

## The Physical Oceanography of the Cape Hatt Region, Eclipse Sound, N.W.T.

J.R. BUCKLEY,<sup>1</sup> B.R. DE LANGE BOOM<sup>2</sup> and E.M. REIMER<sup>3</sup>

(Received 6 June 1986; accepted in revised form 19 March 1987)

**ABSTRACT.** In the spring and summer of 1980 and 1981, detailed measurements of water temperature, salinity and depth, currents, tidal height and waves were made in the vicinity of Cape Hatt, at the northern end of Baffin Island, N.W.T., in support of the Baffin Island Oil Spill (BIOS) Project. Currents in the region were generally weak, averaging less than  $10 \text{ cm}\cdot\text{s}^{-1}$  near the surface and about  $2 \text{ cm}\cdot\text{s}^{-1}$  in the deeper waters. Deep circulation in Ragged Channel, on the western side of Cape Hatt, was usually counterclockwise. On the western side of Cape Hatt, a strong (up to  $30 \text{ cm}\cdot\text{s}^{-1}$ ) northward flowing coastal current existed. It was occasionally reversed by a flood tide or prolonged south winds. Eddies were observed in bays on the western side of Cape Hatt driven by this coastal current. These eddies were clockwise when the flow offshore was northward and counterclockwise when the flow was southward. Evidence was found for an internal  $M_2$  tide in Ragged Channel. Some of the variations in the observed currents and density fields were explained with a simple model of this tide. Under-ice density profiles showed a typical well-mixed layer just above freezing temperature that reached to the bottom in the nearshore regions and to about 35 m depth in mid-channel. In the ice-free season, there was a pronounced shallow mixed layer that ranged from 4 to 10 m in depth. Water properties at the bottom of Ragged Channel were essentially unchanged from winter to summer. In the winter, water properties in Z-Lagoon were similar to those in Ragged Channel. In the summer, they showed the result of being cut off from the main body of Eclipse Sound. In Ragged Channel, wave conditions were very mild, not exceeding 20 cm in significant height, while on the eastern side of Cape Hatt, they were worse, up to 1.4 m, but still not severe.

**Key words:** Eclipse Sound, oceanography, currents, tides, internal tides, water temperature, salinity, waves

**RÉSUMÉ.** Durant le printemps et l'été de 1980 et de 1981, on a effectué des mesures détaillées de la température de l'eau, de la salinité et de la profondeur, des courants, de la hauteur de la marée et des vagues, aux environs du cap Hatt, à l'extrémité nord de l'île Baffin (T. N.-O.), dans le cadre du projet BIOS (projet de déversement de pétrole à l'île Baffin). En général, dans cette région les courants étaient faibles, avec une moyenne de moins de  $10 \text{ cm}\cdot\text{s}^{-1}$  près de la surface, et d'environ  $2 \text{ cm}\cdot\text{s}^{-1}$  dans les eaux plus profondes. Dans le chenal Ragged du côté ouest du cap Hatt, les courants plus profonds allaient en général dans le sens inverse des aiguilles d'une montre. Du côté ouest du cap Hatt, il y avait un fort courant côtier en direction du nord (jusqu'à  $30 \text{ cm}\cdot\text{s}^{-1}$ ). De temps en temps, il était inversé par une marée montante ou des vents du sud prolongés. On a observé des tourbillons formés par ce courant côtier dans les baies du côté ouest du cap Hatt. Ces tourbillons allaient dans le sens des aiguilles d'une montre quand le courant vers le large se dirigeait vers le nord, et dans le sens inverse quand le courant se dirigeait vers le sud. On a prouvé l'existence d'une marée interne  $M_2$  dans le chenal Ragged. On a expliqué quelques-unes des variations dans les courants et les champs de densité grâce à un modèle simplifié de cette marée. Les profils de densité sous la glace ont révélé une couche typique bien mélangée dont la température était juste au-dessus du point de congélation, et qui atteignait le fond dans les zones proches du littoral et une profondeur d'environ 35 m au milieu du chenal. Durant la saison libre de glace, on a trouvé à une faible profondeur une couche mélangée bien distincte, dont la hauteur allait de 4 à 10 m. Les propriétés de l'eau au fond du chenal Ragged restaient essentiellement les mêmes de l'hiver à l'été. Durant l'hiver, les propriétés de l'eau dans la lagune Z étaient les mêmes que celles du chenal Ragged. Durant l'été, les résultats montrent que ces eaux étaient coupées de l'ensemble des eaux de Eclipse Sound. Dans le chenal Ragged, la mer était très calme, avec des vagues ne dépassant pas 20 cm de hauteur significative, alors que du côté est du cap Hatt, elle était plus agitée sans toutefois l'être trop, avec des vagues allant jusqu'à 1,4 m.

**Mots clés:** Eclipse Sound, océanographie, courants, marées, marées internes, température de l'eau, salinité, vagues

Traduit pour le journal par Nésida Loyer.

### INTRODUCTION

The Baffin Island Oil Spill (BIOS) Project was a multi-year experimental examination of the fate and effects of oil released near arctic shorelines. In order to meet the general objectives of this project, it was essential to understand the physical oceanographic environment of the project setting and to be able to monitor and predict changes in it throughout the experimental program. In this paper, we describe the measurement programs carried out to study the physical oceanography of the Cape Hatt region of northern Baffin Island and the results of those programs and we discuss those results. We suggest a model that would connect many of the observed oceanographic phenomena important to the understanding of the chemical and biological results of the project. Although they are not strictly necessary for a general oceanographic description of the region, we also include an analysis of the physical oceanographic reasons for the choice of the three experimental bays and a detailed description of water movement during and after the two experimental releases of oil in 1981.

Cape Hatt is a peninsula at the north end of Baffin Island in the eastern Canadian Arctic. The east side of Cape Hatt is exposed to the open waters of Eclipse Sound and Pond Inlet. The west side is bounded by a narrow channel that separates it from Ragged Island. This channel has no depth obstructions to the north, but has a 5 m deep sill at the south end, effectively closing it to all but surface interactions at that end. The main experimental area for the BIOS Project was a series of small bays along the eastern side of Ragged Channel and in Z-Lagoon in the centre of the peninsula. Potential experimental bays along Ragged Channel and in Z-Lagoon were identified by numbers shown in Figure 1. Bay 7 is not shown in Figure 1 because it is located considerably south of the other bays on the east shore of Ragged Channel. Bathymetrically, Bays 7, 9, 10 and 13 are similar, with a narrow shelf dropping off quickly to the deeper waters of Ragged Channel. Bays 11 and 12 are separated from the main body of Ragged Channel by a 13 m deep sill across their mouth. The waters of Z-Lagoon are also separated from Eclipse Sound by a 6 m deep sill. A more detailed description of the region is available in Sergy and Blackall (1987).

<sup>1</sup>Institute of Ocean Sciences, Patricia Bay, Sidney, British Columbia, Canada V8L 4B2

<sup>2</sup>Seakem Oceanography Ltd., P.O. Box 2219, Sidney, British Columbia, Canada V8L 3S1

<sup>3</sup>Canpolar Consultants Ltd., Ashley Bldg., 31 Peet Street, St. John's, Newfoundland, Canada A1B 3W8

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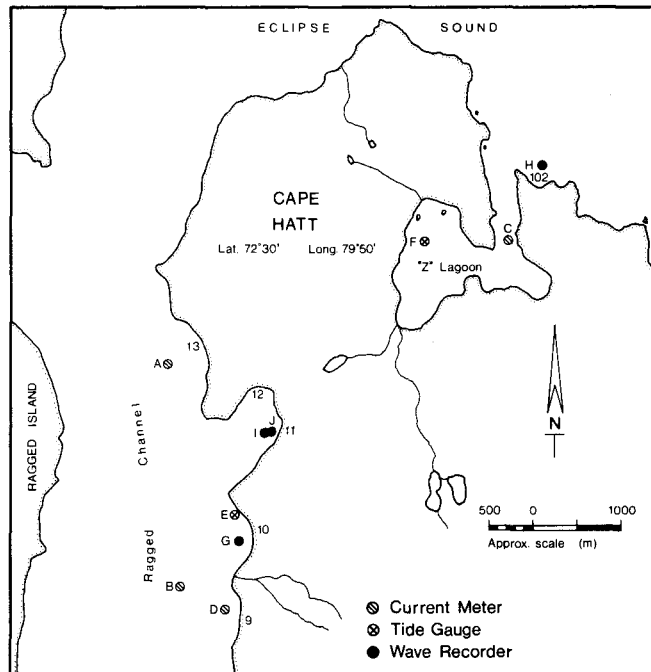


FIG. 1. Locations of the moored oceanographic instruments 1980-83.

Site	Instrument	Location	Year
A	Current meters	Ragged Channel North	1980
B	Current meters	Ragged Channel South	1980
C	Current meter	Z-Lagoon	1980
D	Current meters	Bay 9	1981
E	Tide gauge	Bay 10	1980, 1981
F	Tide gauge	Z-Lagoon	1980
G	Wave recorder	Bay 10	1980
H	Wave recorder	Bay 102	1980, 81, 82
I	Wave recorder	Bay 11	1981, 82
J	Wave recorder	Bay 11	1983

In the baseline year of the project, 1980, the prime objective of the physical oceanographic program was to describe quantitatively the oceanography of the Cape Hatt region in general and of the experimental bays in detail. These descriptions were important to determine the typicality of Cape Hatt as an oceanographic regime in the eastern Arctic and to help in the design, location and timing of the experimental oil releases to take place the next year. In 1981 the objectives were to predict those parameters critical to the successful operation of the two oil releases, to monitor those parameters important in determining the fate of the released oil and to determine how their values related to values measured in the baseline year. In subsequent years only the latter two objectives were important.

