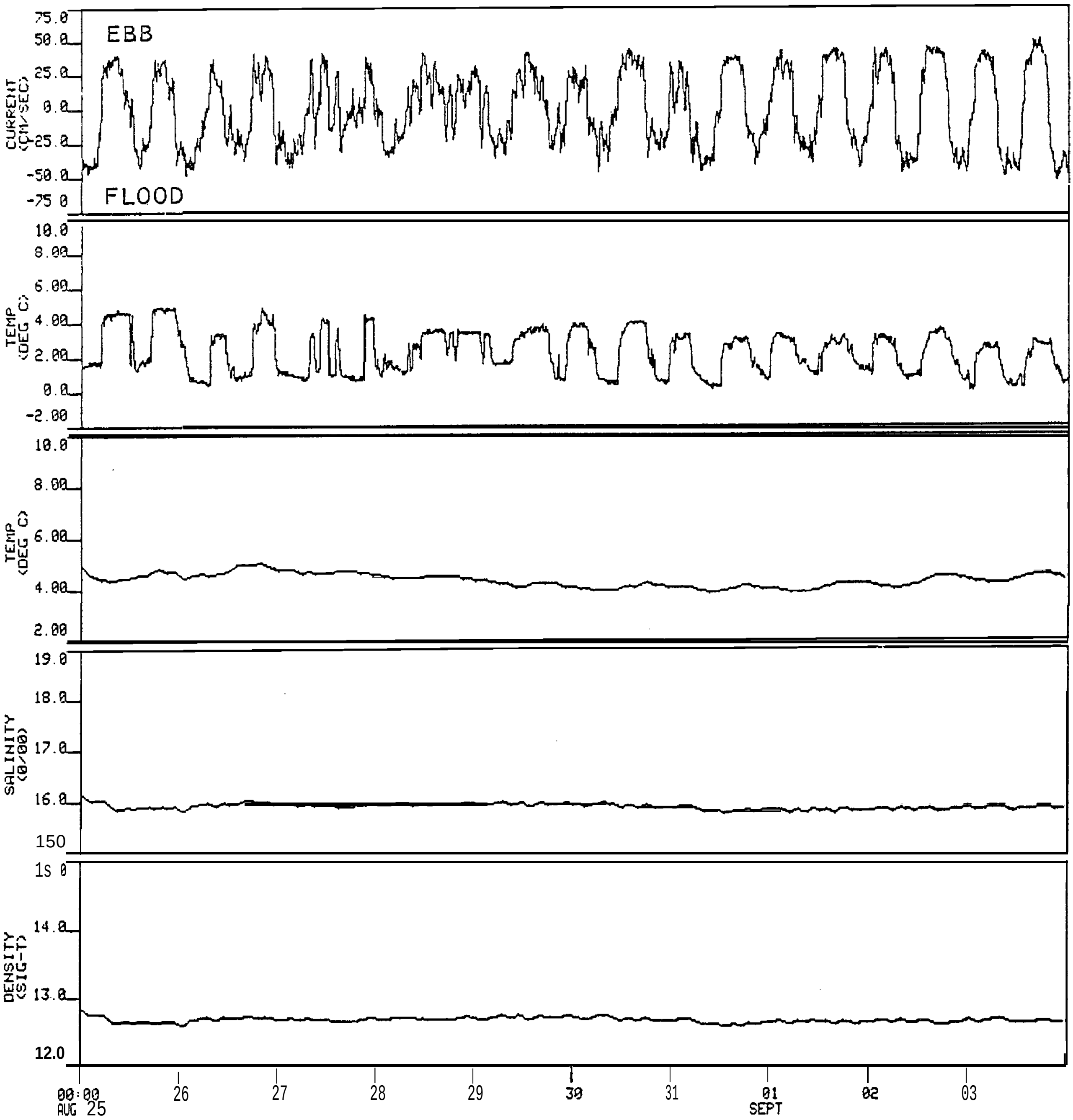
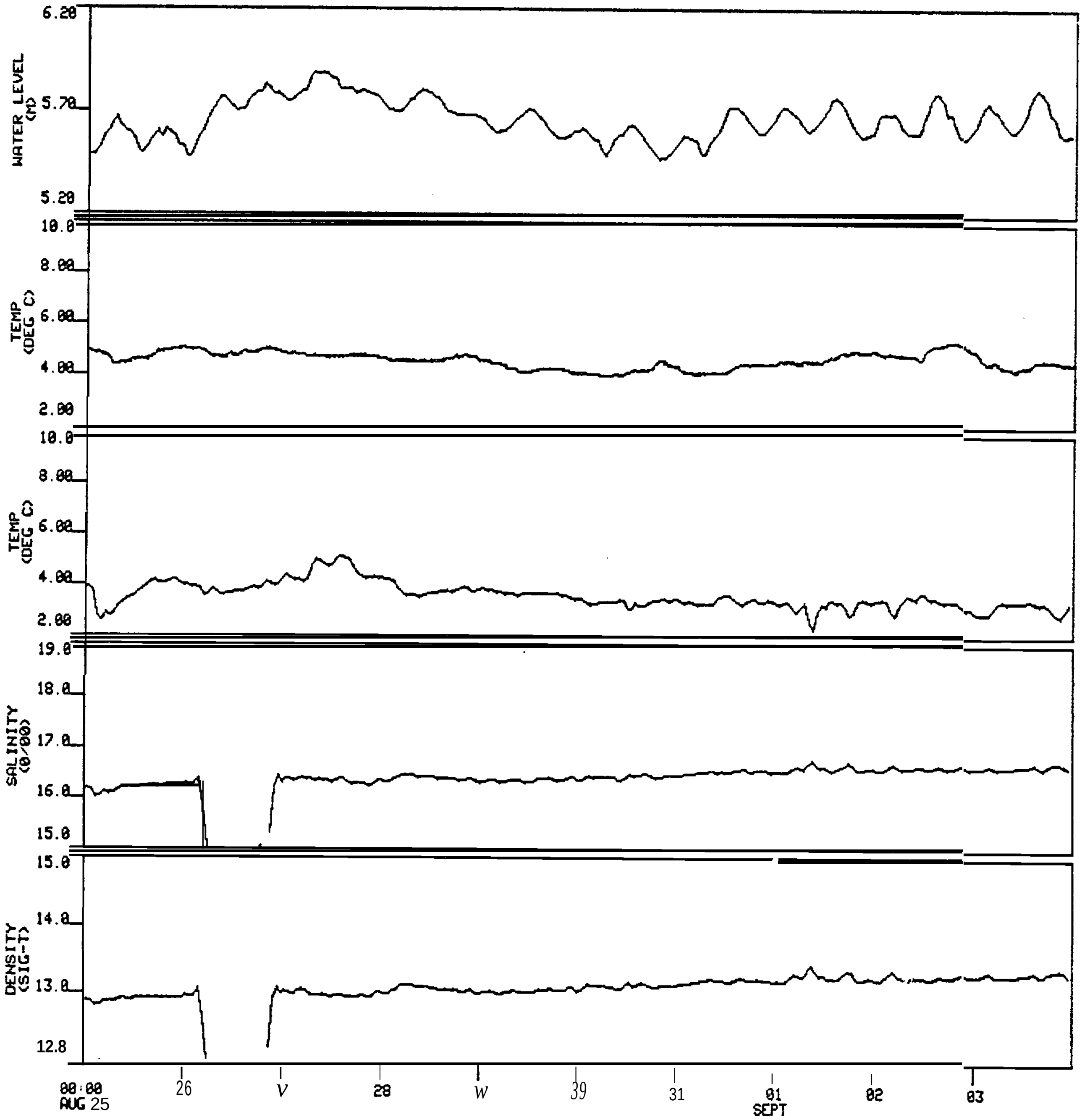


Figure 7-1o. Mooring data from Angun Lagoon interior (top two traces) and Pokok Bay interior (bottom three traces) for ten days beginning 15 August.



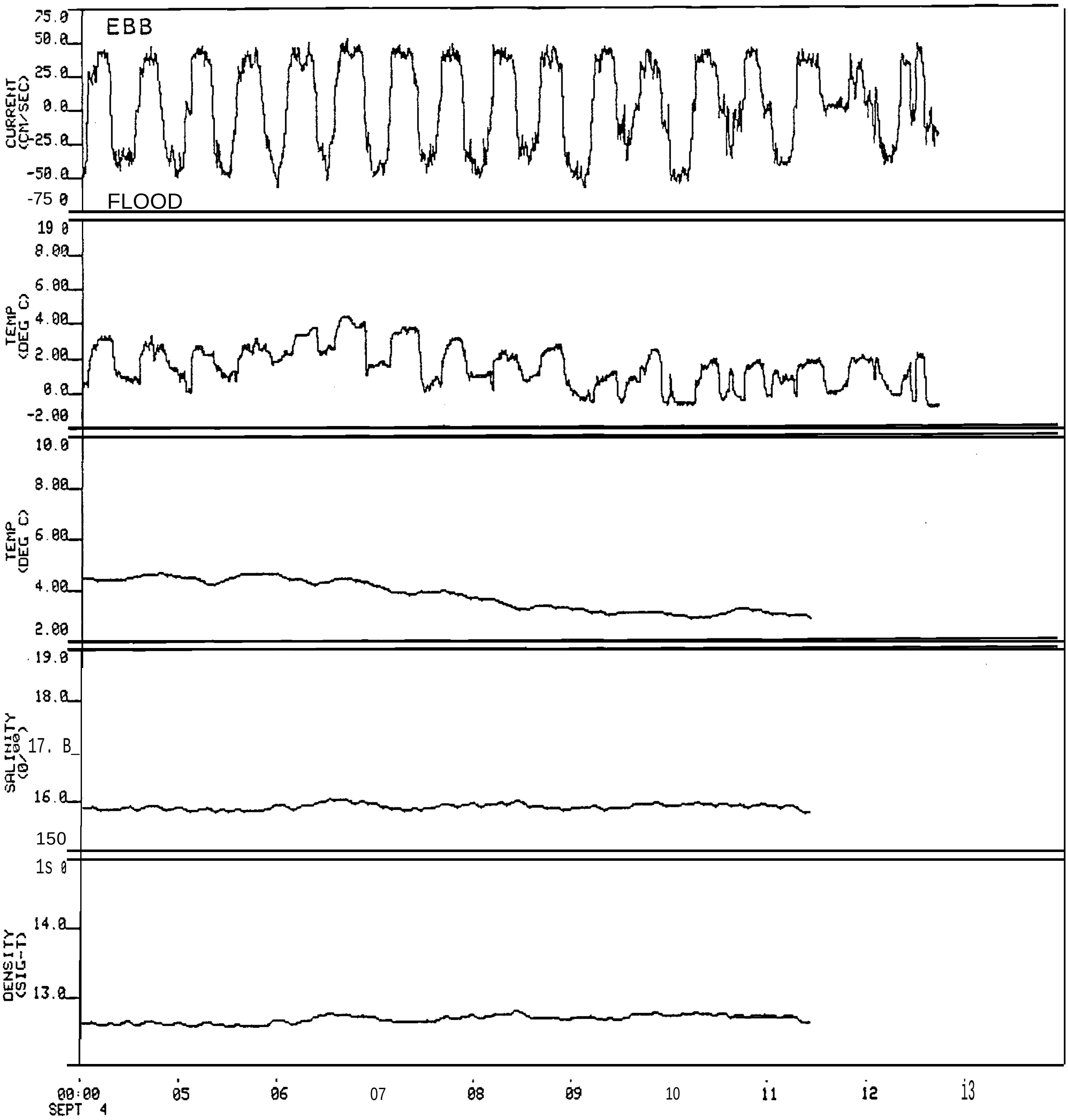
BEAUFORT LAGOON ECOLOGICAL STUDY

Figure 7-11. Mooring data from Angun Lagoon entrace (top two traces) and Angun Lagoon interior (bottom two traces) for ten days beginning 25 August.



BEAUFORT LAGOON ECOLOGICAL STUDY

Figure 7-12. Mooring data from Angun Lagoon interior (top two traces) and Pokok Bay interior (bottom three traces) for ten days beginning 25 August.



BEAUFORT LAGOON ECOLOGICAL STUDY

Figure 7-13. Mooring data from Angun Lagoon entrance (top two traces) and Angun Lagoon interior (bottom three traces) for ten days beginning 4 September.

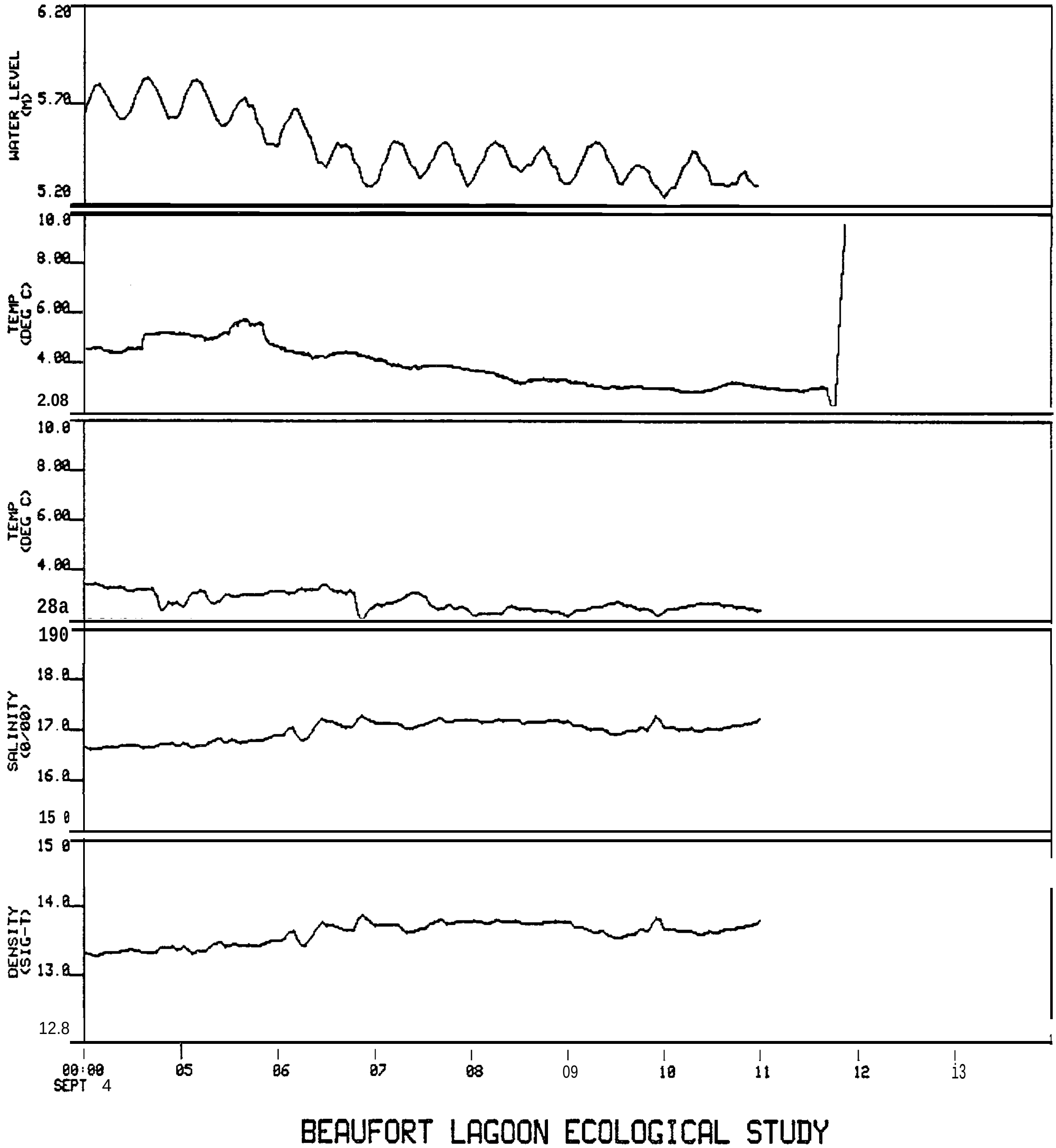


Figure 7-14. Mooring data from Angun Lagoon interior (top two traces) and Pokok Bay interior (bottom two traces) for ten days beginning 4 September.

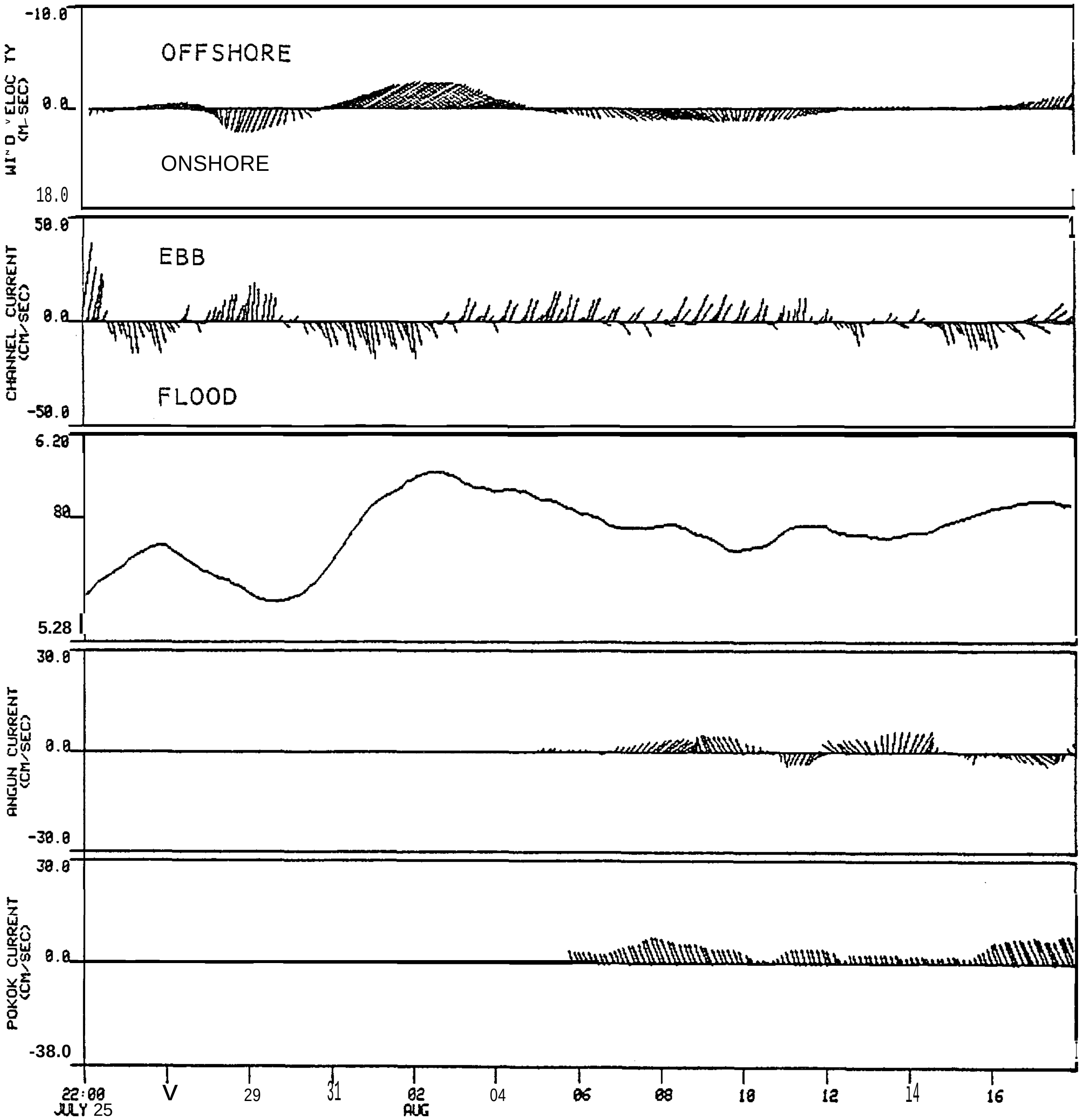
water at this time went from 2°C to approximately 0°C. During this 20-day cooling process a 1 to 2°C temperature difference was maintained between water at the west end of Angun Lagoon and the lagoon entrance.

This last set of observations has some implications relevant to understanding circulation and exchange processes in the two lagoons. (These points are further discussed in the "DISCUSSION" section of this Chapter.) Of particular note is the fact that the current direction in the western end of Angun Lagoon is almost always to the north or northeast, indicating clockwise circulation For reference, Figures 7-15 and 7-16 show 30-hr filtered wind and current data from the field program. It must be cautioned that both of the Aanderaa current speed records from Angun Lagoon and Pokok Bay may be contaminated by surface wave effects, and the Instruments were primarily placed in the lagoons for their recordings of temperature and salinity. In addition, a compass-bearing problem on the Pokok Bay mooring is believed to have rendered current direction data useless. In any event, the strong correlation between winds, current speeds and water level are obvious in these figures.

Hydrographic Data

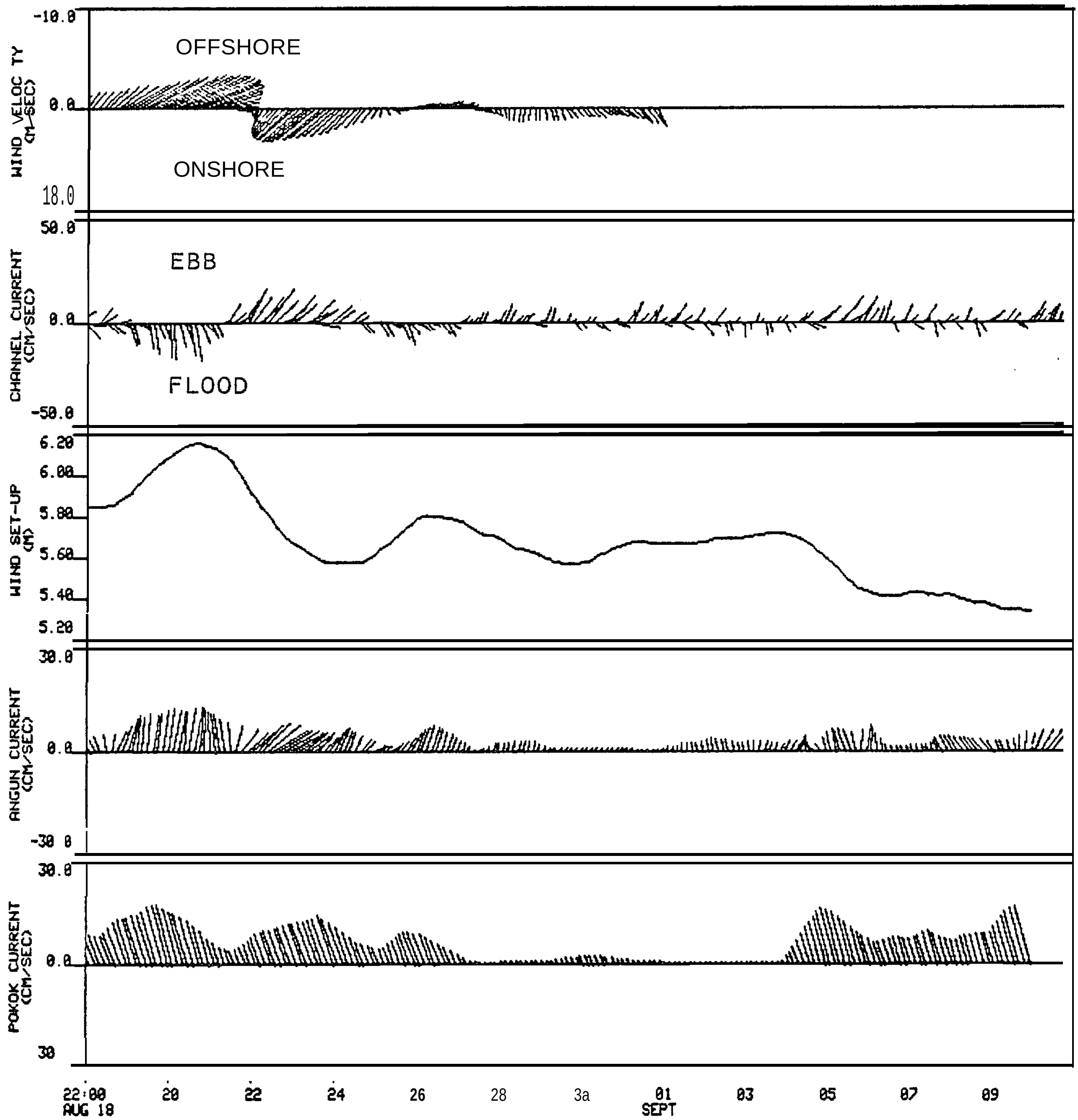
Several CTD and depth sounding transects were made in Angun Lagoon during the physical oceanography field measurement program. In addition, water bottle samples were collected in Beaufort and Angun Lagoons as well as in the nearshore region by the primary productivity biologists (Schell, this volume). Table 7-2 summarizes the CTD and depth soundings made by the physical oceanography program. Figure 7-17 indicates the location of each of these casts. These measurements were made from a specially equipped Zodiac designed to perform both the CTD work and the current meter mooring recoveries during the second phase of the field program.

CTD casts made in Angun Lagoon have been analyzed to determine the distributions of temperature and salinity in the lagoon basin. Figures 7-18 and 7-19 show examples of data from two of the CTD casts made near the entrance of the lagoon on 10 September during Phase II of the field program. A definite two-layered structure can be seen in these profiles. Cold and high-salinity water intruding from the nearshore region is observed overlain by warmer lower-salinity water from the lagoon interior.



BEAUFORT LAGOON ECOLOGICAL STUDY SUMMARY

Figure 7-15. Filtered wind data for Beaufort Lagoon (top trace), current data for Angun Lagoon entrance (2nd trace), wind set-up and current data in Angun Lagoon interior (3rd and 4th traces), and current data in Pokok Bay interior (bottom trace) beginning 25 August. (Wind data has been rotated by 35° to better indicate onshore and offshore components.



BEAUFORT LAGOON ECOLOGICAL STUDY
SUMMARY

Figure 7-16. Filtered wind data for Beaufort Lagoon (top trace), current data for Angun Lagoon entrance (2nd trace), wind set-up and current data in Angun Lagoon interior (3rd and 4th traces), and current data in Pokok Bay interior (bottom trace} beginning 18 August. (Wind data has been rotated by 35° to better indicate onshore and offshore components.)

Table 7-2. CTD and bathymetric measurements,

CTD transects: (see Figure 17)

	Date	Location	Latitude/Longitude	No. of Casts
1.	9/1 0/82	Angun Lagoon	69°56.8'N, 142°24.7'W to 69°56.5'N, 142°26.0'W	6
2.	9/10/82	Angun Lagoon	69°56.5'N, 142°25.3'W to 69°57.8'N, 142°30.0'W	8

Depth sounding transects:

	Date	Location
1.	7/25/82	Angun Lagoon major entrance
2.	7/25/82	Angun Lagoon minor entrance
3.	9/10/82 "	Angun Lagoon interior
4.	9/12/82	Angun Lagoon major entrance

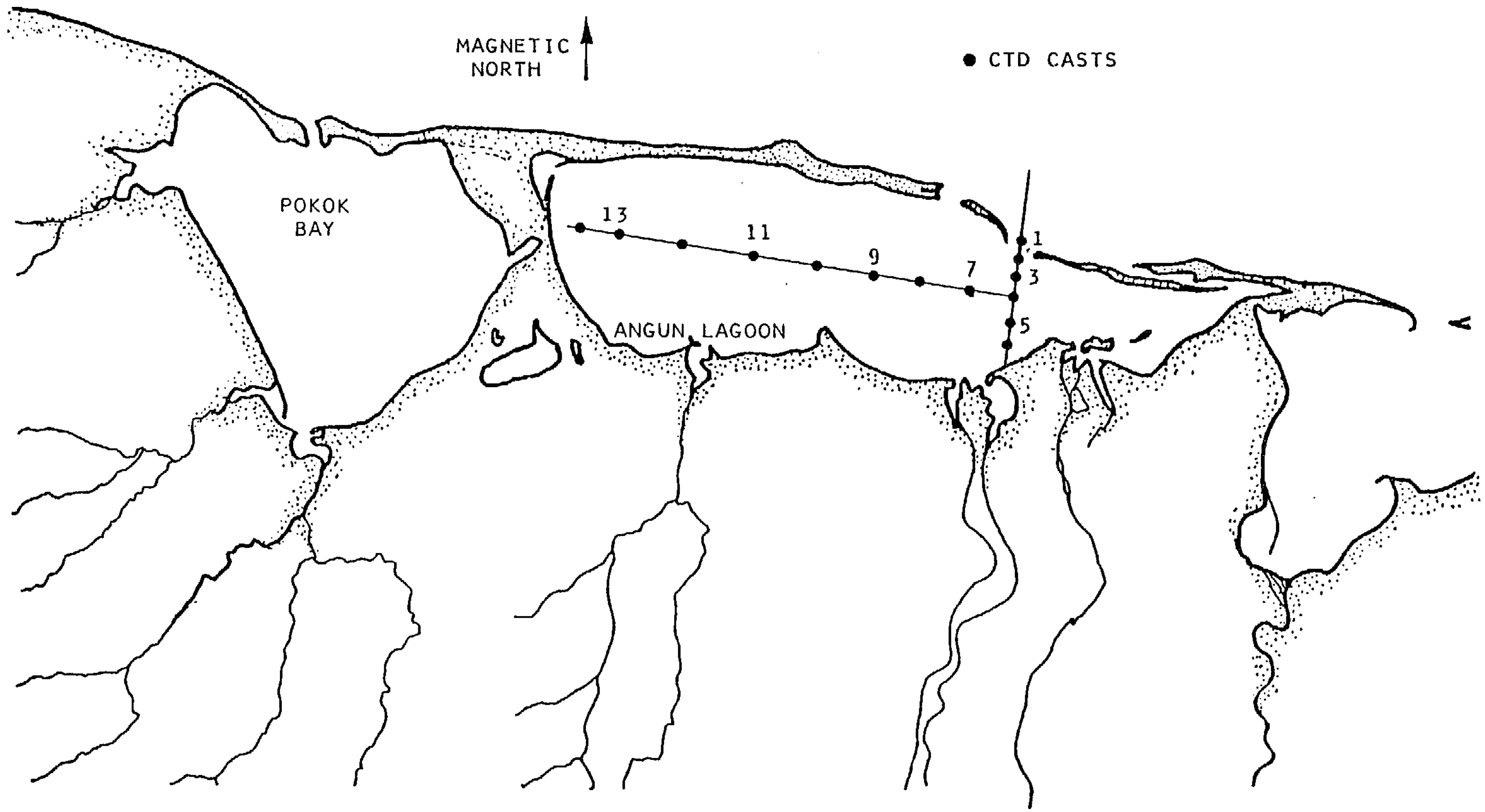


Figure 7-17. Angun Lagoon CTD transects.

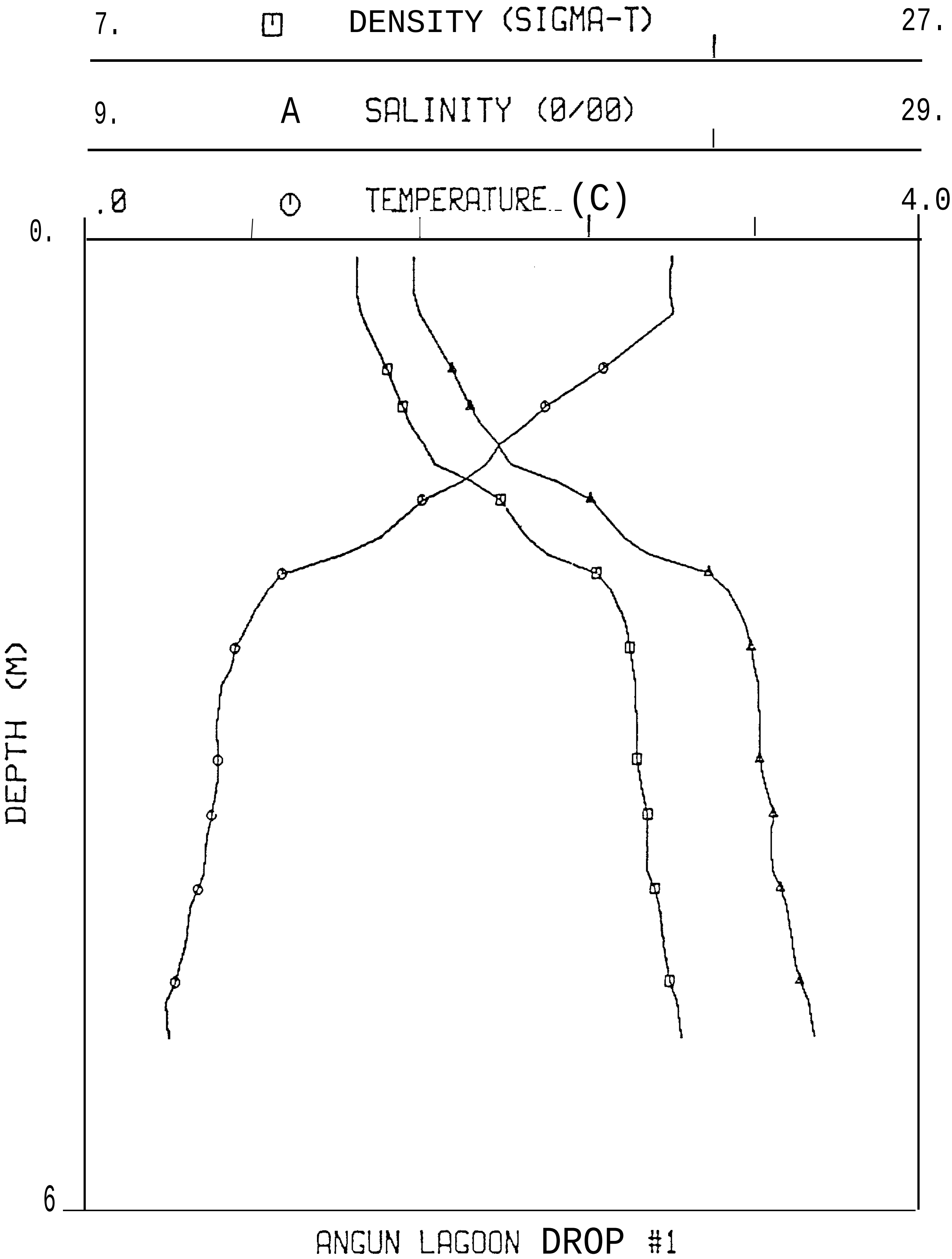


Figure 7-18. Example of data from CTD cast, Angun Lagoon entrance on 10 September during Phase 11 of the program.