#### MEASUREMENT PROGRAMS

##### Currents

Knowledge of the strength, direction and timing of the motions of the surface layer of the ocean was necessary to determine the potential for transfer of surface oil slicks from one bay to another and to choose the appropriate timing for the surface-oil release. Knowledge of the ocean currents below the surface layer was necessary to assess the potential for bay-to-bay fouling by dispersed oil, to choose the best bay for the

dispersed oil release, the best diffuser location and the best time for the release.

Ocean currents were measured by a variety of methods. The most precise and long-term of these was the deployment and subsequent recovery of moored recording current meters. Seven instruments were used in the summers of 1980 and 1981. The instruments used were Aanderaa RCM-4 current meters modified for arctic use by rewiring the compass circuit to prevent the compass being disturbed by the magnetic field emanating from the motor of the recording system. They were equipped with temperature, pressure and conductivity sensors and were set to record every 20 min (1980) or every 5 min (1981). The meters were deployed on taut line moorings between concrete anchors and spherical subsurface floats. Mooring locations are shown in Figure 1.

Nearshore currents were measured with radar-tracked drogued drifters similar in design to those described by Buckley (1977). The 2 m × 3 m drag elements could be suspended in the 0-2 m, 4-6 m or 8-10 m range. Each drifter had a radar reflector mounted 2 m above the water's surface. The drifters were tracked by a standard marine radar mounted about 50 m above water level in Bays 9 and 10 and 20 m in Bays 11 and 12. Data were acquired by photographing the radar Plan Position Indicator (PPI) screen every 5 min using a 12 s exposure. In August and September 1980 between 7 and 10 h of data were collected on three separate days in Bays 9 and 10 and on two days in Bays 11 and 12. Up to 18 drifters were tracked at one time. Attempts were made to obtain data under different conditions of wind and tide. While the data collected represented both ebbing and flooding tidal conditions, no wind-related information was collected, since only calm conditions prevailed throughout the experimental period.

Data on the film negatives were digitized and computer processed to produce drifter positions and velocities as a function of time. Buckley (1977) showed that water velocity could be inferred with little error from the measured velocity of these drifters under conditions of low to moderate winds, such as were measured here. Drifter studies were also undertaken in the 1981 field season, but since only qualitative results were desired, the radar and photographic system was not used.

A third system of current measurement used near the end of the 1980 field season and again throughout the 1981 season employed a number of "tapes." These tapes consisted of three 3 m lengths of surveyor's tape tied to fishing line suspended between a rock anchor and a bottle float on the surface. Tapes were attached at the surface, at 2 m and at 4 m depth. These tapes were placed in 35 locations in Bays 9, 10, 11 and 12 (Fig. 2). The surveyor's tape was slightly negatively buoyant and therefore would hang down toward the bottom in calm water. As the current speed increased, the angle formed between the tape and the horizontal decreased. The tapes were observed either from a boat or from the helicopter at regular intervals between 5 and 13 September 1980.

Observation of the surface tapes was relatively easy, but the deeper tapes were often obscured by turbidity or surface agitation. Estimates of current magnitude were crude at best, especially for the deeper tapes, where the angle was not easily seen. The relationship between current speed and the angle of the tapes, as determined by tow-tank tests, is shown in Table 1. A number of the tapes were redeployed in the 1981 field season.

Currents were also inferred from other visual evidence. Movement of such features as tide lines and sediment plumes

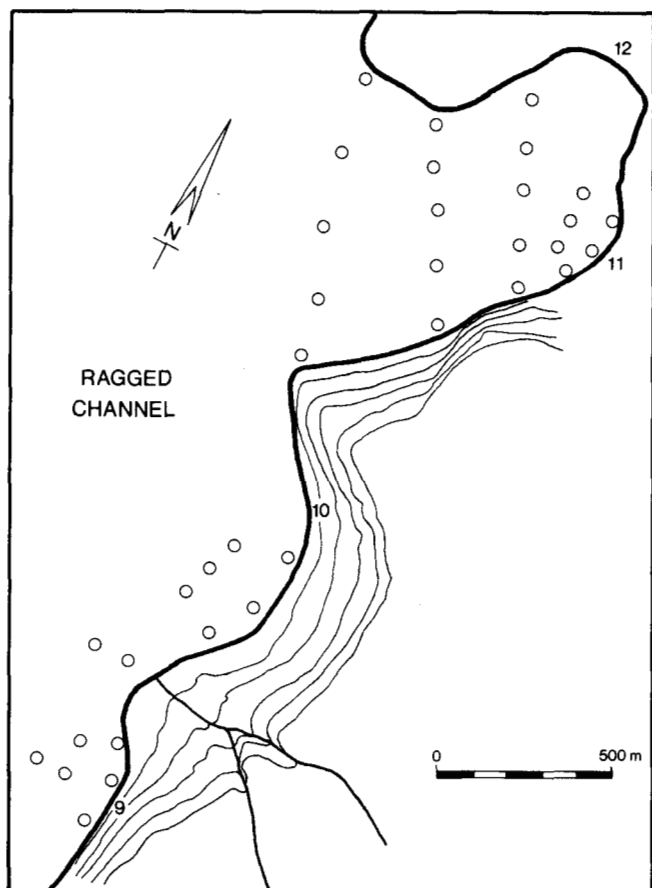


FIG. 2. Location of the tape floats used in the 1980 program. Locations were similar in 1981.

was observed from either boat or helicopter. Dye releases were used in association with drifters and tapes to fill in details of the nearshore circulation.

#### Temperature and Salinity Profiles

Vertical profiles of temperature and salinity with depth were needed at numerous locations throughout the Cape Hatt region to help in assessing the overall current structure for the region, to determine the optimal depth for oil/dispersant release and to assess the typicality of oceanographic conditions in the bays and in the region.

Measurements were made with an Applied Micro Systems CTD-12 conductivity-temperature-depth recorder. Temperature was measured in the range  $-2$  to  $32^{\circ}\text{C}$ , with a resolution of  $0.008^{\circ}$ . Conductivity ratio was measured in the range  $0-1.7$ , with a resolution of  $0.0004$ . Pressure was measured  $0-1000$

TABLE 1. Current speeds estimated from surveyor's tape

Observation	Angle range (degrees)	Current speed ( $\text{cm}\cdot\text{s}^{-1}$ )
Nil	$> 60$	$< 1.5$
Weak	$60-45$	$1.5-2.5$
Moderate	$45-10$	$2.5-10.0$
Strong	$< 10$	$> 10.0$

dbar, with a resolution of  $.25$  dbar and an accuracy of  $.40$  dbar. This sensor was replaced for the 1981 field season with one having a range of  $0-100$  dbar, a resolution of  $0.024$  dbar and a calibrated accuracy of  $0.015$  dbar. Attempts were made to take independent calibration samples for salinity, but since they had to be transported south for processing, the samples degraded and showed an unacceptable level of scatter for cross-calibration.

Profiles of water temperature and conductivity with depth were collected in three field sessions: the spring and summer of 1980 and the summer of 1981. Stations were occupied at intervals of approximately two days. Two stations were located in each of Bays 9, 10 and 11. Five stations were located on each of two transects across Ragged Channel and along the axis of Z-Lagoon. In 1981 profiles were collected in Bay 7 as well. Station positions in the experimental bays were coincident with the microbiology sampling stations. Stations along the three transects were determined by sextant fixes on known shore points. Station positions are shown in Figure 3.

In 1980, data were calibrated using formulas supplied by the manufacturer. The instrument was recalibrated between the 1980 and 1981 field seasons by the Frozen Sea Research Group of the Institute of Ocean Sciences, Patricia Bay. Salinity was calculated from temperature, conductivity and pressure using the formula of Lewis (1980).

#### Other Measurements

The timing of the experimental oil releases depended critically on the stage of the tide, so a measurement program was undertaken to ensure that high quality predictions would be possible. Applied Micro Systems TG-12A tide gauges were placed on the sea bed in Bay 10 and in Z-Lagoon on 20 June 1980 and remained there, recording water pressure and temperature every 10 min, until 13 September 1980, when the Bay 10 instrument was recovered by a diver. The Z-Lagoon instrument

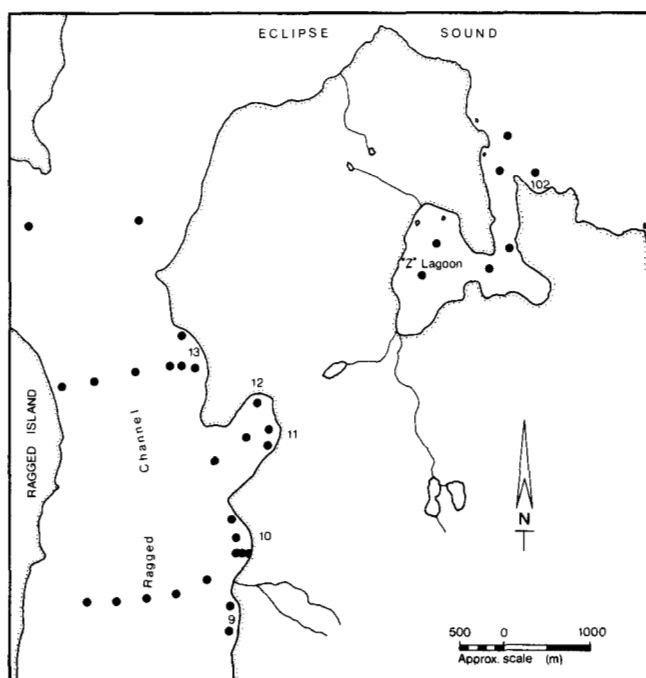


FIG. 3. Locations of the CTD stations in 1980 and 1981: Profiles were taken at these locations one or more times in the two years.

was not recovered until 29 August 1981. The Bay 10 instrument was redeployed on 8 August 1981 and was recovered late that month.