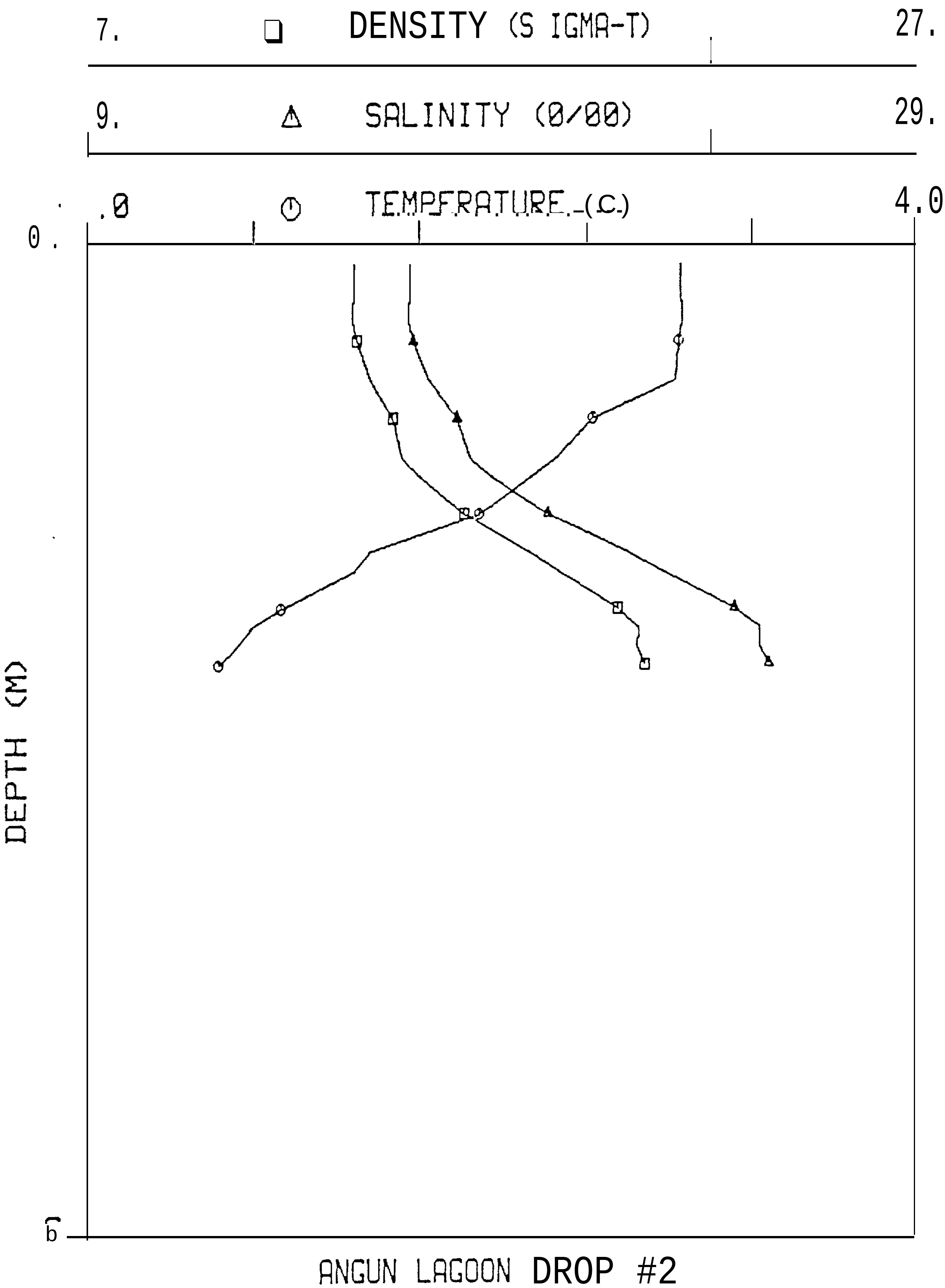


Figure 7-19. Example of data from CTD coast, Angun Lagoon entrance on 10 September during Phase II of the program.

Depth soundings of the lagoon combined with the CTD cast data were used to produce sections of the temperature distribution in the lagoon. Results of this analysis are shown in Figures 7-20 to 7-22. Referring to Figures 7-17 and 7-20, a core of cold nearshore water (with corresponding higher salinity and density) can be seen Intruding south across the bottom of the lagoon along the north-south section and mixing vertically into the water column (slightly increased salinity and density in surface waters is seen at the southern end of the lagoon). To the west of an observed colder bottom water core near the lagoon entrance is a warm water surface core with properties similar to water in the more isolated western end of the lagoon. It is apparent from these data and from bottom and surface drifter study results that there is a net influx of nearshore water into the lagoon at the bottom of Angun entrance and a net outflow of warmer surface water imposed on time varying tidal and meteorologically-forced flow fields.

Referring again to Figures 7-20 to 7-22, it is possible that the hydrographic structure observed near the lagoon entrance is related to a closed gyre with a radius of from 1-.1.5 km which during periods of light wind isolate the region near the lagoon entrance from the western lagoon interior. This hypothesis is not inconsistent with predictions by lagoon circulation models and would account for the apparent isolation of the far western end of the lagoon from the lagoon entrance, as seen by the much longer response time for the western end of Angun Lagoon compared to the interior of Pokok Bay and the region near the entrance to Angun Lagoon. (This is discussed further in the "DISCUSSION of this chapter.)

Water bottle samples and temperature measurements collected by Schell's (this volume) primary productivity study show considerable density stratification in Angun Lagoon in late July. Observed salinities on 26 July ranged from 15.6 ppt in the upper several meters of water throughout the central and western portions of Angun Lagoon to as high as 27.5 ppt near the bottom. Although continuous profile data are not available at these stations, the high salinity layer is indicated to be on the order of 1 m in thickness or less. Measured salinities show little horizontal variation across the length of the lagoon beyond a localized region of about 1 lagoon width near the main entrance (approximately 1 km). This is consistent with fall observations by the physical

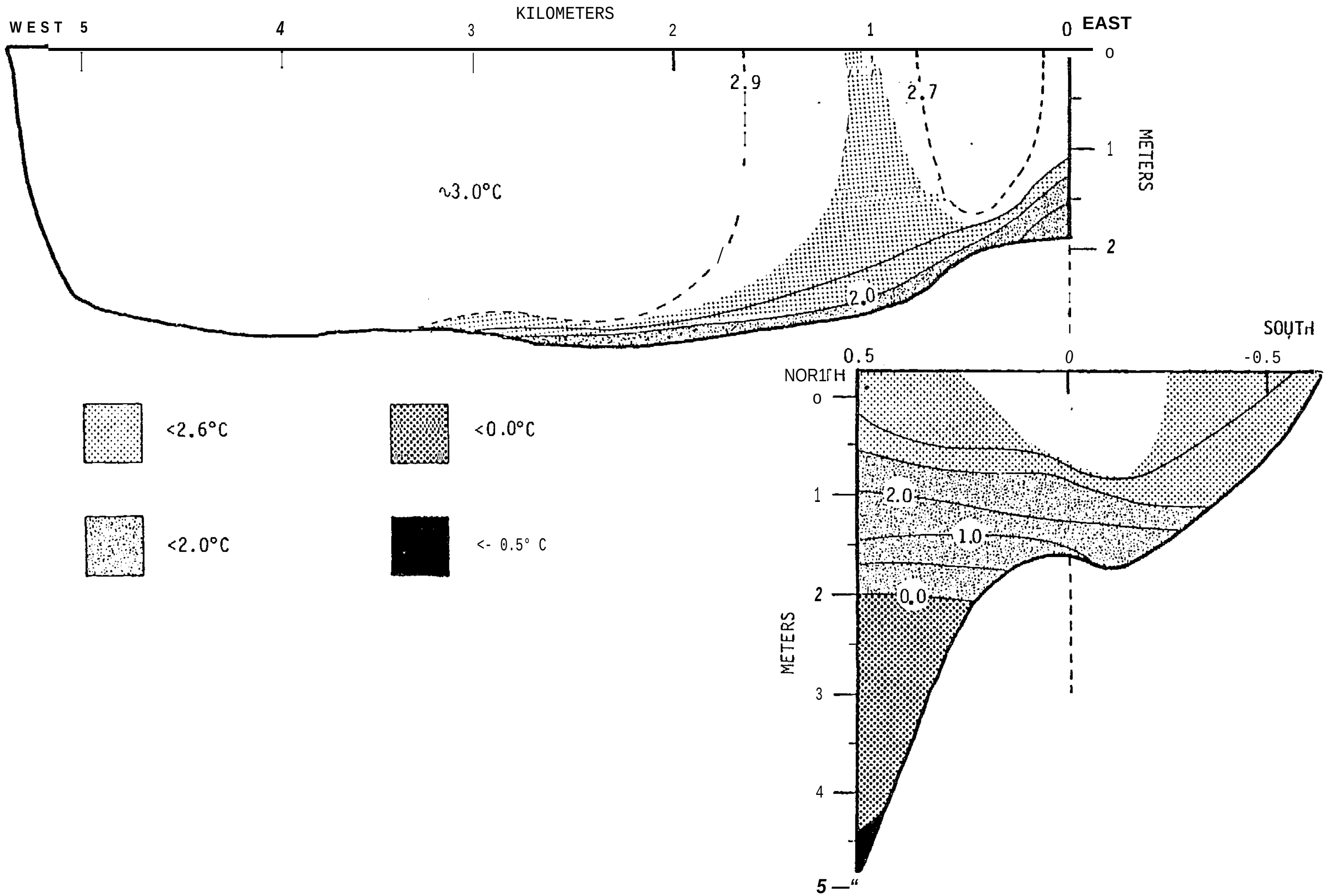


Figure 7-20. Two temperature sections along (upper) and across (lower) Angun Lagoon. See Figure 17 for station locations.

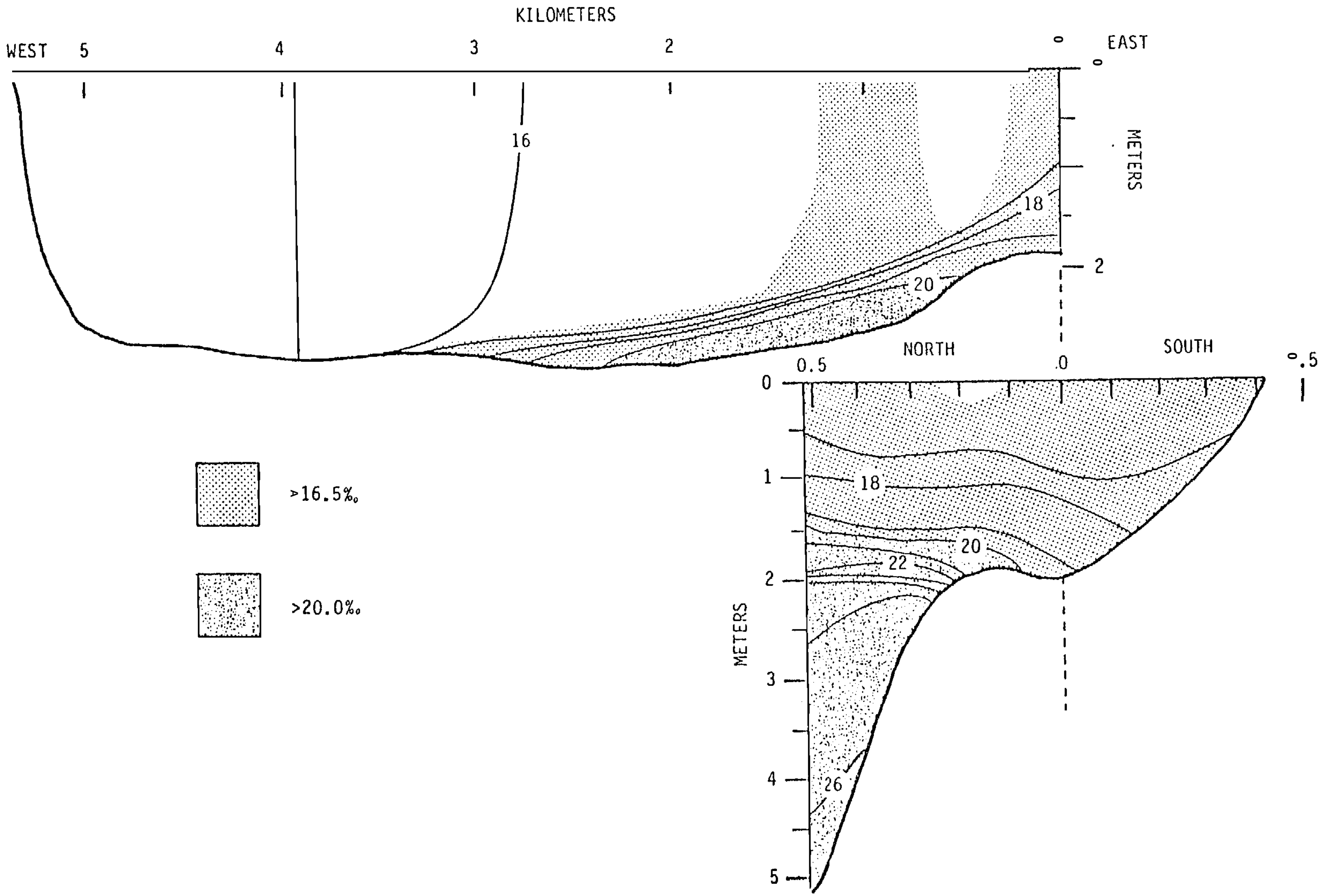


Figure 7-21. Two salinity sections along (upper) and across (lower) Angun Lagoon. See Figure 17 for station locations.

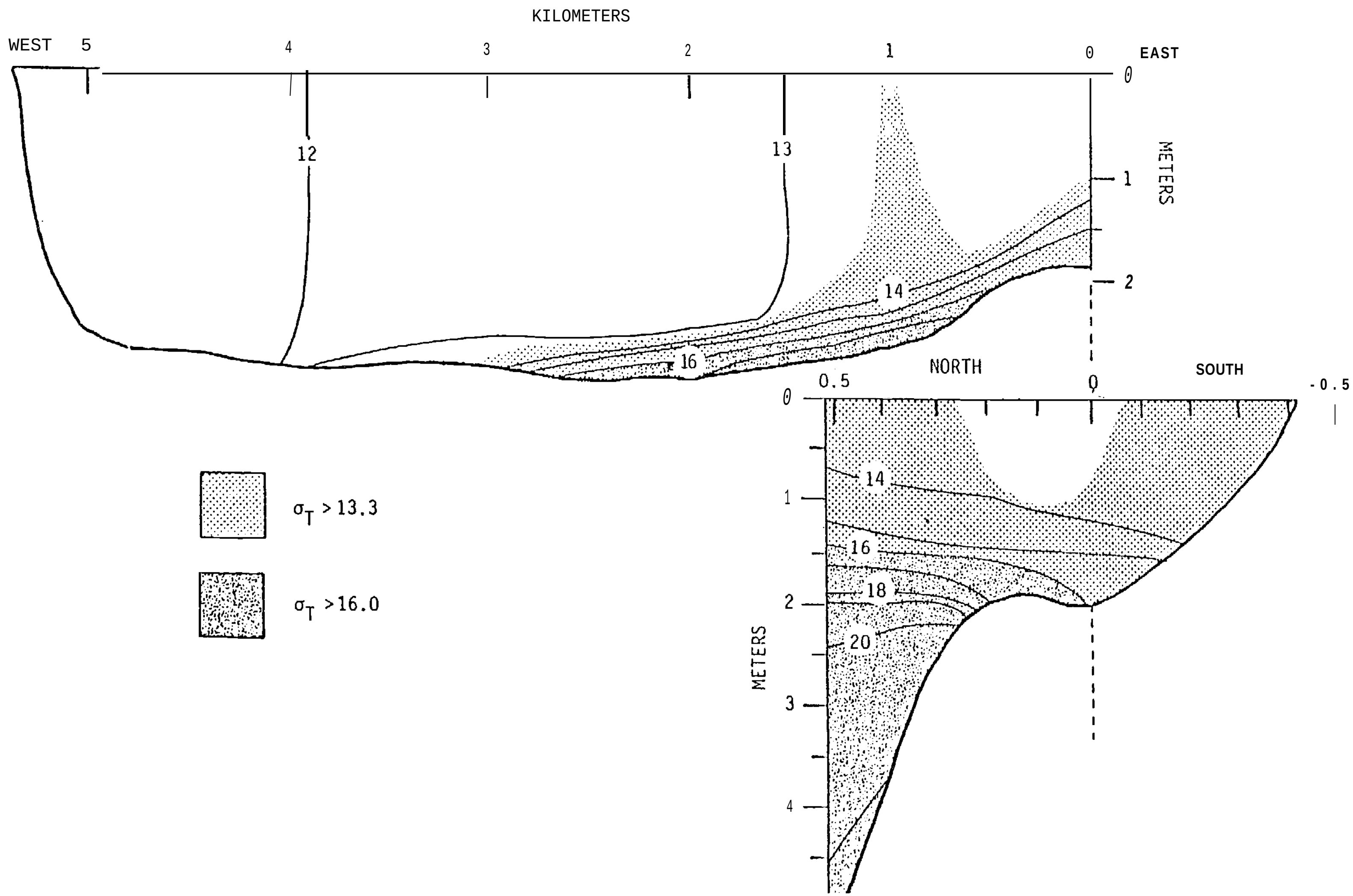


Figure 7-22. Two density sections along (upper) and across (lower) Angun Lagoon. See Figure 17 for station locations.

oceanography program which also found most variability near the lagoon entrance. As observed by Kozo (this volume), Schell's light intensity measurements were also high during this early period, indicating little vertical wind mixing. Kozo's data show that winds were light and variable for several days preceding 27 July. 0n29 July Schell's measured light intensity data are 10 % that observed on26 July implying that vertical wind mixing may have occurred. Meteorological measurements previously discussed recorded 12 hours of strong winds (approximately 22.8 kt from the WNW) late on 27 July which may have produced the mixing. In addition, Schell's data show that the higher salinity bottom layer has vanished by 29 July and that surface and bottom salinities are almost identical in the central and western end of the lagoon.