These tide gauges were equipped with quartz pressure transducers with a calibrated pressure range from 0 to 200 psia (0-137.9 dbar, or roughly 0-130 m depth plus atmospheric pressure). The digital resolution of the gauges is one part in  $2^{20}$ , or about 0.1 mm. The accuracy of the sensor calibration is 0.025%, or about 3.3 cm.

The 86-day record collected in 1980 from the Bay 10 instrument was processed by the Tides and Currents section of the Institute of Ocean Sciences, Patricia Bay, B.C., which prepared relative tidal height predictions for the next three years from the results. Since the tide gauge locations were not surveyed into the regional elevation grid, it was not possible to calculate absolute tidal height relative to the chart datum for the region.

A time history of wave energy was important for interpreting weathering of oiled plots on the east side of Cape Hatt and removal of oil from the test beach contaminated by the surface oil release. Applied Microsystems Ltd. Model 750A Wave and Tide Recorders were deployed for one month each summer from 1980 to 1983 on both sides of Cape Hatt. Depths at the deployment sites varied between 3 and 12 m. Deployment locations for the wave and tide recorders are shown in Figure 1.

The gauges measured pressure fluctuations at wave frequencies at the measurement depths. Significant wave heights were calculated from these fluctuations using standard linear wave theory.

## RESULTS

### Currents

Measurements of the currents in Ragged Channel show that in the ice-free season they may be separated into at least three distinct zones by their relative strength and the factors that influence them. These three zones are the central region, the nearshore zone and the surface layer. The central region, the bulk of Ragged Channel below the pycnocline and away from the influence of the shoreline, is characterized by a steady, relatively weak counterclockwise circulation. Evidence for this circulation comes from the cross-channel density sections, as discussed later, and from the current meters moored east of the centre of the channel in 1980. The agreement in current direction of the two sets of measurements indicates that the flow is predominantly baroclinic, i.e., the barotropic component of the current must be smaller than the baroclinic component. This circulation is apparently wind driven, since the current meter data show effectively no current until the time of ice break-up in mid-August (Buckley and de Lange Boom, 1981; Hill and Humphrey, 1984).

Table 2 summarizes data from the moored current meters. Mean speeds are 1-2  $\text{cm}\cdot\text{s}^{-1}$  and the direction of the mean velocity is to the north. The steadiness ratios of 0.48 and greater for the Ragged Channel South mooring imply that the flow is not dominated by fluctuations. Although current fluctuations at tidal period are observable in the Ragged Channel data records, they are insufficient in strength to overcome the mean northward progress of the water (see Fig. 4). The apparent lack of steadiness in the Ragged Channel North meter was due to a single southward excursion of ten days' duration in late September 1980. Other data available for this period are not sufficient

TABLE 2. Measured currents in the Cape Hatt region

Meter	Location	Depth (m)	Speed <sup>1</sup>		Velocity <sup>1</sup>		SR <sup>3</sup>
			Max	Mean	Mag	Dir <sup>2</sup>	
3666	Ragged Channel S	35	17.0	0.88	0.61	347	0.69
3667	Ragged Channel S	73	16.3	2.13	1.03	354	0.48
3675	Z-Lagoon	11	24.3	1.47	0.34	285	0.23
3668 <sup>4</sup>	Ragged Channel N	35	—	—	—	—	—
3669	Ragged Channel N	72	30.0	1.61	0.50	339	0.31
3688	Bay 9	8	30.0	8.02	4.34	353	0.54
3789	Bay 9	11	28.9	6.95	4.04	356	0.58

<sup>1</sup>Speed and Velocity Magnitude are in  $\text{cm}\cdot\text{s}^{-1}$ .

<sup>2</sup>Direction is in degrees true.

<sup>3</sup>SR = Steadiness Ratio (mean velocity magnitude/mean speed).

<sup>4</sup>No data were recorded by meter 3668.

to ascertain the cause, meteorological or otherwise, of this excursion. Otherwise the currents measured by this instrument were similar to those measured farther south.

The general nature of the tides in the eastern Arctic indicates that tidal currents in Ragged Channel ought to progress southward on a flooding tide and northward on an ebbing tide. Since Ragged Channel is essentially closed at the southern end, barotropic tidal currents should be negligible. In the ice-covered season they are evident only as a twice daily shift in the current direction. Their magnitude was less than the instrument threshold of  $1.5 \text{ cm}\cdot\text{s}^{-1}$ . Under summer conditions tidal currents were noticeable, although small (about  $5 \text{ cm}\cdot\text{s}^{-1}$ ). The existence of these currents above the  $1-2 \text{ cm}\cdot\text{s}^{-1}$  level when stratification was present, but not when the water column was essentially unstratified, indicates the existence of a baroclinic component to the tide.

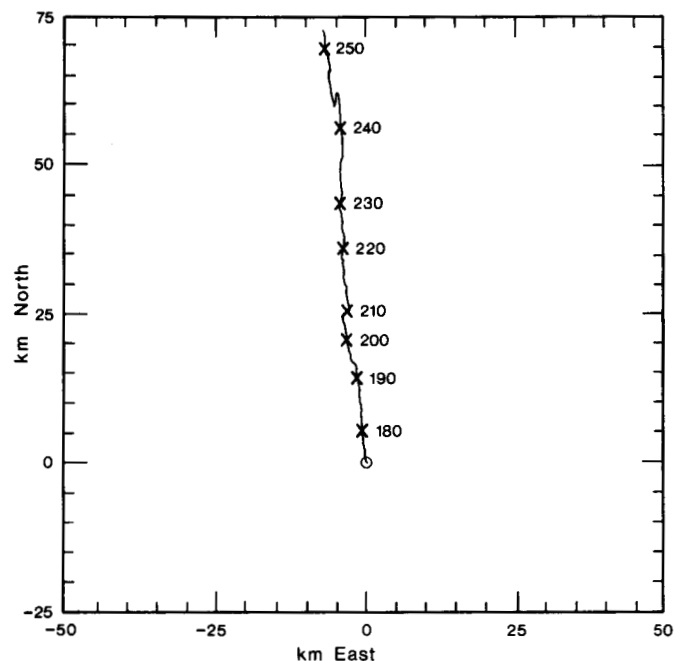


FIG. 4. Progressive vector diagram of the currents measured at 70 m depth at the Ragged Channel South location in 1980. The starting point of the progressive vector, indicated by the circle at (0,0), is at Julian day 171 (19 June) 1980. The crosses are placed every ten days along the vector. Each cross is identified with its Julian day.

In the nearshore zone on the eastern side of Ragged Channel in the vicinity of the experimental bays, the main feature of the currents was a "jet" that flowed northward along the 20 m isobath. This jet reached velocities of up to  $30 \text{ cm}\cdot\text{s}^{-1}$ . It was observed whenever either north or south winds blew and on all stages of the tide, except occasionally during the first few hours of the flood tide. It persisted for several days after any strong wind event. This jet caused clockwise circulation in Bays 9, 10, 11 and 12. The drifter tracks in Figures 5a and 5b show these eddies. The occasional southward flow along the coast caused the eddies to reverse in direction.

Southward flow along the coast was observed under two conditions: when the tide was flooding with little or no wind blowing either at the time or for the previous day or so, and when strong southeasterly winds blew out of the valley behind Bay 7. In the first case, the current was seen to reverse to northward before the time of high tide. On the few occasions when observing conditions were just right, a front was seen to form in the vicinity of Bay 7 and progress up the channel toward Bays 9 and 10. The position of this front was indicated by sediment concentrations and accumulations of flotsam. It passed these bays about one hour before high tide and seemed to be associated with this change in direction.

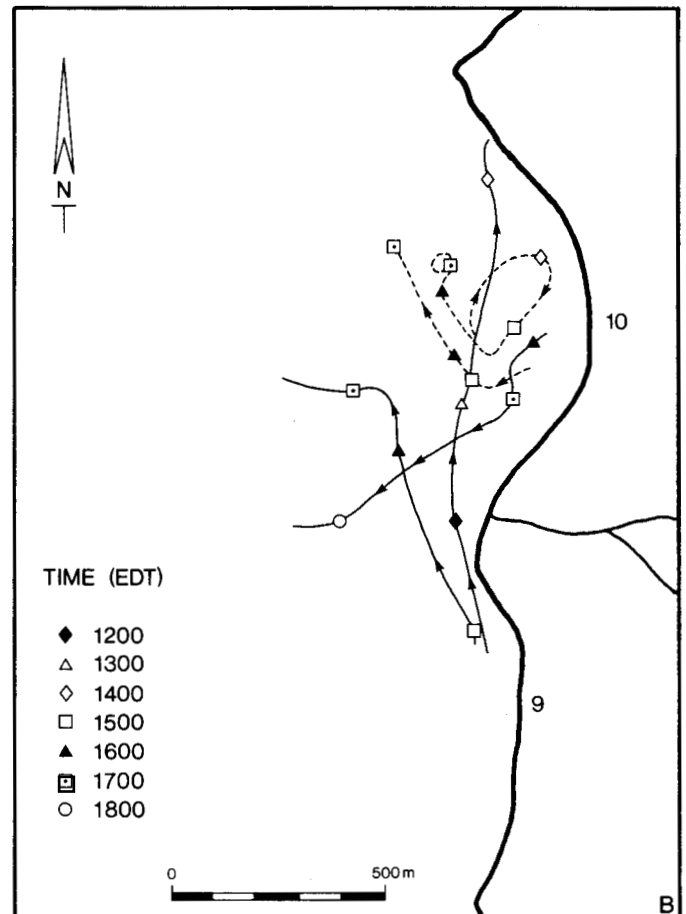


FIG. 5B. Bays 9 and 10, 7 September 1980.

indicates flow in at least three layers, with the currents at the surface and deep tapes moving in the direction of the wind and the mid-depth currents moving in the opposing direction in Ragged Channel. In Bays 11 and 12 the flow is basically clockwise, as expected, but not in the same direction at all depths. The tapes showed that the movement of the water's surface was almost always downwind. This effect was not normally felt below about 1 m, where the coastal jet was usually seen.

#### Temperature, Salinity and Density Structure

**Ragged Channel:** Data collected through the ice in June 1980 in central Ragged Channel showed that temperature and salinity were constant from beneath the ice to a depth of 35 m. The temperature of this isothermal layer was approximately at the freezing point for water of this salinity. Above this homogeneous layer there was a thin layer of warmer, fresher melt water trapped in the hole cut through the 2 m thick ice and just below it. Below 35 m, temperature, salinity and density all gradually increased (see Fig. 7). These profiles are typical of those measured under ice cover and indicate the presence of a convective layer about 35 m deep driven by brine rejection from freezing sea water.

Summer conditions, as seen in August and September 1980 and 1981, were very different from winter conditions, except near the bottom of Ragged Channel. As can be seen in Figure 7, temperatures ranged from over  $4^{\circ}\text{C}$  near the surface to less than

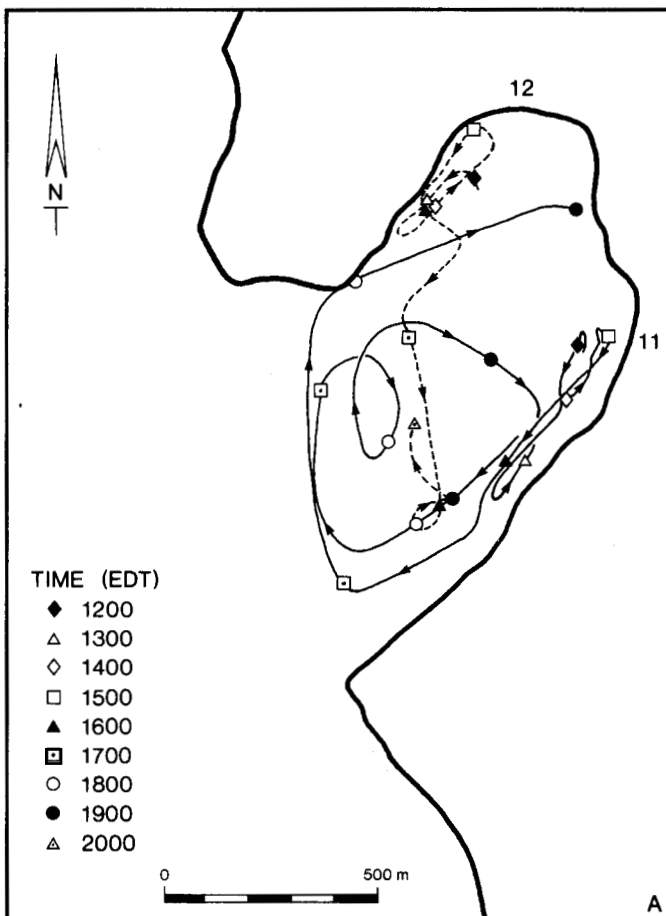


FIG. 5. Paths of radar-tracked, near-surface drogued drifters. The crossed circles indicate the radar site. Taken from de Lange Boom and Buckley (1981). A. Bays 11 and 12, 30 August 1980.

The tapes showed that seldom were currents in the top 6 m in the same direction. One set of observations, shown in Figure 6, made at low tide under conditions of light northerly winds,

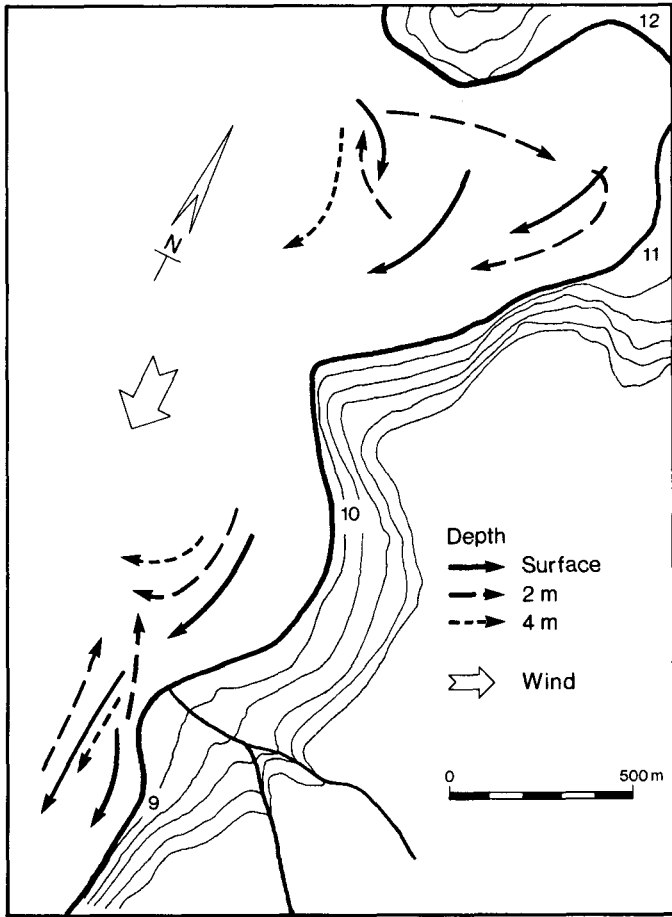


FIG. 6. Current direction at 0, 2 m and 4 m depths as inferred from observations of "tapes," 6 September 1980.

-1.5° near the bottom. Salinity varied rapidly from 24 at the surface to 30 at 10 m, then slowly to 32.7 at the bottom.

A contoured time series of all the profiles taken in central Ragged Channel in 1980 is shown in Figure 8. This figure shows the dramatic and rapid change in water structure following the break-up of the ice cover in mid-August. After break-up, the downward sloping isotherms and isohalines below about 35 m show that the summer's influx of heat and fresh water was being slowly mixed down through the water column. The upward sloping isotherms above 35 m show that the colder nights in early fall were beginning the extraction of heat from the surface layer that would eventually lead to the formation of ice.

A mass of colder, less saline water entered the channel at shallow to mid-depths just before the last CTD cast on 13 September 1980. Since the temperature-salinity characteristics of this water do not match any in the inlet before that date, the water must have been advected from Eclipse Sound. The wind had blown strongly from the north for the day and a half prior to 13 September. Therefore this advection was probably a wind-driven event.

A contoured density section, shown in Figure 9, was prepared from data collected across Ragged Channel on 5 September 1980. It shows that below the surface layer the isopycnals slope down toward the centre of the channel. Since the data were collected within a 75 min period, with the easternmost station first and the next-easternmost station last, the slope is unlikely to be an artifact of aliased sampling in an internal wave field.

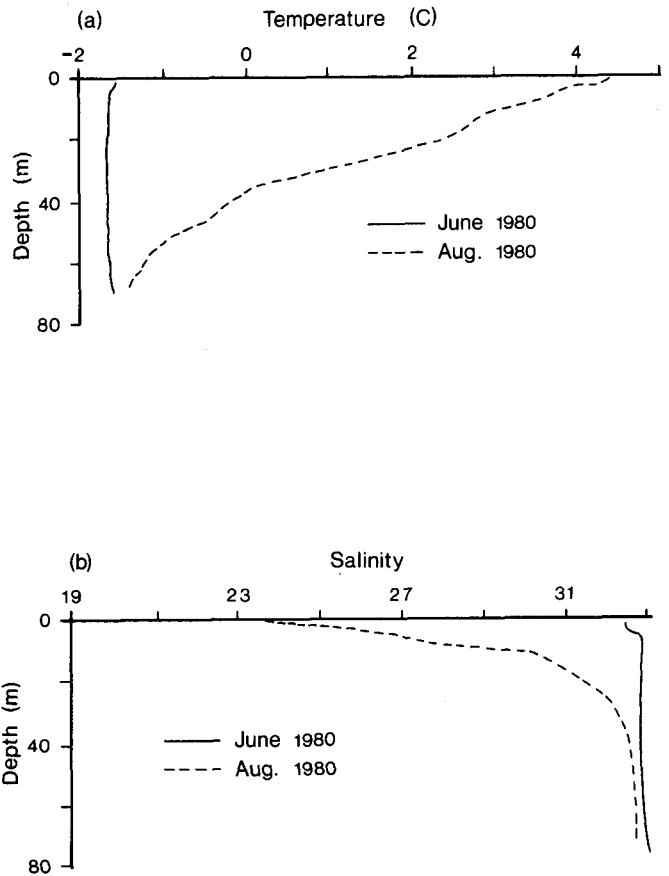


FIG. 7. Spring and summer temperature and salinity profiles in central Ragged Channel: (a) Temperature. (b) Salinity.

This slope is therefore indicative of a baroclinic current flowing south along the west side of Ragged Channel and north along the east side. The moored current meter measurements also show this northward flow along the eastern side of Ragged Channel. The downward slope of the isopycnals toward the coast at about 20-30 m on the extreme western edge of the channel indicates the possible presence of an internal wave. At the time this section was taken, the wind had been calm for several days and the tide was at essentially full ebb. The existence of an internal

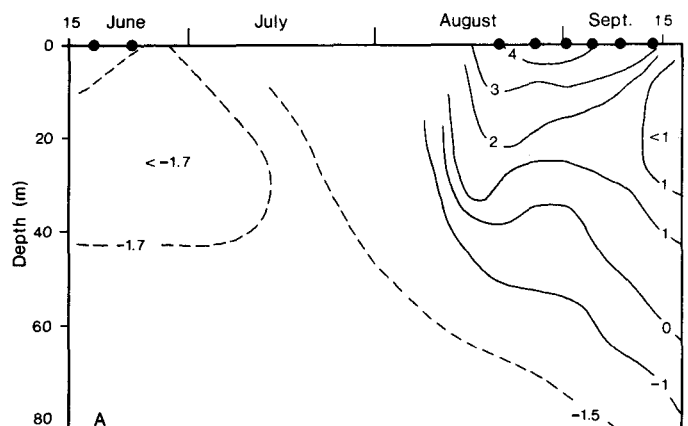


FIG. 8. Temperature and salinity in Ragged Channel, spring and summer 1980. The dots on the time axis indicate the dates of CTD casts used to construct this figure. Contours in the July-August period were inferred with the help of data from the Ragged Channel South current meters. A. Temperature.