By 5 August three more smaller wind events had occurred and the western end of the lagoon was again vertically homogeneous with still higher salinities of 18.8 ppt. Higher salinity water required to achieve these higher values was probably made available for tidal exchange at the lagoon entrance during a 40-hr period of easterly winds on 29-30 July. Some water with salinities greater than 20 ppt was observed near the lagoon bottom after this period on 31 July; this may have moved into the lagoon by tidal influx during 29-30 July and then vertically mixed during the three wind events greater than 20 kt on 1, 2 and 3 August.

If we again utilize Schell's data and assume that the upper 3 m of water in the western end are at 18.2 ppt on 31 July and that 1 m of 20.2 water is at the bottom then 18.7 ppt water should be observed after complete vertical mixing. Schell's data indicate that 18.8 ppt water is present in the western and central lagoon. Light intensity data are unfortunately *not* available for Angun Lagoon during this period; however, Beaufort Lagoon light intensity data on 6 August show considerably lower values than those for comparable depths in Angun Lagoon on 31 July prior to the hypothesized vertical mixing and may support the conjecture that wind mixing has occurred.

Other evidence of wind mixing can be seen in the Angun Lagoon temperature and salinity time series (Fig. 7-9). On 16 August salinities recorded in the far western end of Angun Lagoon were 15.6 ppt. Wind conditions at that time were quite mild and had been for the preceding 2-3 days (Fig. 7-15). By mid-day a southwesterly wind had developed which continued to intensify for" the next four days. This wind forced water onto the nearshore, increasing water level in the lagoon by over 30 cm. A layer of 17 ppt water was detected at the current meter mooring in Angun Lagoon several hours later. By 17 August the wind speed had reached 15 kt and a second and third pulse of higher salinity water were observed at 17.3 ppt and 18.4 ppt. On 18 August, under the continued influence of these winds, all variability in the salinity records had ceased and it is assumed that the water column had been vertically mixed. Water level continued to rise in the lagoon until 21 August when the difference between lagoon and nearshore waters was greatly reduced and only minor variations were observed in the lagoon salinity and temperature records.

A simple calculation beginning on 17 August indicates that if 1 m (approximate distance of conducting sensor from the lagoon bottom) of 17.3 ppt water is mixed with 2 m of 15.6 ppt water, then uniform 16.2 ppt water results. This 16.2 ppt water is observed on 17 August just prior to the influx of 18.4 ppt water previously mentioned. If these two water masses are then vertically mixed (1 m of 18.4 ppt plus 2 m of 16.2 ppt water) then 16.9 ppt water results. Time series data show that 16.8 ppt water is present after the final pulse of 18.4 water was detected. These data indicate that a critical wind speed was required to vertically mix water layers in the lagoon (note that no mixing occurred of the pulses of water on 16 August where maximum winds only reached 6.8 kt but that these winds did induce layered flow within the lagoon). However, when winds reached 12-15 kt on 17 August, vertical mixing occurred and the layered structure was not reestablished at this end of the lagoon for the remainder of the summer measurement program, probably as a result of the considerably reduced influx of freshwater runoff by mid-August. As observed in the CTD data, a layered structure did remain in a region nearer the lagoon entrance.

Examination of the T-S diagrams from the Angun Lagoon and Pokok Bay current meter moorings (Figs. 7-23 and 7-24) indicate that residual higher salinity water was present in Angun Lagoon after the mixed event described on 27 July. The core of summer water for both Angun Lagoon and Pokok Bay lies principally in a band between 5-9°C and 15.5-17.0 ppt. The Pokok Bay core is on the average 0.8 ppt more saline and 0.5°C cooler than the observed Angun Lagoon water. However, beyond 22 August when winter

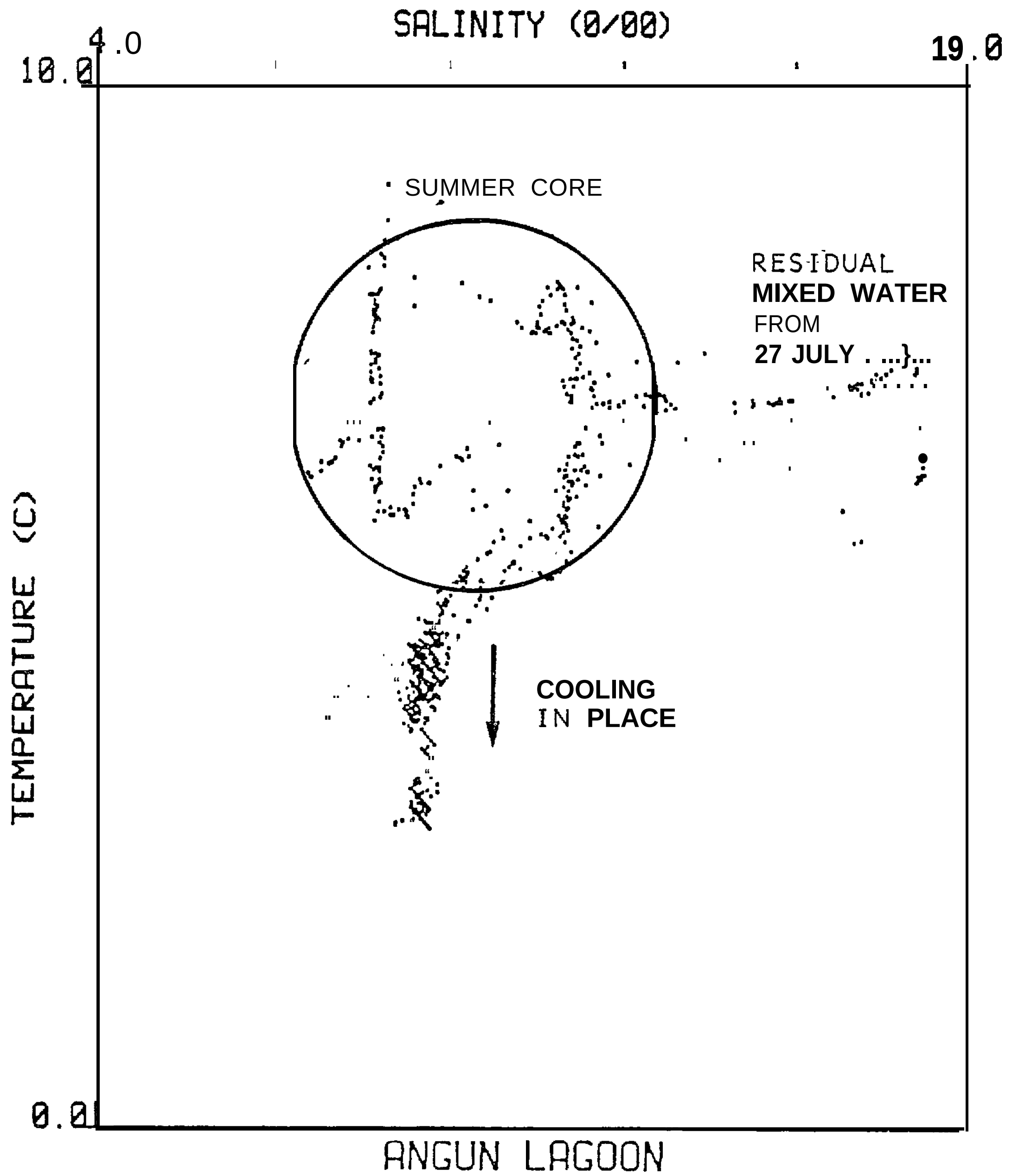


Figure 7-23. Temperature salinity diagram from Angun Lagoon current meter moorings.

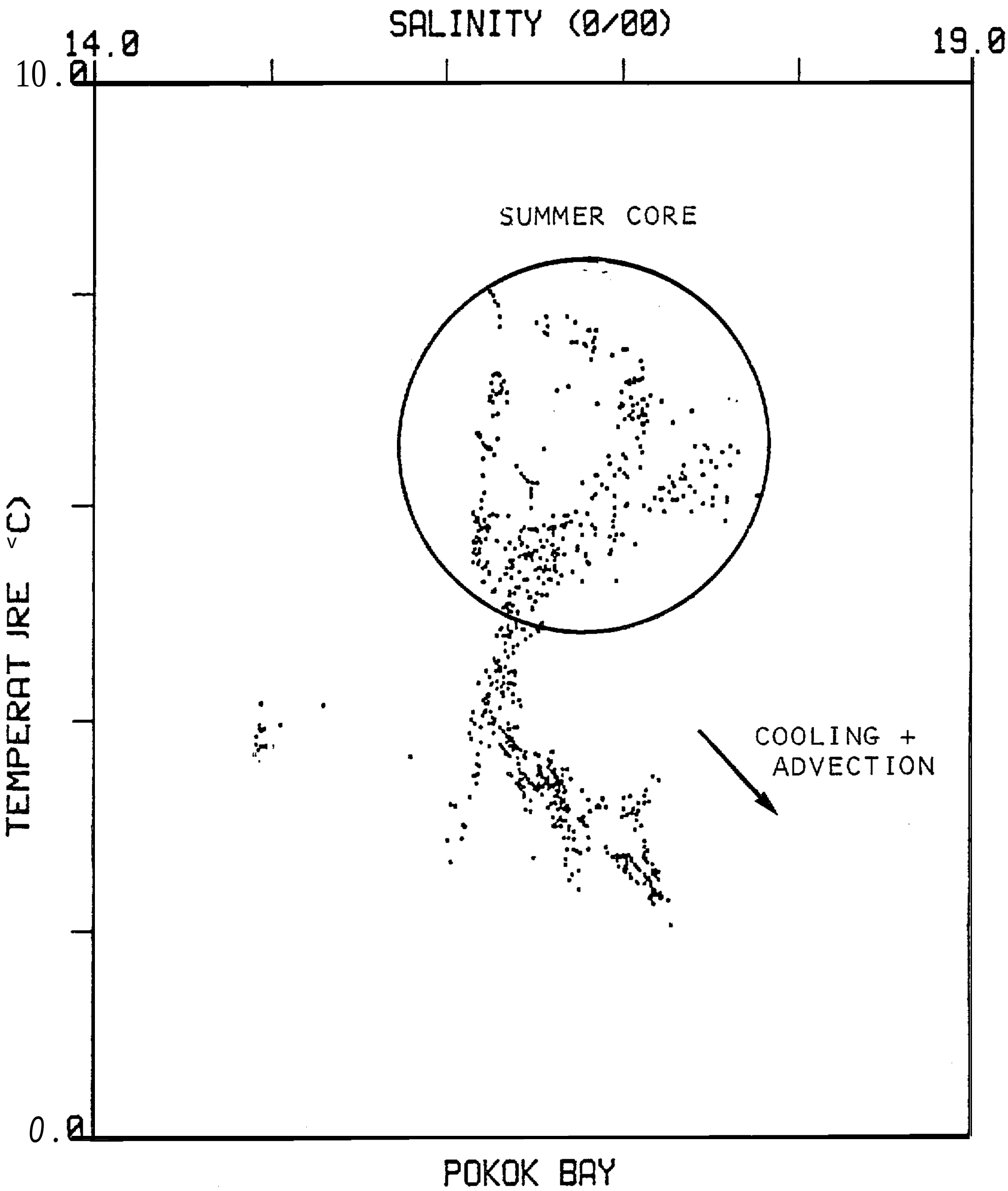


Figure 7-24. Temperature salinity diagram from Pokok Bay current meter moorings.

cooling begins to set in, water temperatures fall below 5oC. Figure 7-23 shows that after 6 September cooling of western Angun Lagoon water takes place without change in salinity, indicating cooling in place and no lateral mixing with nearshore waters.

Figure 7-25 shows a combined T-S diagram of several CTD casts taken in the central and eastern end of Angun Lagoon on 10 September. Note that if waters in the eastern endof the lagoon were mixing with central and eastern lagoon waters, a continued increase in salinity should have accompanied the decrease in temperature from 5 to 3oC shown in Figure7-23.

Pokok Bay also shows a 2oC cooling trend (Figs. 7-12 and 7-14) which began on 25 July and continues until 10 September, closely following the observed trend in temperature reduction of nearshore waters indicated in the lagoon entrance data (Figs. 7-11 and 7-13). However, accompanying this cooling trend is a uniform increase in the Pokok Bay salinity from approximately 16.0 ppt on25 August to 17 ppt on 6 September (Figs. 7-12 and 7-14), indicating mixing with more saline and cooler nearshore waters. If one assumes a uniform 20 cm M2 tidal fluctuation during this period and 20-22 ppt nearshore water (see 10 August CTD casts in Figs. 7-18 and 7-19) for 0-1oC water, then a 15-20% flushing efficiency is calculated for Pokok Bay during 25 August to 6 September to offset this 1 ppt increase in salinity where flushing efficiency is defined as the ratio of actual flushing (rate of change in salinity in this case) to the ideal flushing (which assumes that all water entering the lagoon is completely mixed with ambient water before exiting the lagoon). This implies that ideal tidal exchange with the nearshore, which would indicate 8-10 day turnover of the lagoon (3.0 m mean lagoon depth/0.15-0.20 m per M2 tidal fluctuation = 8-10 days for volume exchange) may actually be a factor of five low, and 40-50 days may be more realistic numbers. It must be noted, however, that major meteorological events in the region typically occur on shorter time scales than this and that these events may considerably enhance both vertical and horizontal mixing in the lagoons and exchange of lagoon waters with the nearshore. The lack of any significant change in salinity in the western end of Angun Lagoon indicates that flushing efficiency there may be even less than that calculated for central Pokok Bay. Clearly, further investigation into tidal and storm surge flushing of

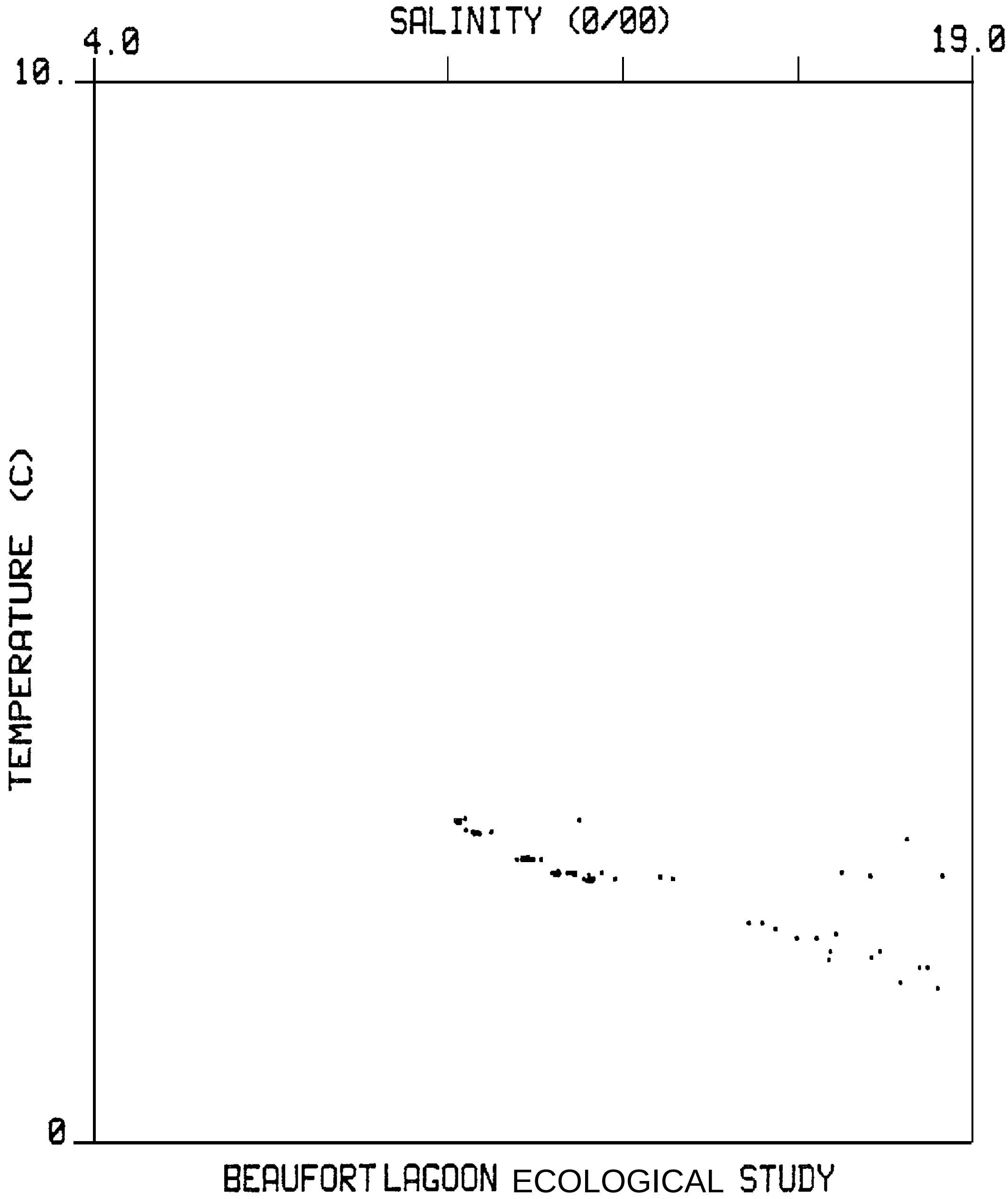


Figure 7-25. Temperature salinity diagram for CTD casts collected in the central and eastern end of Angun Lagoon on 10 September .1982.

limited exchange lagoons is indicated if these results are correct (this discussion is continued in the "DISCUSSION" section of this Chapter).

DISCUSSION

The results of this study will be discussed as they relate to the objectives stated in the "INTRODUCTION" of this Chapter, i.e. characterization of the various types of lagoon/barrier island and nearshore systems which exist along the Beaufort Sea coastline based on hydrographic properties, circulation characteristics, flushing rates, and cross-shelf and longshore exchange. This discussion will draw heavily on previous measurement programs on the Beaufort Sea Shelf, particularly work performed on the western Beaufort Shelf in Simpson Lagoon.