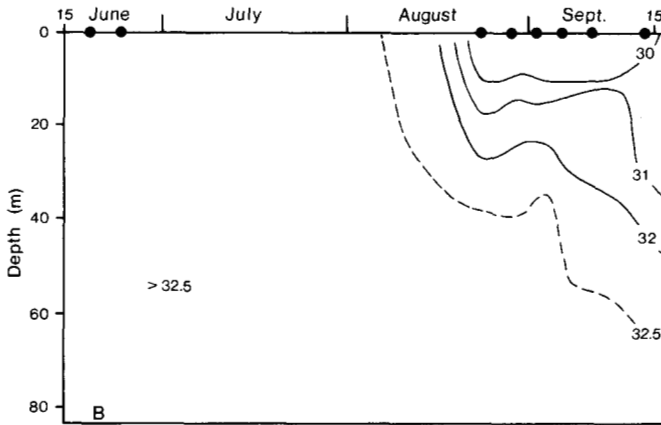


FIG. 8B. Salinity.

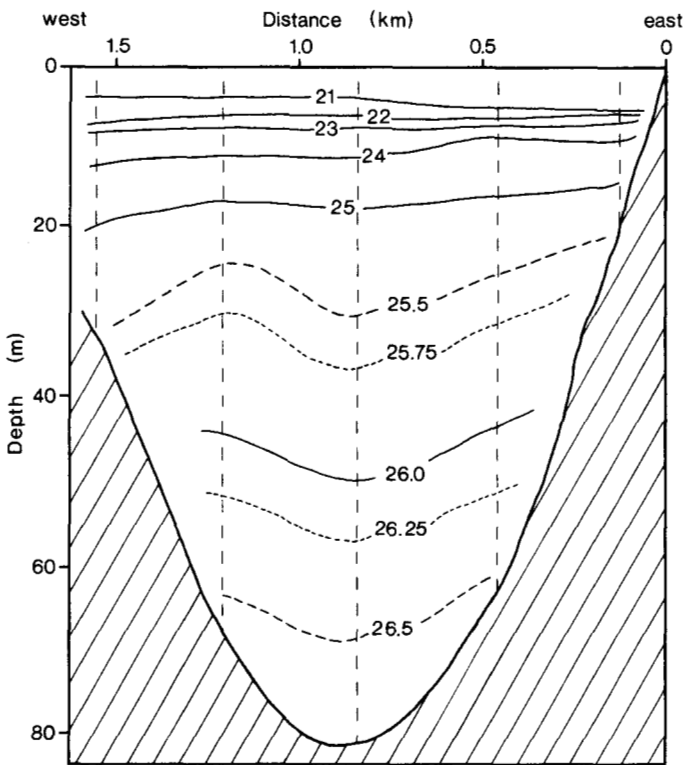


FIG. 9. Density transect across Ragged Channel, 5 September 1980. The transect was made through the Ragged Channel South current meter location. Contours are in units of  $\sigma_t$ . The dots on the horizontal axis indicate the locations of CTD casts used to construct this figure.

tidal wave under these circumstances will be discussed in a later section.

**Nearshore Regions:** Profiles of temperature and salinity collected through the ice in the experimental bays show completely isothermal and isohaline behaviour except in the top 2 m of the profiles (see Fig. 10). In the summer, significant gradients of temperature and salinity occurred in the experimental bays. Typical profiles are shown in Fig. 10. A warm, fresh layer overlay the colder, saltier water below. The depth of the thermocline and halocline, 4 m in this figure, changed rapidly with changes in wind and tide.

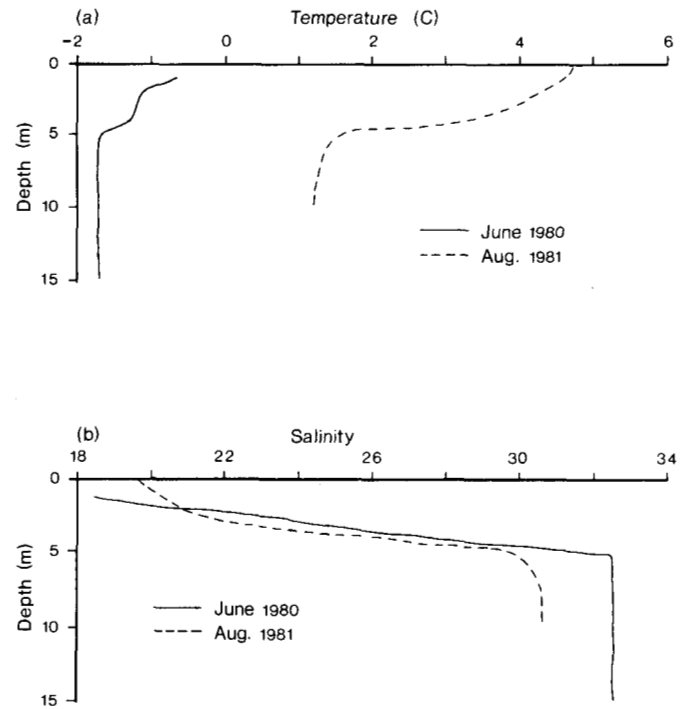


FIG. 10. Spring and summer temperature and salinity profiles in Bay 9: (a) Temperature. (b) Salinity.

A plot of how the temperature structure in Bay 9 changed in the 1980 season is shown in Figure 11. In this figure, the thermocline is roughly at the  $3.5^\circ$  contour. It can be seen to oscillate with an amplitude of about 2 m. These oscillations may be an artifact of the sampling time with respect to the tide or of the inaccuracy of the depth sensor on the CTD. The total removal of the surface layer on 13 September is related to the strong north winds discussed earlier in this section. The lesser removal of the surface layer in late August may also be related to a north wind event, but the wind records for the period are missing, so no firm conclusion can be made.

On any given sampling day, the profiles of temperature and salinity obtained in all the Ragged Channel experimental bays were essentially identical. No longshore gradients were found. As can be seen in Figure 9, little or no offshore gradient of water properties existed in the near-surface waters either.

**Z-Lagoon:** Occasional water property measurements were made in Z-Lagoon, but not with the regularity of those in Ragged Channel, since the experiments scheduled to take place in Z-Lagoon were not so dependent on the water column dynamics as those in Ragged Channel. Through the ice the profiles were identical in nature to those in the Ragged Channel nearshore: isothermal and isohaline, except in the extreme near-surface layer. In the summer, when some structure was present in the water column, the effects of the shallow sill at the mouth of the lagoon were evident. Figure 12 shows a set of temperature contours constructed from four CTD casts made in and around Z-Lagoon on 5 September 1980. Above sill depth the isotherms were horizontal and at the same depth both inside and outside the lagoon. Below sill depth the water outside the lagoon was much warmer than at the same depth inside. The waters outside were free to mix with the water in Eclipse Sound and hence were subject to strong wind and current mixing events, but those inside were affected neither by strong currents

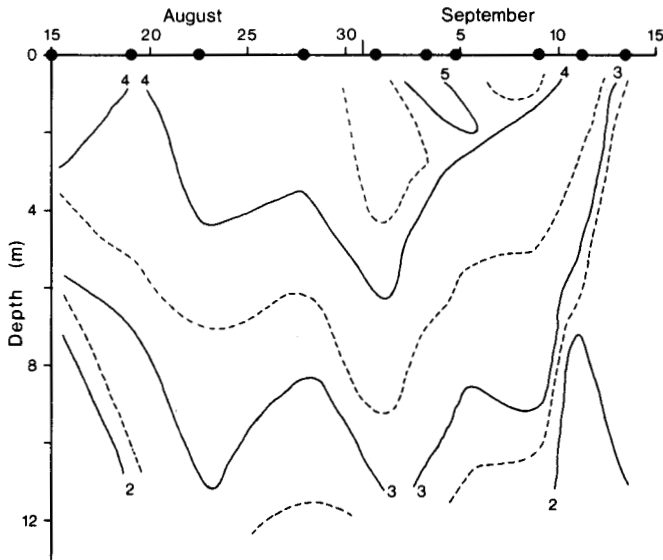


FIG. 11. Temperature in Bay 9, Summer 1980.

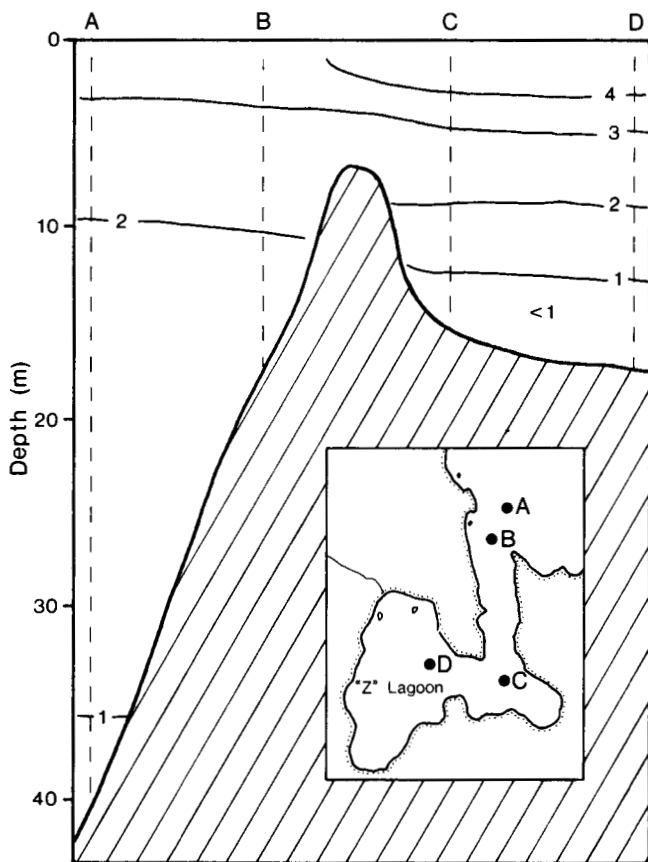


FIG. 12. Temperature transect through Z-Lagoon, 5 September 1980. The inset map shows the station locations. Horizontal distances are not to scale.

nor by large waves, and hence the vertical diffusion of heat inside Z-Lagoon was considerably smaller.

*Tides and Waves*

An analysis of the water level data yielded the harmonic tidal constituents shown in Table 3. These results indicate that the

TABLE 3. Harmonic constituents of tidal height — Cape Hatt

Constituent name	Period (h)	Amplitude (cm)	Phase <sup>1</sup> (degrees)
M <sub>2</sub>	12.42	56.44	22.75
K <sub>1</sub>	23.93	25.47	186.32
S <sub>2</sub>	12.00	18.70	60.87
N <sub>2</sub>	12.66	10.69	6.64
O <sub>1</sub>	25.82	8.98	154.68
P <sub>1</sub>	24.07	8.68	182.42 (inferred from K <sub>1</sub> )
K <sub>2</sub>	11.97	5.35	54.27 (inferred from S <sub>2</sub> )

<sup>1</sup>Phase is the Greenwich phase lag.

tides are predominantly semi-diurnal (twice daily) and that the maximum tidal range is about 2.5 m. The nature of the tides is not significantly different from that at the tidal reference station at Resolute Bay, N.W.T., and the timing of the tides is essentially the same as at the secondary station Pisiktarfik Island, N.W.T., on the western side of Eclipse Sound.

The wave recorders and tide gauges recorded water temperature as well as water pressure. A cross-spectral analysis of the temperature and pressure was performed for the wave recorder in Bay 11 in 1981. Results of this analysis are shown in Figure 13. The power spectra show the two obvious peaks at the diurnal and semi-diurnal frequencies in the tide and a peak at the semi-diurnal frequency in the temperature. The coherence between tidal height and temperature is high at those two frequencies. The phase between the two signals at the semi-diurnal frequency is 193.5°, which means that temperature

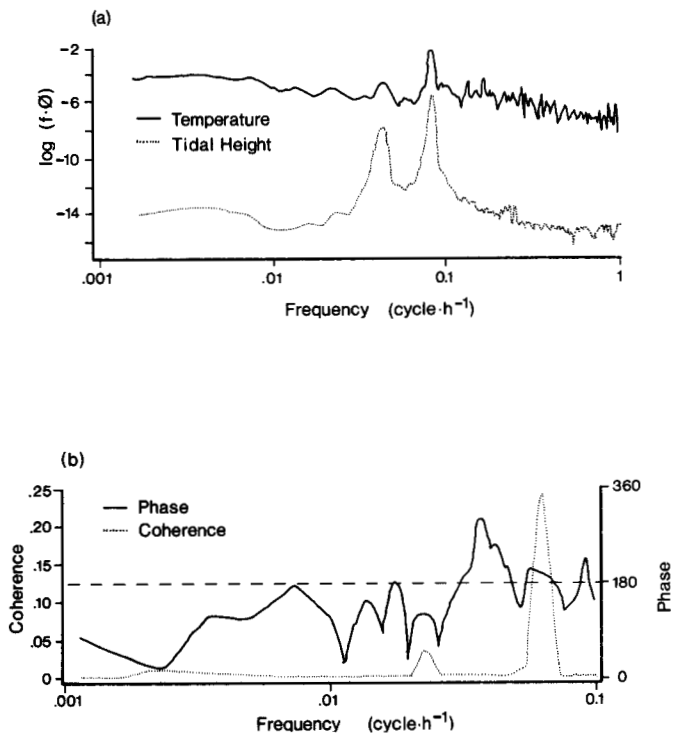


FIG. 13. Spectral analysis of tidal height and temperature Bay 11, 1981: (a) Power spectra of temperature and tidal height. The power spectral density has been multiplied by frequency on the ordinate axis so that peaks of the same height and width will contain the same variance although, since the logarithm of this quantity is plotted, the graph is not strictly variance conserving. (b) Coherence and phase of the cross spectrum between the two quantities. In the phase plot, temperature leads height.



minima precede high water by 28 min. At 9 m, the mean depth of the instrument, the vertical temperature gradient is about  $0.5^{\circ}\cdot\text{m}^{-1}$ . The horizontal temperature gradient at this depth is less than  $0.5^{\circ}$  across Ragged Channel. Therefore the temperature excursions are due to vertical, not horizontal, movement of the water. If the tide were strictly barotropic, then the cold extrema and high water would be exactly in phase. The difference in phase for this ideal case makes it reasonable to propose the existence of a baroclinic component to the tide.

Data from the tide gauge moored in the centre of Z-Lagoon in 1980 were compared to data from the Bay 10 gauge to detect any lag in the occurrence of high or low tides and to see if there was any evidence of reduction of tide amplitude due to the restricted channel at the entrance to the lagoon. No evidence for any modification of the tide was found.

Waves in the vicinity of Cape Hatt were small. The maximum fetch that either the Bay 10 or the Bay 11 wave recorder was exposed to was about 5 km. The maximum significant wave height that may be expected for this fetch, assuming a summer storm wind speed of about  $10\text{ m}\cdot\text{s}^{-1}$ , is about 0.5 m, with an associated period of about 2.7 s. Waves of this size are at the limit of resolution of the instrumentation used in this program when the gauges were placed at about 10 m depth, as they were in 1980 and 1981. No data were collected in 1980 due to instrument failure. In 1981, all waves during the deployment period were smaller than the measurement threshold for the instruments. In Bay 11 in 1982 the same situation occurred. Measurable waves were recorded in Bay 102. In these data were six "storm" events lasting from one to five days. The maximum recorded wave height was 1.4 m. The wave data collected in Bay 11 in 1983 were collected at a sufficiently shallow depth but showed waves no larger than 20 cm, indicating calm or almost calm conditions in Bay 11 during the deployment period.

#### INTERNAL TIDES IN RAGGED CHANNEL

Behaviour of the currents in Ragged Channel may be explained to a large extent with the help of a conceptual model of the semi-diurnal tide in the channel. The geometry of Ragged Channel was simplified to a box of constant width 2 km, length 11 km and depth 80 m, open at the north end and closed at the south end. Two layers of water were placed in this box: a shallow (10 m), less dense ( $\sigma_t = 23$ ) layer on top and a deep (70 m), denser ( $\sigma_t = 26$ ) layer on the bottom. Barotropic tidal prism calculations for this box predict maximum tidal currents of  $1.3\text{ cm}\cdot\text{s}^{-1}$  at the northern current meter location and  $1\text{ cm}\cdot\text{s}^{-1}$  at the southern, below the threshold of the current meters and therefore in agreement with the under-ice current observations when there was no stratification present.

The interfacial wave speed for the specified density structure and layer depths is  $0.51\text{ m}\cdot\text{s}^{-1}$ , yielding a propagation time of 6 h for an internal wave along the length of this model of Ragged Channel. If this wave were to be reflected by the southern end of the channel, then the time required for the wave to complete a circuit of Ragged Channel would be 12 h. This interfacial wave would arrive at the northern end of Ragged Channel at roughly the time of the next peak of the semi-diurnal tide.

Plane waves propagating along coasts are modified by the earth's rotation into Kelvin waves (LeBlond and Mysak, 1978). In two layer flow, Kelvin waves may be formed internally as well as on the surface. These waves have the longshore properties of plane waves but decay in amplitude away from a coastline

exponentially scaled by the Rossby radius (the wave phase speed divided by the Coriolis frequency). In Ragged Channel, the internal Rossby radius is 3.6 km, so that the rotationally induced effects would produce a noticeable 57% reduction in wave amplitude across the channel.

In the northern hemisphere, Kelvin waves propagate with the coast on the right, so that in Ragged Channel they would move south along the western shore and north along the eastern shore. An internal Kelvin wave generated at the head of Ragged Channel in phase with the tidal elevation in Eclipse Sound will propagate southward along the western side of the channel until it reaches the southern end. There it will be reflected and will form another Kelvin wave travelling northward along the eastern side of the channel. To fulfill the boundary condition at the south end of the channel, an infinite series of Poincaré waves must be generated as well as the northward propagating Kelvin wave (LeBlond and Mysak, 1978:273). However, all modes of  $M_2$  Poincaré wave in this channel may be shown to be evanescent and will have no effect on the elevation or current fields farther than approximately one channel width away from the southern end of the channel. Therefore in the region of Ragged Channel of interest to the BIOS Project, internal waves of semi-diurnal tidal period will appear to have a purely Kelvin wave nature.

The near-surface effect of an internal Kelvin wave in phase with the surface tide at the northern end of Ragged Channel would be to thin the surface layer at the northwestern corner of Ragged Channel at high tide. The thinness, which is the crest of the internal tidal wave, would move southward along the western shore and arrive at the south end of Ragged Channel 6 h later, at about low tide. The wave would then reflect and move northward along the eastern shore and arrive at the north end of Ragged Channel close to the time of high tide.