Cross-shelf and Longshore Exchange

The present study was unfortunately unable to collect field data on the inner shelf due to the severe ice conditions encountered during the measurement program. However, based upon historic data from the region and meteorological measurements made by Kozo (this volume), nearshore drifter data collected in this program, and physical processes identified as active on the western Beaufort Shelf, the exchange processes can be given a general description which contrasts conditions on the eastern and western shelf regions.

The 40 m isobath, where a mean eastward flowing subsurface current of Bering Sea water extends across the entire American section of the Beaufort Shelf, has been selected as the boundary between thel.nner and outer shelf. Atmospheric events on the shelf may cause periodic fluctuations or even reversals in the mean eastward flow. It has been postulated that net westward flow may exist in the surface waters immediately above this core of Bering Sea water.

Landward of this region, on the inner shelf, currents have been demonstrated to be primarily wind-driven. In the western Beaufort beyond Barter Island this would indicate year-round mean currents to the west along the coastline, as shownby drifter studiesby Matthews (1981) and

Barnes and Toimil (1979). However, in the eastern Beaufort winds are more bimodal and currents will exhibit a bimodal distribution with a mean eastward flow in the winter and a mean westward flow in the summer (Brewer et al. 1977); this is typical of eight of ten summers according to Kozo (this volume).

During open water periods this flow will tend to move western Beaufort nearshore waters offshore to be replaced by inner shelf waters and, under some conditions, to induce upwelling from the outer shelf as observed by Hufford (1974) and others. Upwelled waters on both the eastern and western inner shelf may then be further transported landward to the nearshore region by estuarine flow or, under proper wind conditions by offshore movement of wind-driven surface waters.

Longshore transport of water has also been demonstrated to be primarily wind-driven (see Fig. 7-26). In the western Beaufort this implies mean longshore transport to the west with easterly reversals occurring as mean wind conditions are modified by the passage of weather systems across the Beaufort. In the eastern Beaufort mean weather patterns are more bimodal in nature. Summer longshore transport is dominated by mean westward motion with reversals to the east as weather systems move through the area. Fall and early winter conditions show mean eastward water movement in this area with very high eastward transport and wind-induced set-up associated with fall storm systems. Westward transport also may be observed to accompany periods of easterly winds.

The innershelf long- and cross-shelf circulation can therefore be summarized as being primarily driven by the local wind fields with longshore current speeds on the order of 3-4% of the wind speed. In the western Beaufort, this implies net westward water movement; in the eastern Beaufort this implies a bimodal distribution of currents with eastward currents dominating in the winter and westward currents dominating in the summer. Mean year-round wind speeds cluster about 4 m/see in the Barter Island area although Kozo (this volume) does indicate some reduction in winds eastward toward Demarcation Bay. These average wind speeds imply mean wind-driven transport at characteristic speeds of 15-20 cm/sec in the open water period. Bath Aagaard (1981) and Matthews (1981) indicate that under-ice speeds would be greatly induced for this wind speed.

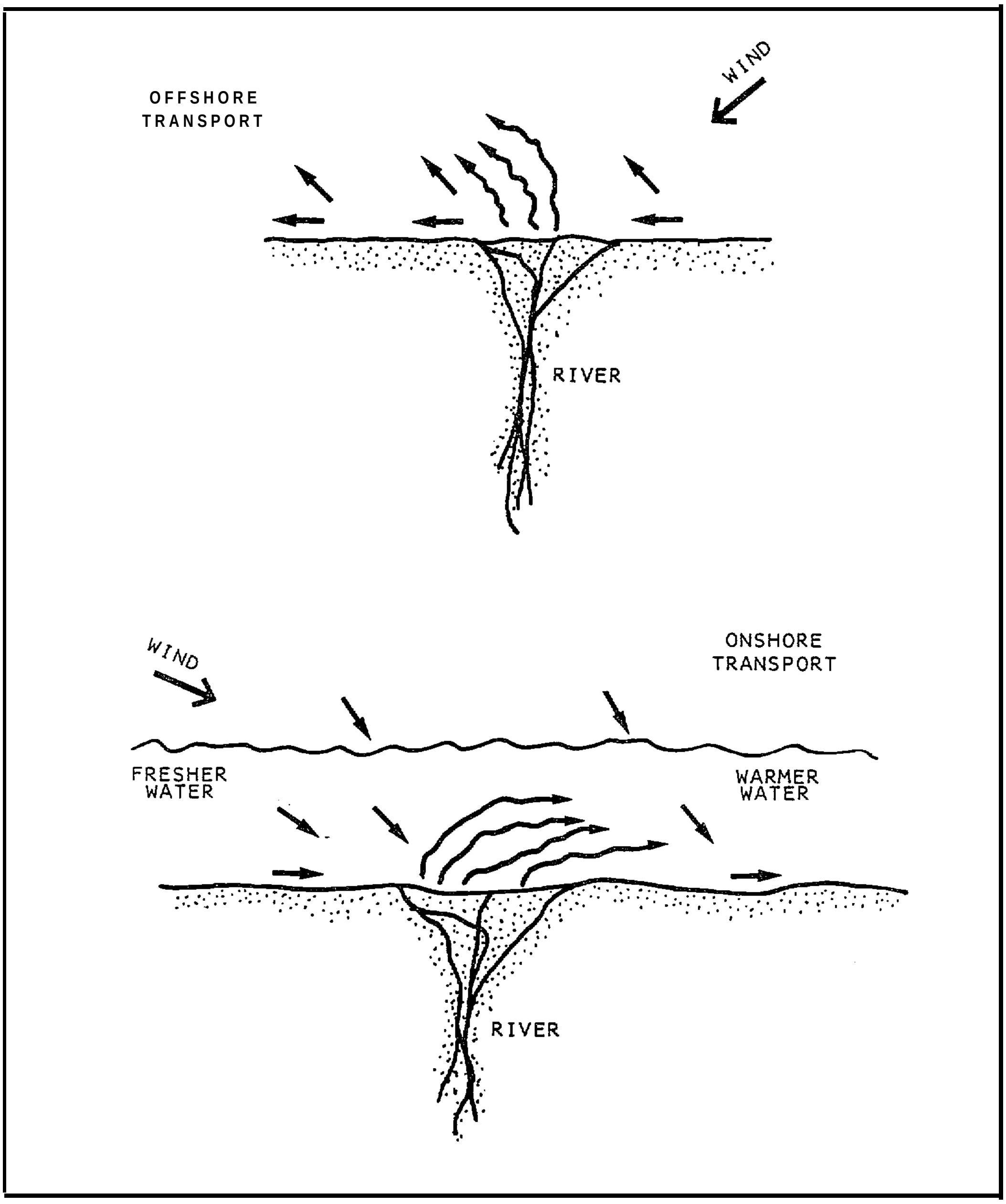


Figure 7-26. Lagoon circulation nearshore, shining general wind effects on onshore and offshore transport.

The basic lagoon types appearing on the Beaufort coastline are illustrated in Figure 7-27. The first type discussed in this Chapter is the open lagoon, i.e. those open to longshore transport as well as to cross-shelf exchange between multiple large openings in the barrier islands. The second lagoon type discussed is the pulsing lagoon, i.e. those with one major entrance through the barrier island. These lagoons are closed to longshore current throughput; exchange with the nearshore waters occurs primarily via tidal pumping of water through a single major entrance, although some smaller amount of exchange may also occur through shallow breaks in the barrier islands. One or more small rivers or streams typically empty into each of these lagoons providing a source of freshwater particularly in early spring.

The third lagoon type is termed a limited exchange lagoon in that it has only limited longshore current throughput via several larger openings in the barrier island system. These lagoons may or may not exhibit pulsing effects due to tidal pumping. These lagoon types will be discussed individually giving specific examples of each.

Open Lagoons

The most extensively studied example of an open lagoon system is Simpson Lagoon. Considerable data have been collected on both the biological and physical environments in multi-year OCSEAP-sponsored field programs of the Simpson Lagoon and nearshore region. This discussion will, however, address only results pertaining to a description of the physical environment of the lagoon. Figure 7-28 illustrates the effects of the mean summer wind conditions on Simpson Lagoon circulation patterns. In general, nearshore water enters the lagoon in the eastern and central portion and is advected through the lagoon in a manner similar to the wind-driven longshore transport seaward of the barrier island chain. Note that the multiple large openings in the lagoon system and the open end allow considerable flowthrough of the nearshore waters. Exchange is therefore largely due to advection of new water masses through the lagoon rather than input/local mixing/output.

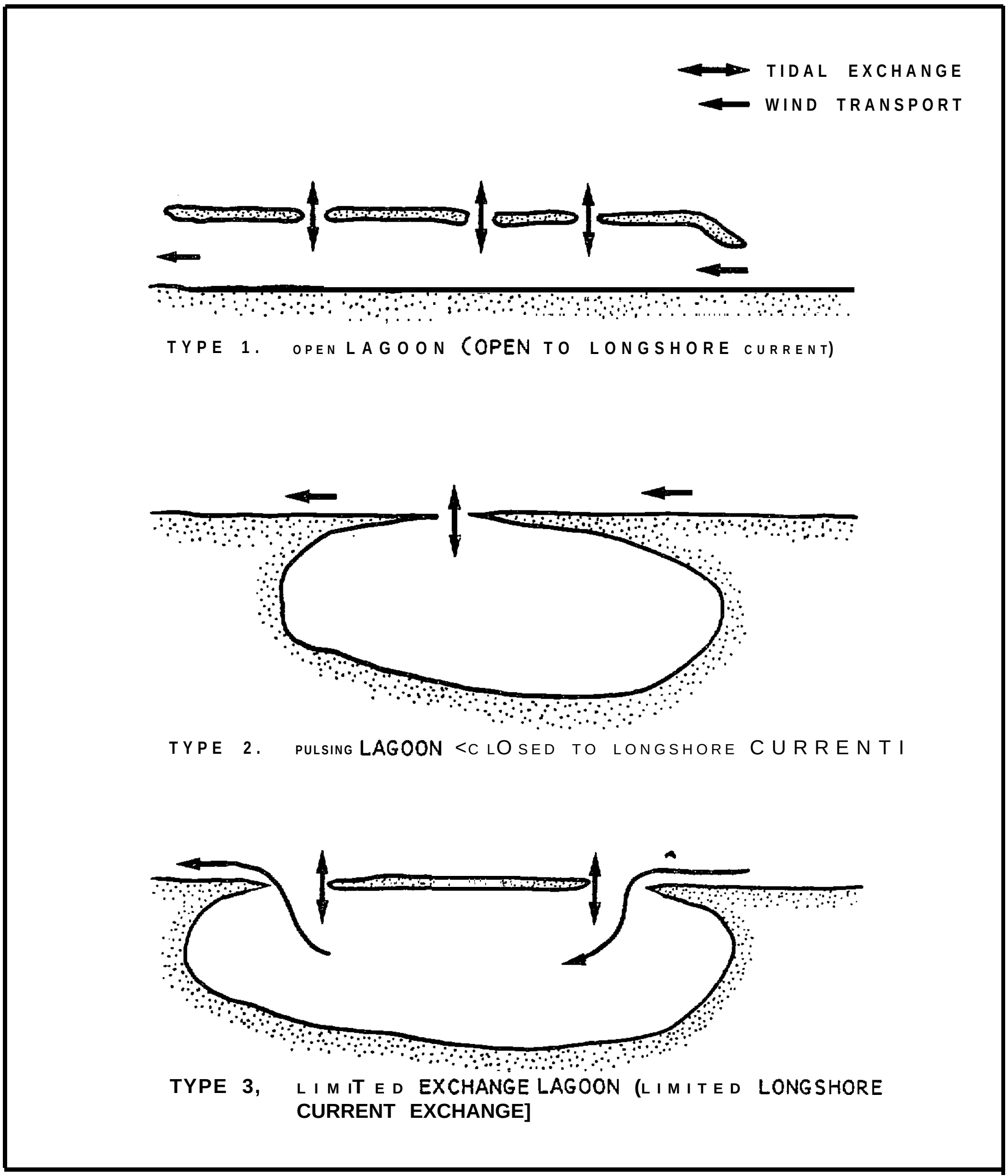


Figure 7-27. **Basic lagoon types:** open, pulsing and limited exchange,

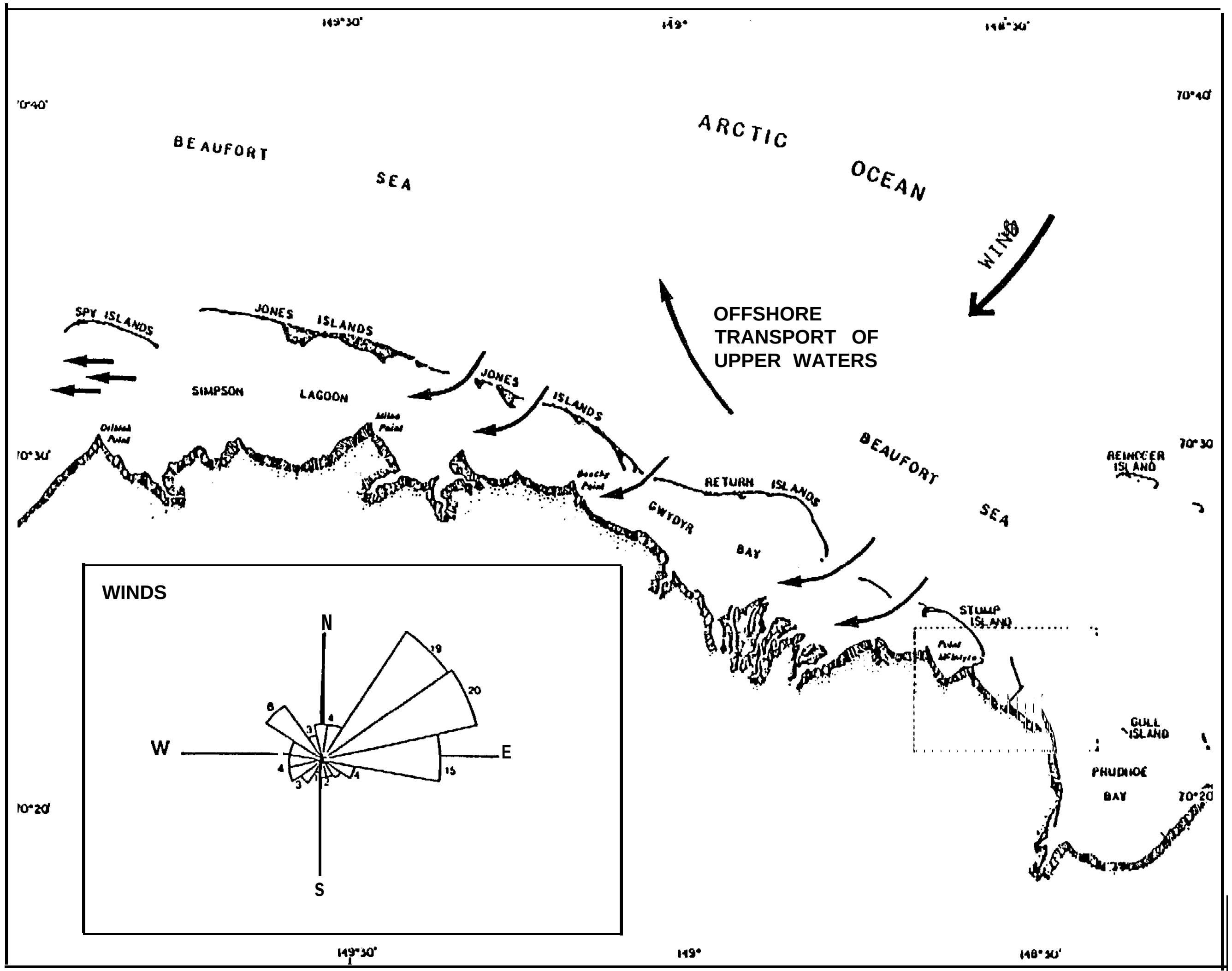


Figure 7-28. Effects of mean summer wind conditions on Simpson Lagoon circulation patterns.

Tidal effects (Fig. 7-29) are superimposed uPon the wind-driven component of the circulation and periodically modulate that component's effect. Depending on the strength of the wind-driven currents in a particular break in the barrier island, the tide may only modulate the mean flow in the entrance or it may actually reverse the flow during the opposing cycle of the tidal current as was observed in the Angun Lagoon entrance data.

When both mean wind-driven and tidal components of the circulation pattern are acting simultaneously, the effect is a pulsing flow pattern in the lagoon with a mean flow from east to west through the lagoon. Matthews (1979) has estimated that the flowthrough occurs at 3-4% of the mean wind speed which would Indicate lagoon water turnover on the order of 3-4 days for mean wind conditions of 10 kt. Matthews has also reported data which substantiate this description of circulation in a lagoon such as Simpson. Figure 7-30 illustrates the type of conditions which might be expected to exist in the lagoon if the description is correct. First, a net wind-driven transport of waters east to west through the lagoon would be accompanied by some offshore transport of the warm fresh surface nearshore waters and replacement by cooler saltier offshore waters. Tidal currents would then selectively introduce this nearshore water to the lagoon interior at each entrance on the successive flood tides. On ebb tides, the net westward flow would be reduced and lagoon waters would collect near the eastern entrances of the lagoon to form pools of warmer fresher water. On successive flood and ebb tides, these pools" of alternating cooler saltier nearshore water and warmer fresher lagoon water (formed by mixing of nearshore water from previous cycles and freshwaer from river runoff) would experience a net westward transport through the lagoon interior.