Currents in the surface layer associated with the wave crest will be in the direction opposite to the one the wave is propagating in, i.e., northward when the wave is moving southward along the western shore and southward as the wave moves northward. Behind the crest, the surface layer deepens and the current shifts to the direction of propagation of the wave. Thus, behind the crest of the internal wave there will be a surface layer convergence of the current. Finite amplitude effects will sharpen this convergence so that it should be of sufficient strength to collect flotsam and hence be visible. In the vicinity of the experimental bays, about 7 km from the south end of Ragged Channel, the internal tide ought to be high (surface layer at its thinnest) about 10 h after high tide. The surface convergence would then follow by about 1 h, and the surface current would shift to strongly northward following the passage of the convergence. This phenomenon was observed on occasions when water turbidity was high and the surface was calm.

The cross-channel density profile shown in Figure 9 contains isopycnals sloping downward to the western side of Ragged Channel at about 30 m depth. This downward slope indicates the passage of the trough of the internal tide. The surface tide at the time was at low water and, therefore, the crest of the internal tide should have been at the south end of the channel. At the location of the section, closer to the north end of Ragged Channel than the south, this model predicts that the surface layer should be thicker than average at this stage of the tide. The isopycnal depression confirms this was the case.

Final evidence to support the existence of this internal tide is the 28 min leading of the cold water maximum at the Bay 11 tide

gauge with respect to the time of high water. The phasing of this extremum implies that the surface layer is at its thinnest about one-half hour before high tide. Since the gauge at which this phase lag was measured was about 750 m from the mouth of Bay 11 and the internal tide would take about 90 min to propagate this distance before being detected, the half-hour lead is in approximate agreement with the two-hour lead experienced in the outer bays.

#### TYPICALITY OF CAPE HATT AS AN EASTERN ARCTIC ENVIRONMENT

The most comprehensive summary of oceanographic conditions in Northwestern Baffin Bay and Lancaster Sound is given by Fissel *et al.* (1981). All descriptions of the general oceanography of the region are taken from that document.

Cape Hatt extends into the southern portion of Eclipse Sound. This sound is connected to Lancaster Sound to the north by Navy Board Inlet and to Baffin Bay to the east by Pond Inlet. Although central Eclipse Sound is 700-800 m deep, sills of 130 m to the north and 600 m to the east prevent exchange of deep water with either of the two outer bodies of water.

The temperature, salinity and density structure of Ragged Channel is typical of an arctic estuarine environment. In the winter the channel has a solid ice cover and has no fresh water input. Consequently, the temperature and salinity are controlled primarily by processes associated with strong cooling from the surface and the freezing of surface waters into ice. In the ice-free season, Ragged Channel behaves like an estuary in more southern climates. There is a large fresh water input into the channel from snow melt and rain runoff. This fresh water establishes a strong surface layer. Heat enters into the system from the surface and is transferred down into the water column by wind and current-induced mixing and diffusion. During this season, the entire region is sufficiently dynamic that all changes in water properties cannot be related to local effects: often changes are the result of water advecting into the region from afar. Currents measured in the region in the summers of 1978 and 1979 indicated a flow south through Navy Board Inlet and east through Pond Inlet. Moored current meter measurements showed a strong tidal signal at depth, but less so near the surface.

Measured salinities near the surface in Eclipse Sound were about 22-24 in August 1979 and about 30 one month later. This rise in salinity indicated that the early summer snow melt had finished. With no further significant input of fresh water to the surface layer, the wind mixed this layer with the underlying saltier water mass. BIOS Project CTD results from August 1980 showed salinities of 17 nearshore. A few days later, wind mixing had caused the salinity at 1 m to rise to 23. By mid-September the salinity had risen to 30. In this period, no significant change in 10 m salinity occurred. Therefore the BIOS results closely match those found in other programs in the region and may be tied into the regional oceanography (Fissel *et al.*, 1981; Lemon and Fissel, 1982). From the standpoint of water properties, this region is typical.

In the eastern Arctic, the tide is predominantly semi-diurnal. The tidal wave propagates northwestward up Baffin Bay and westward in Lancaster Sound. The tide also propagates west in Pond Inlet and south in Navy Board Inlet, creating a southward flow in Eclipse Sound and Admiralty Inlet. Tidal currents observed in Ragged Channel were southward on the flood and

northward on the ebb, as would be expected from this regional description. Harmonic constituents of the tide are similar in magnitude to those at Resolute Bay and are almost identical to those at Pond Inlet and at Pisiqtarfik Island. Thus the region is typical of the eastern Arctic in terms of tides. The presence of the internal tide is, however, unique to Ragged Channel, since the propagation of the tide is determined by the geometry of the channel, which is not common to all such features in the Arctic.

The experimental beaches used in the project are more sheltered than are many in the eastern Arctic. However, the eastern Arctic is a region of many fiords and embayments. Thus the wave climate of Cape Hatt cannot be said to be unusual for the region.

#### ACKNOWLEDGEMENTS

The BIOS Physical Oceanography project team acknowledges the help of a great many people and organizations vital to the achievement of the project team's goals: all the BIOS field camp support personnel, without whom the work could not have even been contemplated; the diving team from LGL, Ltd., who recovered many of the oceanographic instruments in all three years; the Canadian Coast Guard crew, who in 1981 provided vessels and crew to recover current meter moorings; Fred Stephenson, of the Tides and Currents section of Fisheries and Oceans Canada at the Institute of Ocean Sciences, Patricia Bay, for analyzing the tidal data and providing tidal predictions for Cape Hatt for all the years of the field work; the Frozen Sea Research Group at the same institute, for the calibration of the CTD for the second field season; the Canadian Coast Guard, for performing the hydrographic survey of the experimental bays under the direction of hydrographer R. P. Haase, as well as for all the assistance provided in the field seasons.

#### APPENDIX I — INFLUENCE OF OCEANOGRAPHIC DATA ON BAY SELECTION

Physical oceanographic information was very important in the selection of the experimental bays. The primary oceanographic factor in the bay selection process was the probability of cross-contamination of the bays by oil on the surface, oil suspended or dispersed in the water column or oil in the sediments.

The presence of the northward-flowing coastal jet caused a significant contamination problem. It, combined with its associated back eddies in the bays on the east side of Ragged Channel, transports water between adjacent bays. Oil released in any bay was expected to be carried by the jet into adjacent bays, contaminating them. Therefore releasing oil in Bay 10 would have precluded the use of Bays 9, 11 and 12 for experimental or control use, and oil released in Bay 9 probably would have contaminated Bay 10. The oceanographic evidence showed that contamination of Bays 11 and 12 by oil released in Bay 10 was not likely. Similarly, oil released in Bays 11 or 12 was not expected to enter Bay 9. Bay 7 was deemed to be sufficiently far upstream of the other bays with respect to the coastal jet that contamination of it by oil from either of the two releases was expected to be extremely unlikely. It was expected, however, that dispersed oil might be detectable at low concentrations anywhere in the surface layer of Ragged Channel within a couple of days of the release, as the counterclockwise circulation in that layer caused mixing of the oil throughout the water mass.

Predictability of the subsurface current field in the chosen bay was a major consideration in the choice of bay for the dispersed oil release. The presence of the coastal jet and the back eddies in Bays 9 and 10 was known to be fairly consistent and predictable. The circulation pattern in Bays 11 and 12 was less predictable and was known to be weaker. The residence time for water in Bays 9 and 10 had been expected to be on the order of a few hours. Predictions of residence time in Bays 11 and 12 were considerably less certain and considerably longer. The design of

the dispersed oil release experiment called for a period of exposure of the benthic community to the oil/dispersant mixture thought to be representative of what would occur after an accidental spill (see Dickins *et al.*, 1987). The circulation patterns in Bays 9 and 10 seemed more satisfactory from this point of view.

Oceanographic information was also useful in the selection of the location of the diffuser pipe for the dispersed oil release in Bay 9. Initially the pipe had been located at the northern end of the bay with the expectation that the oil would be carried southward in the clockwise gyre in the bay, but a flow test using dye pumped through the pipe at that location showed that the flow could just as easily go north and miss the bay altogether. The pipe was then moved to the south end of the bay in the expectation that either the flow along the coast would be to the north or that, if the clockwise gyre were in existence, the oil would be carried northward in the coastal jet and then would enter the bay from the north in the gyre. This second placement was tested with dye and proved to work by the first mechanism. In the actual oil release, it also worked, but by the second mechanism.

Transport of nearshore sediment between bays was also anticipated to pose a contamination problem both in the summer due to water movement and in the winter due to ice movement (Dickins, 1987; Sempels, 1987). Oiled sediments in the wave zone on the beach subjected to the surface oil release were expected to be suspended by wave action and then transported by currents some distance from the beach. The bathymetric survey of Bays 11 and 12 showed that the bays were rather deep in the middle and were separated from the bays to the south by a shallower sill. Movement of sediment out of Bays 11 and 12 would be inhibited by the presence of the sill. Therefore these bays were well suited for the surface oil release. Longshore transport of sediment

by wave action was observed to occur between Bays 9 and 10. No bathymetric discontinuity separated these bays from each other or from the rest of Ragged Channel. Thus, neither of these bays was well suited for the surface release.

Contamination of bays not directly involved in a release by oil on the water's surface was not entirely an oceanographic problem, since oil slicks are moved directly by the wind as well as by the ocean's surface currents. The main means of control of the surface slicks was to be booms. Booms require a not too severe wave field and an easily enclosable area to be most effective. Since the major surface slick was to be generated by the surface oil release, these two conditions had to be met for this release.

Fortunately, Bay 11, which was so suitable for the surface oil release by virtue of its sediment transport properties, was the most enclosed of the potential experimental bays. Therefore, it could be expected to have the mildest wave climate and to be the most suitable for secure booming.