Figure 7-31 (from Matthews 1979) shows an example of temperatures salinity and current measurements from Milne Point during August 1978, along with a time series of sea level taken during the same time period. Note that when there is a mean westward flow through the lagoon (15-22 August) the temperature and salinity traces show the passage of alternating pools of cool saltier (0°C and 30 ppt) and warmer fresher (3-4°C and 24 ppt) water past the mooring site. This effect is observed to a

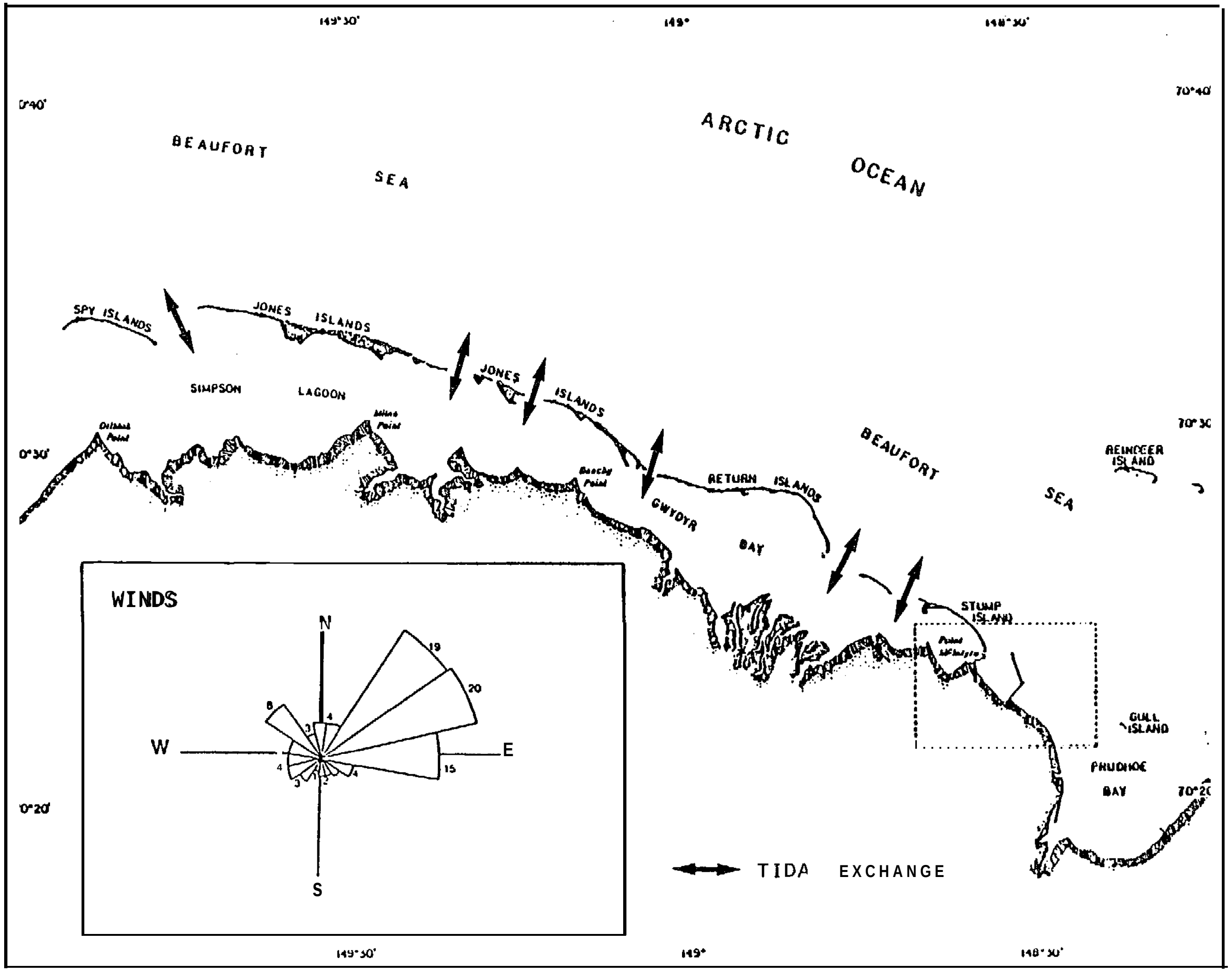
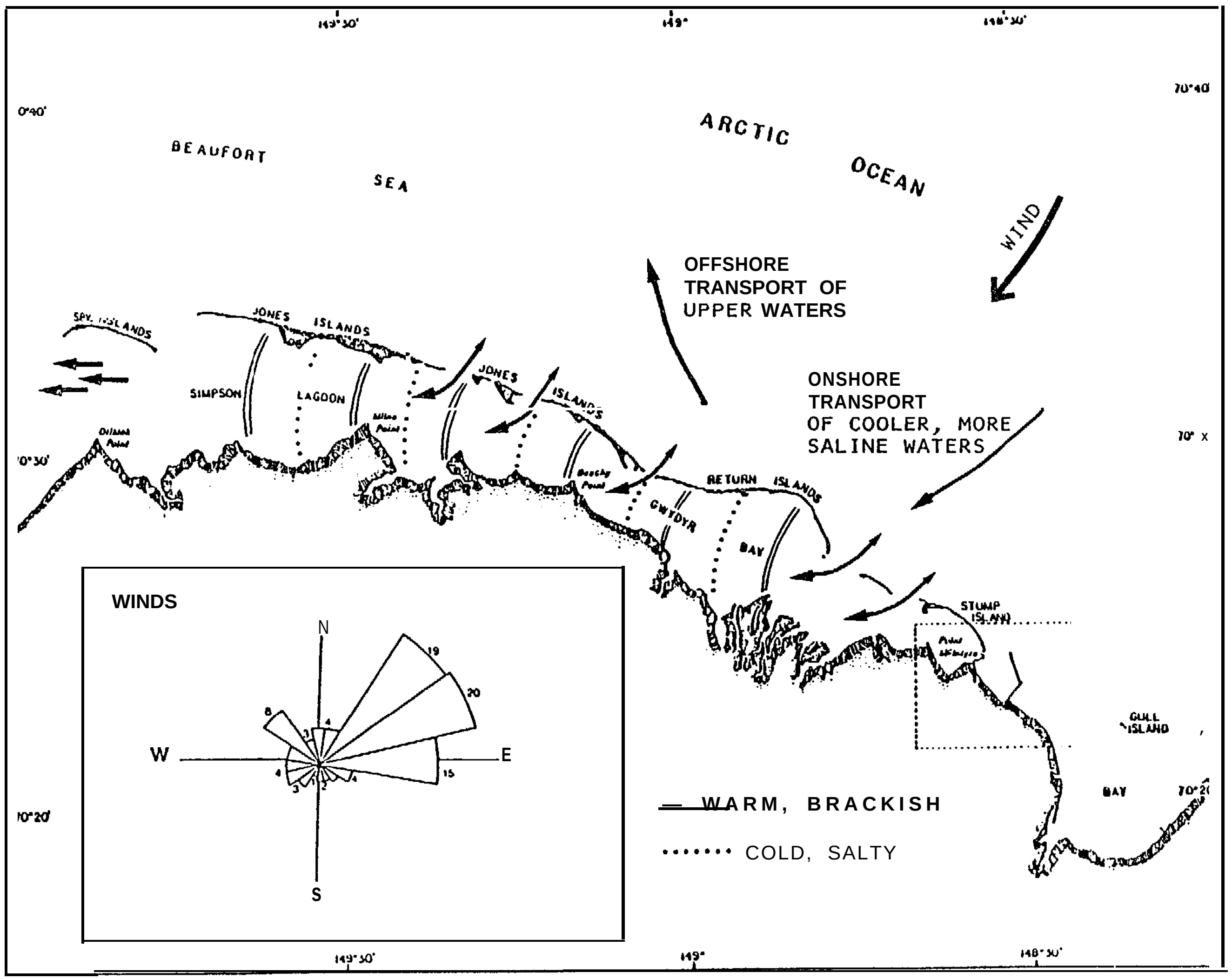


Figure 7-29. Tidal effects on Simpson Lagoon circulation patterns.



'igure 7-30. **Combined effects of wind and tide *on* Simpson Lagoon circulation.**

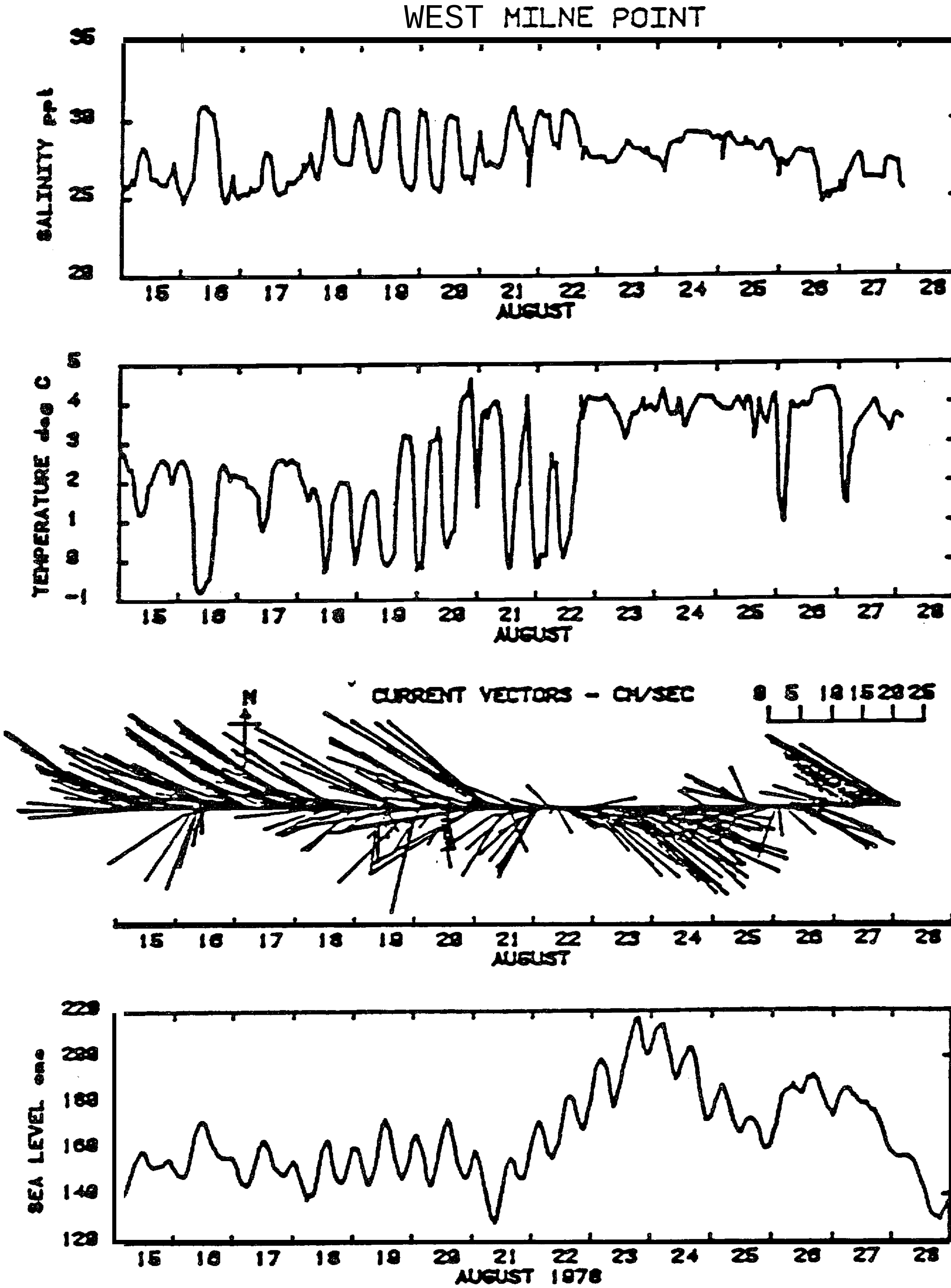


Figure 7-31. Temperature, salinity and current measurements taken at Milne Point August 1978 (from Matthews 1979).

greater or lesser extent at other mooring sites eastward of the Milne Point site.

When an abrupt change is observed in the wind pattern during the mean lagoon flow, a corresponding abrupt change is observed in the characteristics of the lagoon waters. On 22 August the winds changed from predominantly easterly to westerly, causing a reverse in the direction of the mean flow through the lagoon. This in turn retained the warm nearshore waters on the coast and reversed the direction of the longshore current. Figure 7-32 illustrates the change anticipated in the lagoon circulation patterns during mean westerly winds, using as an example the reversal in the direction of the lagoon flow observed in Figure 7-31 beginning on 22 August and lasting until 26 August. This reversal would be accompanied by the disappearance of the alternating nearshore and lagoon water masses past the mooring site (as nearshore and lagoon waters become identical) and observance of uniform warm intermediate-salinity water past the mooring site. An accumulation of nearshore water along the coastline would also lead to the observed sea level increase of apparently 50 cm. The reestablishment of the mean easterly lagoon flow as observed on 25 August would begin to produce the observed differential between lagoon and nearshore waters. Transport through the lagoon appears to be approximately the same both before and after the abrupt wind shift. In the former case, however, nearshore and lagoon waters appear to be identical and in the latter case they exhibit differences in both temperature and salinity.

Pulsing Lagoons

The pulsing lagoon type was the focus of study in the present field program. Figure 7-33 illustrates the combined wind and tidal effects of available exchange in this type of lagoon using Angun Lagoon and Pokok Bay as examples. Illustrated in this figure are mean summer conditions with winds predominantly from the east. In a manner similar to the open lagoon case, easterly winds result in somewhat higher nearshore salinities and lower nearshore temperatures for exchange with the lagoon. In addition, as discussed earlier, circulation in the lagoon itself may depend on the

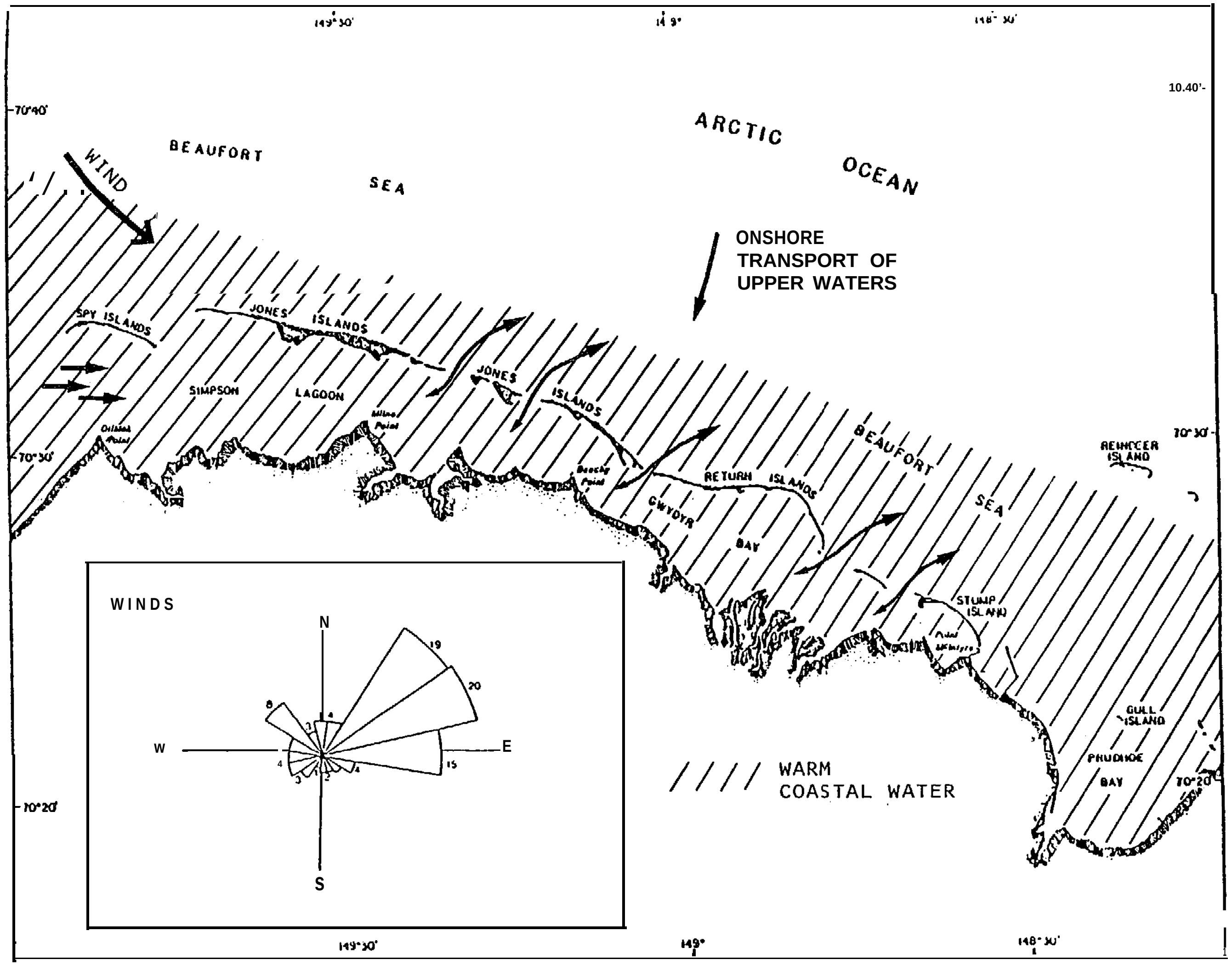


Figure 7-32. Combined effects on wind and tides during a mean westerly wind.

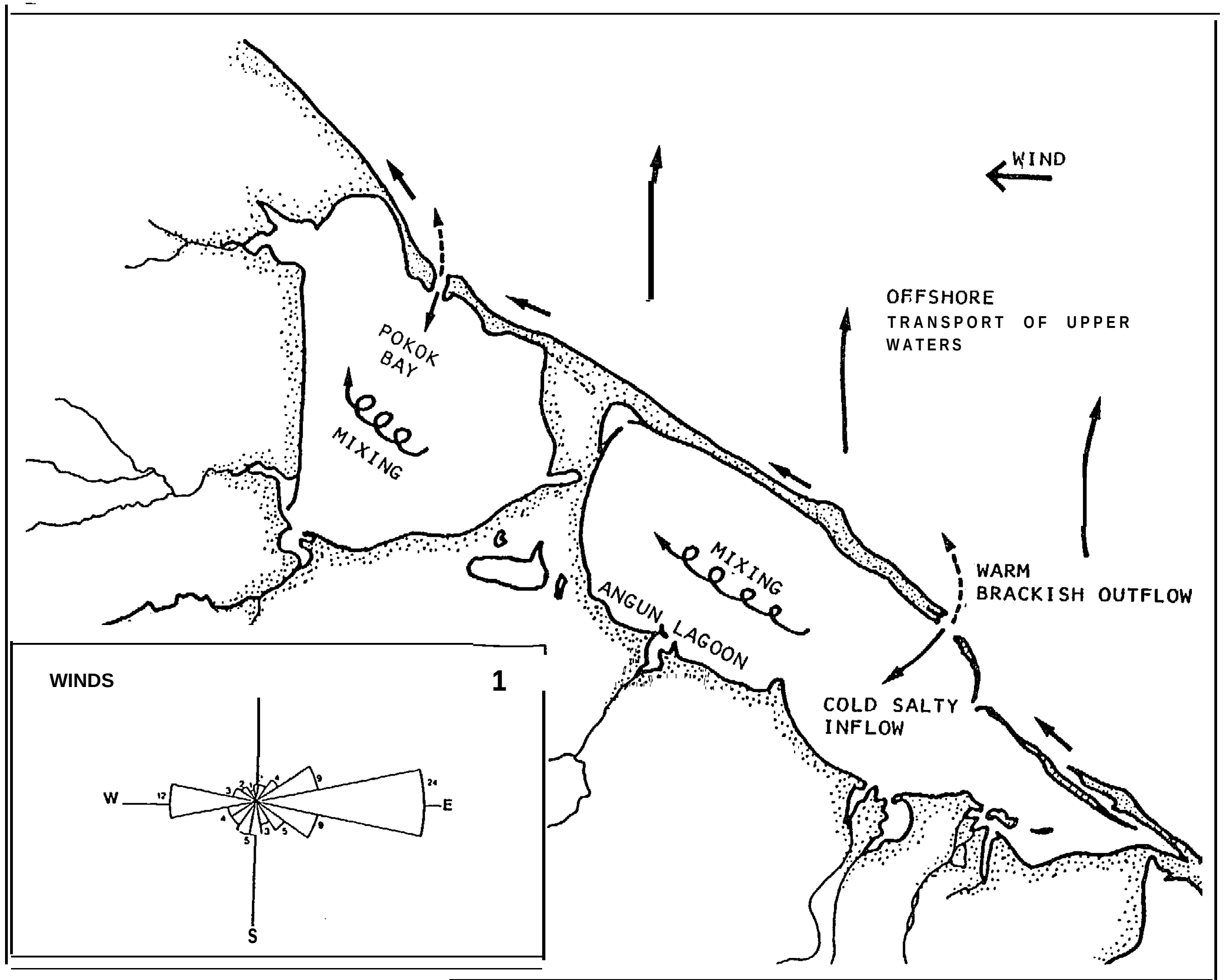


Figure 7-33. Combined wind and tidal effects in a pulsing lagoon such aa Pokok Bay and Angun Lagoon.

lagoon geometry with greater mixing observed for a lagoon with the geometry of Pokok Bay than for a lagoon with the shape of Angun Lagoon.

Figure 7-34 illustrates the circulation patterns anticipated for westerly winds. As in the open lagoon case, the fresher warmer nearshore water is maintained on the coast and advected eastward in the longshore current. Figures 7-9 and 7-16 (previously discussed in "RESULTS" section) show an example of a rapid shift from predominantly westerly to easterly winds and the resulting changes to the water entering Angun Lagoon. As observed in the Simpson Lagoon data, during westerly winds the nearshore water is warmed to temperatures equal to lagoon water and the nearshore and lagoon entrance waters become identical. However, when easterly winds are reestablished the nearshore waters cool as warm water is driven offshore and the pulsing effects of cool-water-in/mixing/warm-water-out is observed. Because there is no net flowthrough of the waters entering the pulsing lagoons, sensors placed in the interior of Angun Lagoon and Pokok Bay do not experience the alternating patterns of nearshore and lagoon water observed in Simpson Lagoon.

Physical models developed to study circulation and flushing in lagoons and small embayments provide useful information for interpreting measurements made in the present study. Recent work by Nece et al. (1979) studied the effects of planform geometry and the size and placement of lagoon entrances on flushing efficiencies of small embayments. Figure 7-35 shows an example of the distribution of exchange coefficient (percent water exchange per tidal cycle) in an embayment similar to Pokok Bay in geometry. Note the uniform distribution of the flushing properties in this case. The average flushing efficiency for a lagoon with this shape, according to this study, ranges from 90 to 100%. For comparison, in the "RESULTS" section, flushing efficiency for Pokok Bay was crudely estimated at 15 to 20% near the lagoon center. It should be noted, however, that the tidal ranges utilized in Nece et al. were a factor of ten greater than those observed in the Beaufort Lagoon system. Flushing efficiencies might therefore be expected to be greater in the model studies than in the actual lagoons. Regardless, the results for Simpson Lagoon are considerably different, giving estimated exchanges on the order of 3 to 4 days (8-10 days for ideal tidal flushing) which yields over a 200% efficiency compared to tidal flushing alone.

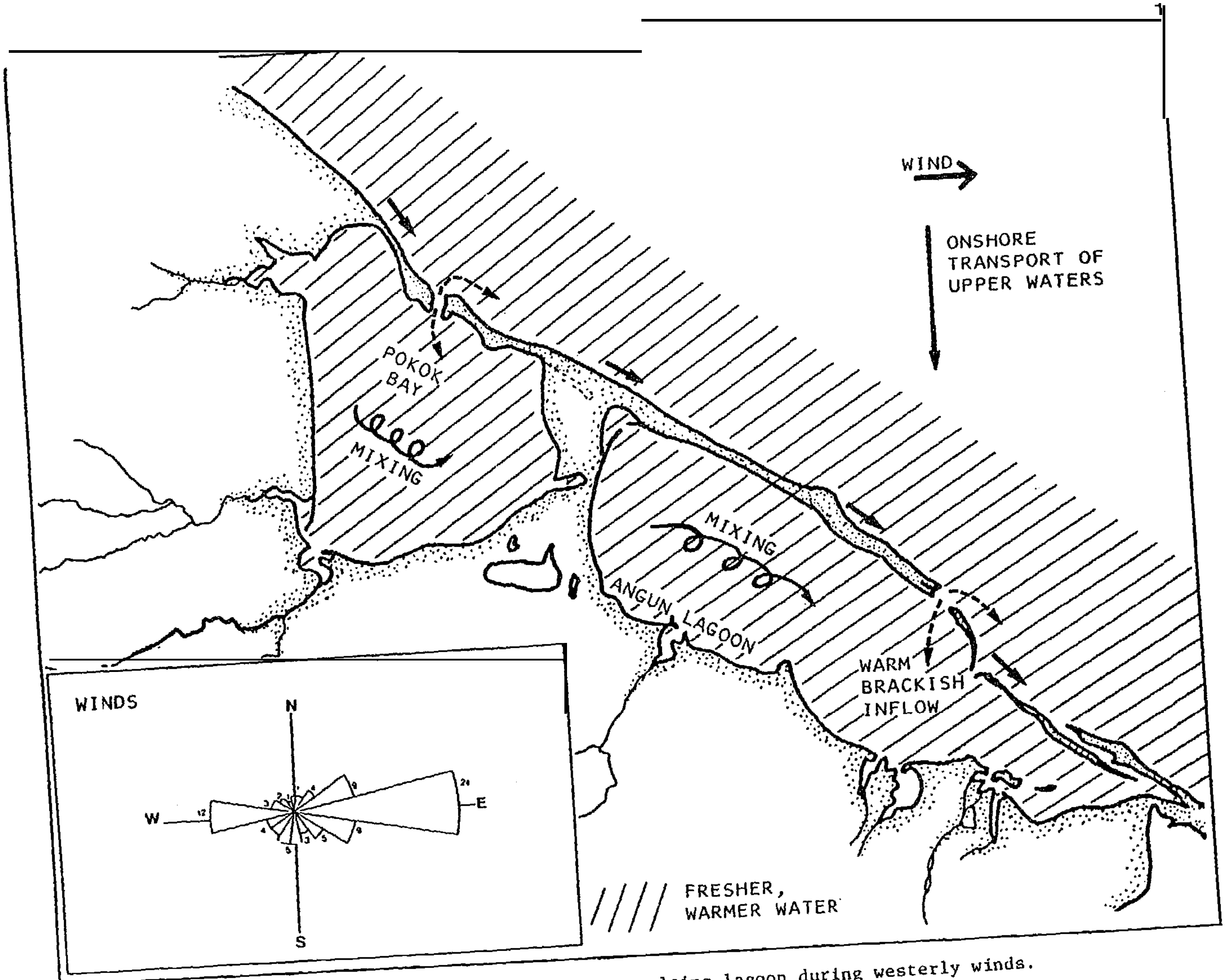
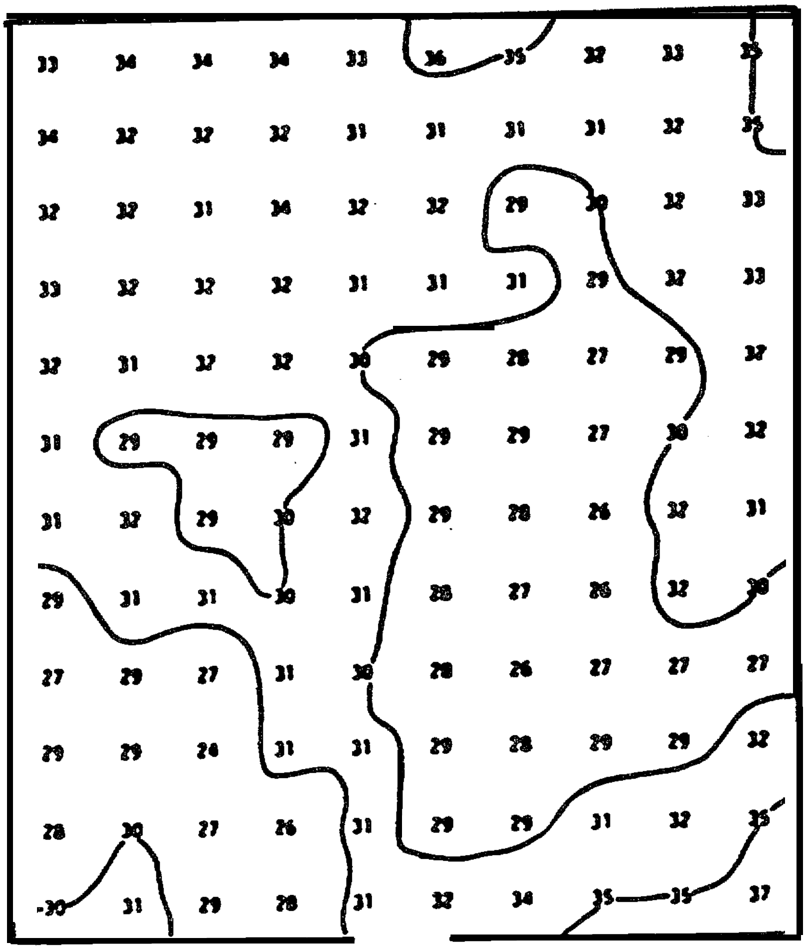


Figure 734. Combined wind and tidal effects for a pulsing lagoon during westerly winds.



AVERAGE EXPERIMENT EXCHANGE COEFFICIENT = 51%
IDEAL EXCHANGE COEFFICIENT = 31%
FLUSHING EFFICIENCY = 100%

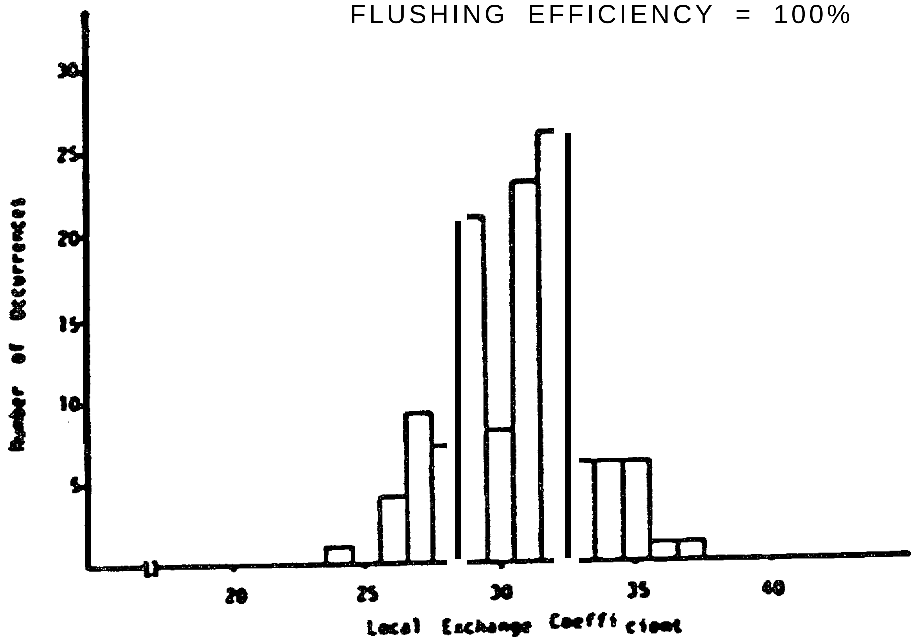
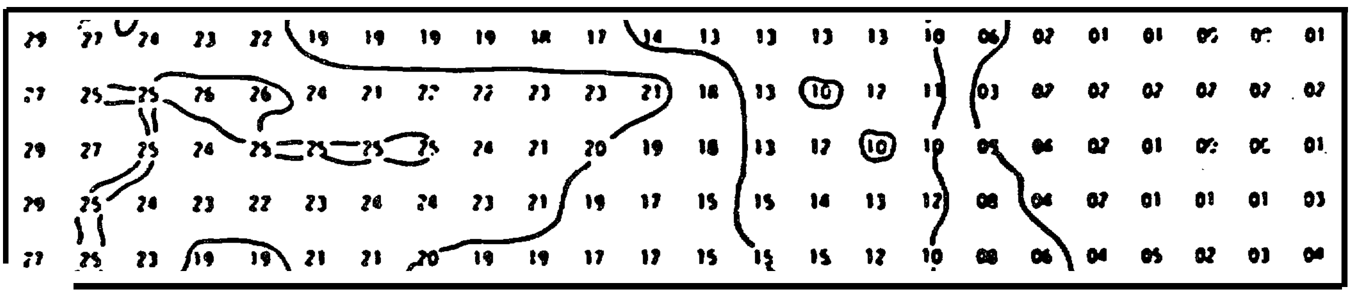


Figure 7-35. Example of exchange coefficient distribution in an embayment similar to Pokok Bay (from Nece et al. 1979).

For a planform model geometry similar to Angun Lagoon an Interesting phenomenon arises. Nece et al. find that multiple circulation cells develop in the lagoon when lagoon length-to-width ratios are greater than three; as a result, cells furthest from the entrance do not participate fully in the exchange processes and exhibit reduced flushing efficiencies. (The previous section alluded to existence of these cells in Angun Lagoon.) For a lagoon with a geometry similar to Angun Lagoon (length-to-width ratio = 5) three circulation cells would be observed. Figure 7-36 illustrates the results of a model study with an embayment having approximately the same geometry as the western portion of Angun Lagoon. The results indicate that near the lagoon entrance exchange coefficients may be as high as for the Pokok model results (23027%). However, exchange as low as 1-2% is observed at the far end of the lagoon away from the entrance. The overall flushing efficiency due to tidal effects alone therefore would be on the order of 48% which is less than half of the efficiency predicted for a pulsing lagoon similar to Pokok Bay. The region of the lagoon furthest from the lagoon entrance is, however, virtually isolated from the exchange processes, showing efficiencies as low as 8-10%. As in the case of the Pokok model, however, modeled tides are a factor of 10 greater than those observed in Angun Lagoon and actual flushing efficiencies are expected to be considerably less than those modeled.

Of particular note is the fact that current measurements in the far western end of Angun Lagoon show persistent north-northeast current direction indicating a mean clockwise circulation in this portion of the lagoon. Following Nece et al., if three circulation cells exist in the lagoon west of the main entrance then the central cell should exhibit net counterclockwise circulation and the cell immediately adjacent to the entrance should exhibit clockwise circulation, This is substantiated by visual observations of inflowing currents and surface drifter motions near the lagoon entrance.

It must be remembered at this point that these results are for tidal flushing only and that considerable wind mixing may occur in addition to the exchange which is enhanced by the input of freshwater into the surface waters at the isolated end of Angun Lagoon. However, in the absence of large quantities of freshwater as might be expected in the late summer and



AVERAGE EXPERIMENTAL EXCHANGE COEFFICIENT = 15%
IDEAL EXCHANGE COEFFICIENT = 31%
FLUSHING EFFICIENCY = 48%

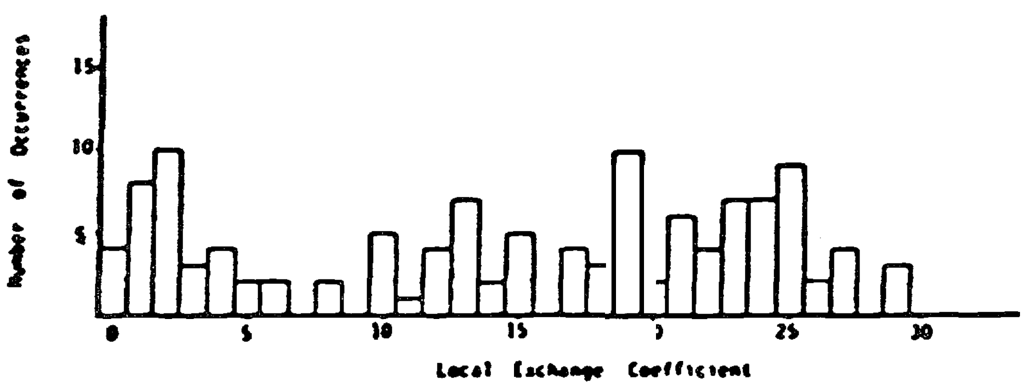


Figure 7-36. Example of exchange coefficient distribution in an embayment similar to Angun Lagoon (from Nece et al. 1979).

fall under mean easterly wind conditions, flushing of lagoons similar to Angun Lagoon might be considerably lower than indicated by typical ideal flushing estimates based on volume exchange alone.

Limited Exchange Lagoons

The final lagoon type to be discussed has been termed the limited exchange lagoon since only limited throughout of nearshore waters is possible. An example of this type is Beaufort Lagoon which is actually composed of several small interconnected narrow lagoons with an extensive barrier island system. The barrier island system (commonly referred to as Icy Reef) has a relatively small number of openings distributed along its extent but several of the openings are quite large, allowing the possibility of net wind-driven flowthrough of the waters from the longshore current. At the far western end of Beaufort Lagoon is Nuvagapak Lagoon, followed by (moving eastward) Egaksrak Lagoon, Siku Lagoon, Pingokraluk Lagoon, and finally Demarcation Bay. Major entrances include Nuvagapak entrance to the west (which actually consists of two openings: one narrow and quite deep, the other wider but relatively shallow), Egaksrak entrance, Siku entrance, and the main entrance to Demarcation Bay.

Although water samples were collected in Nuvagapak Lagoon, sufficient information does not exist to substantiate the hypothesis that nearshore water input to the Beaufort Lagoon system on the upwind entrances would be slowly advected through the lagoon system and output through the downwind entrance to the lagoon. Visual observations on 2-3 August, however, indicate a large influx of nearshore ice floes at the deep western entrance which were advected into the lagoon interior during mean westerly winds. However, once in the lagoon and subject to both higher water temperatures and wave activity, the ice floes quickly melted and were lost as tracers of the net water movement through the lagoon.

Flowthrough, hence purely advective exchange as was discussed for the open lagoon types, is expected to be considerably less than observed for Simpson Lagoon. However, considerably more advective exchange than for the pulsing lagoons is anticipated. The observed range of flushing efficiency calculated for open and pulsing lagoons has been estimated at 200% and 15-20%, respectively, for Simpson and Pokok lagoons. If model results for Pokok Bay and Angun Lagoon geometries scale the same (100% flushing efficiency for Pokok Bay and 48% average efficiency for Angun Lagoon) then actual average efficiencies for Angun Lagoon may be as low as 7-10% given a 15-20% estimate for Pokok Bay. Therefore, a considerable gain in flushing efficiency might be expected for the limited exchange lagoons dependent on the degree of wind-driven advection through the lagoons. For example, if advection in Nuvagapak Lagoon is only 0.5% of a 3 m/see easterly wind (1.5 cm/see) as compared to 3-4$ observed in Simpson Lagoon, then flushing efficiency could be increased to 75% with water exchange occurring in as little as 12 days.

A considerable number of limited exchange lagoons exist in the eastern Beaufort including those lagoons typically considered as forming Beaufort Lagoon and the lagoon systems inside- Icy Reef to Demarcation Bay. To the west, Oruktalik, Tapkaurak, and Jago lagoons are of similar configuration. These limited exchange lagoons, whose entrances may or may not exhibit some phenomenon characteristic of pulsing lagoons depending on the degree of wind-driven advection through the particular lagoon encompass over 75% of the coastline of the Beaufort nearshore east of Barter Island. Perhaps another 15% of the coastline can be accounted for by pulsing lagoons in this region. Further study of the flushing characteristics of these lagoons is clearly warranted. In contrast, the lagoons in the western Beaufort from Barter Island to Pt. Barrow are almost all of the open type similar to Simpson Lagoon.

Continued OCSEAP-sponsored studies in the Chukchi Sea nearshore will deal almost exclusively with the limited exchange lagoons which have extensive barrier island systems and multiple small entrances distributed along the coastline. A study of the Peard Bay lagoon system In particular will be undertaken in the summer of 1983. Figure 7-37 shows the results of a model study of a small embayment with two small entrances (one entrance is twice the size of the other) similar to Peard Bay; the predicted flushing efficiency for a lagoon with this geometry would be 84% which compares to 48% for a single entrance lagoon with the geometry of Angun Lagoon. In addition, given two entrances and the relationship of

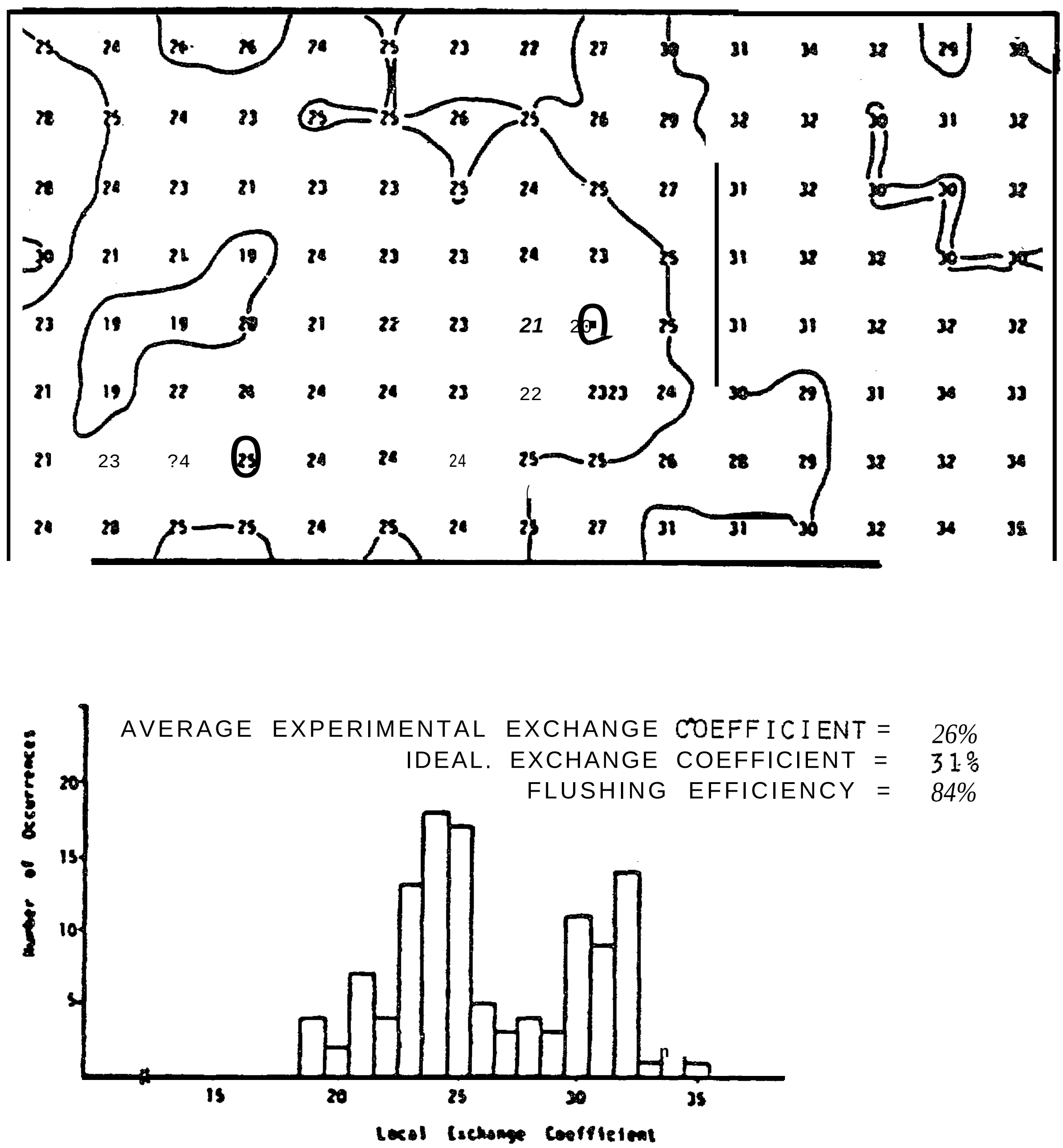


Figure 7-37. Example of exchange coefficient distribution in a small embayment with two entrances similar to Peard Bay (from Nece et al. 1979).

the Peard Bay geometry to the local wind field, it is probable that considerable flowthrough of' nearshore waters may occur during strong easterly or westerly wind events.

CONCLUSIONS

Circulation patterns and exchange properties of nearshore and lagoon/barrier island systems on the eastern and western Beaufort Shelf show many dissimilarities. Observed differences may be attributable both to differences in coastal and lagoon geometries and to differences in their surrounding external physical environments. The major difference in the physical environment affecting eastern and western Beaufort systems is the mean wind field. Mean winds in the western Beaufort are primarily from the ENE whereas in the eastern Beaufort winds are bimodal, being directed from both the ENE and WSW with ENE winds dominating In the summer and WSW winds dominating in the winter. Because currents on the inner shelf and nearshore are primarily wind-driven, circulation patterns should vary considerably in the two regions. However, there is not yet sufficient data on either inner shelf region to adequatly describe current patterns.

The mean summer wind conditions in the eastern Beaufort tend to move nearshore surface waters offshore and to the west to be replaced by cooler saltier water from the inner shelf. These conditions occur 35% of the time for an average summer. During periods of easterly winds, water entering the lagoons from the nearshore is typically cooler and saltier than the ambient lagoon water. Of the remaining open water season, 25% of the time winds are from the WSW and nearshore waters are retained along the coast and are advected to the east. During these periods of westerly winds, lagoon and nearshore waters tend to exhibit similar properties

Mean summer conditions in the western Beaufort are similar to those in the eastern Beaufort during periods of easterly winds. However, in the western Beaufort easterly winds dominate over a greater percentage of time including the fall and winter periods. This is reflected in the movement of warmer fresher nearshore water away from the coast to be replaced by cooler saltier inner shelf water and in the observed cooler mean temperatures and higher mean salinities in the western Beaufort lagoons.

Fall conditions in the eastern Beaufort are dominated by westerly winds which move the ice and inner shelf surface waters onshore and to the east. Fall is the period when large storm setup may occur and significant longshore transport may result.

Hypersaline water observed in the western Beaufort open lagoons has not been detected in eastern lagoons. Even very early (26 July) measurements in Angun and Beaufort Lagoon interiors failed to detect residual hypersaline water from the winter season. This may be due partially to the lack of sills in the pulsing and limited exchange lagoon entrances which enable the brine extruded during the winter freezing to escape the lagoons, or perhaps to probable higher winter tidal exchange rates in the eastern lagoons which have deeper entrances and interiors than were observed in the western open lagoons. It is also probable, however, that the absence of this water is due simply to the spring river discharge which purged the lagoons prior to July, similarly to observations in Simpson Lagoon.

Lagoon/barrier island geometries vary between the eastern and western Beaufort Shelf, with open lagoons being the dominant form along the western nearshore regime and pulsing or limited exchange lagoons being the dominant form along the eastern Beaufort. The largest flushing efficiencies for the three lagoon types occur in the open lagoons similar to Simpson Lagoon in the western Beaufort. These lagoons are open to flowthrough by the coastal longshore currents and may exhibit flushing efficiencies equal to 200% of tidally-induced exchange alone.

Flushing efficiencies for pulsing or limited exchange lagoons may, however, be considerably less. For example, the flushing efficiency of Pokok Bay (a pulsing lagoon that should exhibit good flushing characteristics with a centrally located entrance and a length-to-width ratio of approximately 1) may be as low as 15-20% in the absence of enhanced baroclinic flow. On the other hand, Angun Lagoon (a pulsing lagoon with a length-to-width ratio of 5 and an off-center entrance, thus predicted poor flushing characteristics) may show average overall flushing efficiencies which are half of those observed for Pokok Bay. In addition, Angun Lagoon contains some isolated regions away from the entrance which may have tidal flushing efficiencies only 10% of those calculated for Pokok Bay.

However, under the influence of wind forcing and particularly under the influence of westerly winds which forces water onto the nearshore region and into the lagoons, vertical mixing and increased horizontal exchange occurs which may temporarily increase the exchange efficiencies of these types of lagoons to equal that observed for Pokok Bay. The critical wind speed required to mix the lagoon waters appears to be on the order of 10 kt for early spring stratifications, and is anticipated to be considerably less for late summer conditions when vertical stratification is reduced. In either case, however, flushing efficiency for these eastern Beaufort Lagoon types is considerably less than that observed for the open western lagoons, and it appears only a fraction (15-20%) of that which would be estimated from volume exchange calculations alone. These reduced flushing rates make the eastern Beaufort Lagoon systems more vulnerable to impact by oil and gas exploration activity due both to disruptions in the exchange processes which renew the lagoon properties via interactions with the nearshore waters and to direct contamination by oil or drilling byproducts.

NEED FOR FURTHER STUDY

Results of this program indicate the need for a better understanding of the flushing properties of pulsing and limited exchange lagoons. OCSEAP is presently sponsoring a numerical modeling program to study circulation and exchange in various lagoon types. Data to validate these models can be obtained by either field measurement programs or Laboratory model studies. These studies could most effectively be carried out in a laboratory modeling program similar to that conducted by Rece for small embayments in the State of Washington. These studies should include both the effects of tidal flushing for various planform lagoon geometries (simulated 20-cm tidal amplitudes) and the effects of enhancements due to fresh water runoff in the lagoon interiors. These model studies, unfortunately, cannot model the effects of wind-driven circulation and mixing but could be used to validate portions of current numerical codes being developed to model Beaufort Lagoons. These codes, when validated, will accommodate wind-induced mixing and circulation effects for comparison to observed wind mixing thresholds and measured lagoon circulation.

LITERATURE CITED

Aagaard, K. 19810 Current measurements in possible dispersal regions of the Beaufort Sea. In: Environmental Assessment of the Alaskan Continental Shelf. Volume 3: Physical Sciences Studies. USDC Office of Marine Pollution Assessment. Washington, D.C.

Barnes, P.W. and L.J. Toimil. 1979. Maps showing inner shelf circulation patterns, Beaufort Sea, Alaska, Map MF-1125. U.S. Geol. Survey, Denver, Colorado.

Brewer, W.A., et al. 1977. Climatic atlas of the outer continental shelf waters and coastal regions of Alaska. NOAA/AEIDC Publication B-77.

Foreman, M.G.G. and R.F. Henry. 1979. Tidal analysis based on high and low water observations. Institute of Ocean Sciences, Patricia Bay, Sydney, B.C., Pacific Marine Science Report 79-15. 39 PP.

Foreman, M.G.G. 1979a. Manual for tidal heights analysis and prediction. Institute of Ocean Sciences, Patricia Bay, B.C., Pacific Marine Science Report 77-10. 101 PP.

Foreman, M.G.G. 1979b. Manual for tidal currents analysis and prediction. Institute of Ocean Sciences, Patricia Bay, B.C., Pacific Marine Science Report 78-6. 70 pp.

Godin, G. 1972. The analysis of tides. University of Toronto Press.

Matthews, J.B. 1981. Observations of surface and bottom currents in the Beaufort Sea near Prudhoe Bay, Alaska J. Geophys. Res. 86(C7):6653-6660.

Mountain, D.G. 1974a. Bering Sea water on the North Alaskan Shelf. Ph.D. Thesis, University of Washington, Seattle, WA.

Mountain, D.G. 1974b. Preliminary analyses of Beaufort Shelf circulation in summer. In: The Coast and Shelf of the Beaufort Sea (J.C. Reed and J.E. Satu, Eds.), Arctic Institute of North America, Arlington, Va.

Murphy, D.L. et al. 1981. Long-term movement of satellite-tracked buoys in the Beaufort Sea: Interim Report. USCG Research and Development Center, Avery Point, Groton, CT.

Nece, R.E. et al. 1979. Effects of planform geometry on tidal flushing and mixing in marinas. Dept. Civil Engr. Report No. 62, University of Washington, Seattle, WA.

Schell, A. 1982. Personal communication.

Searby, H.W. and M. Hunter. 1971. Climate of the North Slope of Alaska. NOAA Tech. Memo NWS-AR-4. Anchorage, AK. 53 PP.

Schaeffer, P.J. 1966. Computation of a storm surge at Barrow, Alaska. Archiv fur Meteorologic, Geophysik and Bioklimatologie, Ser. A: Meteorologic und Geophysik. 15(3-4):372-393.

Truett, J.C. 1981. Environmental assessment of the Alaskan continental shelf: Synthesis, impact analysis and a monitoring strategy. NOAA/OCSEAP Final Report Contract 03-022-35193.

Oral Presentation

Hachmeister, L.E. 1983. Classification of lagoonal types in the Beaufort Sea. Presentation at Sale #87 Synthesis Meeting, Chena Hot Springs, 25-28 January 1983.