These three considerations led to the choice of Bay 9 for the dispersed oil release and of Bay 11 for the surface oil release.

#### APPENDIX II — OCEANOGRAPHIC CONDITIONS DURING THE SURFACE OIL RELEASE

The surface oil release occurred on 19 August 1980. It is fully described in Dickins *et al.* (1987). What follows here is a description of those oceanographic conditions relevant to the movement of oil during and after the release. Meteorological conditions are more fully described in Meeres (1987). Strong southwesterly winds overnight, abating to calm conditions by the evening of 19 August, created a wave field that

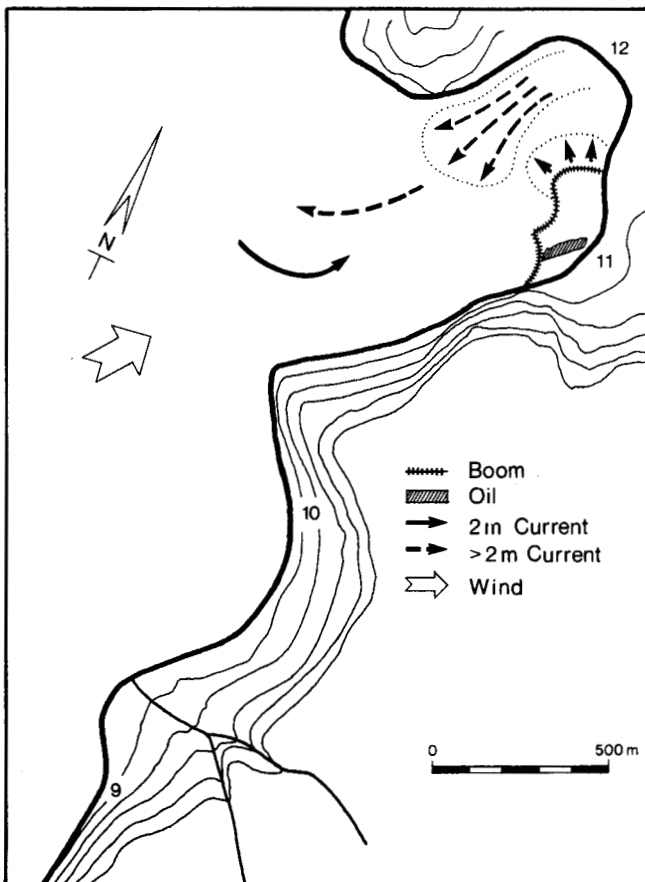


FIG. 14. Oceanographic conditions during the surface release of oil.

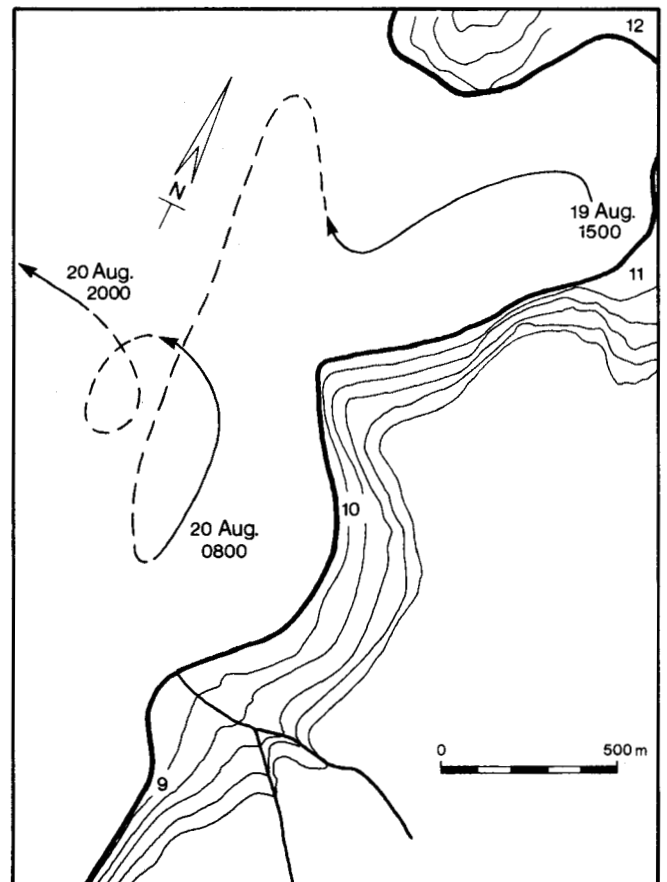


FIG. 15. Trajectory of the oil after the surface oil release. The solid line indicates observed movement of oil, the dashed line inferred.

entered Bays 11 and 12 and impinged almost directly on Bay 12. The waves created a visible sediment plume radiating from the centre of the Bay 12 shoreline to the approximate centre of Bays 11 and 12. Surface currents in Bays 11 and 12 swept along the southern shore, up past Bay 11 and into Bay 12, diverging toward the centre of 11 and 12. Surface circulation patterns were visible in the bays as a result of turbidity (see Fig. 14). These conditions persisted throughout the release of the oil. Wave conditions were calm by evening and overnight. A brief easterly squall on the evening of 20 August carried some sheen out of the bay. Continuous leaching from the boomed area was observed for the following ten days. There did not appear to be any major losses of oil or impingement of sheen on Bays 9 or 10.

A synthesis of the surface water trajectory for 19 and 20 August is shown in Figure 15.

APPENDIX III — OCEANOGRAPHIC CONDITIONS DURING THE DISPERSED OIL RELEASE

Moderate to strong northerly and northwesterly winds on 25 August and again on the morning of 27 August had set up a strong northerly coastal circulation on the east side of Ragged Channel (see Fig. 16). At the beginning of the dispersed oil discharge (at high tide) the coastal jet off Bay 9 had accelerated to about  $20 \text{ cm} \cdot \text{s}^{-1}$ . The Bay 9 back eddy had just begun to form but was narrower than usual. This eddy developed at depths from 1 to 6 m. Below this depth the flow was to the north at about  $20 \text{ cm} \cdot \text{s}^{-1}$ .

The Bay 10 eddy was well developed, with its centre in the south-central region of the bay. Relatively strong waves from the northwest were raising sediment along the coastal shelf and driving the

shallow water to the south in the breaking wave zone. Northerly winds carried the surface (<0.1 m) layer in a southerly direction.

Although the coastal jet crossed the mouth of Bay 10, some component of the flow was entrained in the Bay 10 eddy at the north end of the bay. It appeared that the deeper circulation levels were more likely to enter Bay 10. It is possible that a finger of the deeper currents also entered Bays 11 and 12. By the time the discharge was completed at low tide, the situation stood as is shown in Figure 17. The apparent concentrations of dispersed oil were very high at the south end of Bay 9 (Humphrey *et al.*, 1987).

Concentrations over the test area at the north end appeared to be moderate. Currents below 7 m had carried dispersed oil as far as the point between Bays 10 and 11 and some portion of the deep circulation had entered Bay 10.

Currents stalled during the flood tide, with very little relative motion except for some water that entered Bay 9 from Bay 10 when the Bay 10 eddy disintegrated (Fig. 18a). At the beginning of the next ebb (about midnight), a front of clean water swept northward through Bay 9, pushing the highly contaminated area in front of it. This event may have caused entry of some of the highly contaminated water into Bay 9 (fig. 18b).

During 27 August, sheen from the release had steadily moved southward with the surface layer and by 2000 extended almost to Bay 7 in a narrow band along the coast. Winds had become calm by this time.

The last visual sightings of oil contamination were made on the morning of 28 August. The earliest direct observations on the morning of that day indicated sheen nearshore off Bays 13 and 14 and moving into Eclipse Sound. Winds had come up from the southwest overnight. The only visible evidence of oil in the water column was an oblong path

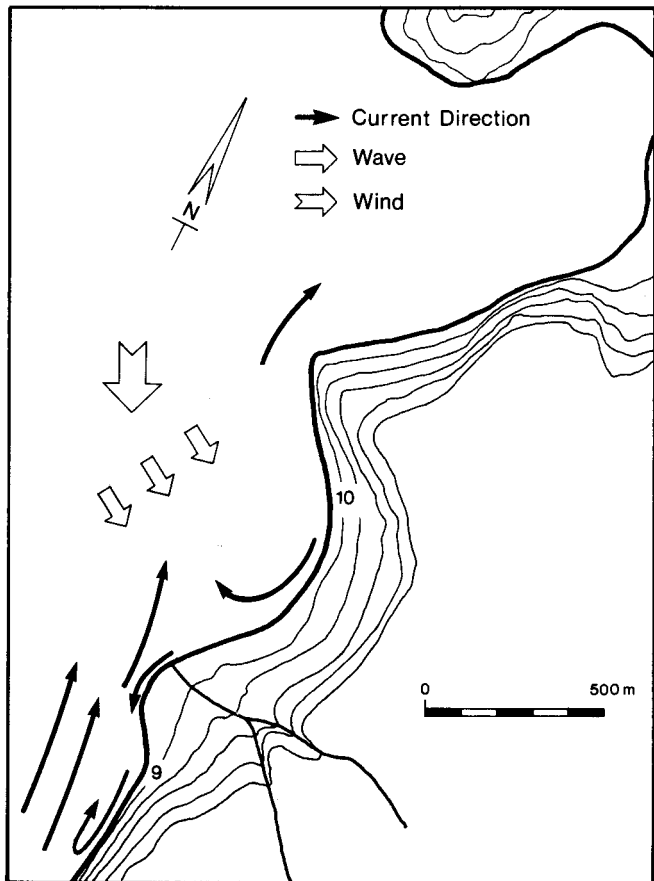


FIG. 16. Oceanographic conditions prior to the dispersed oil release.

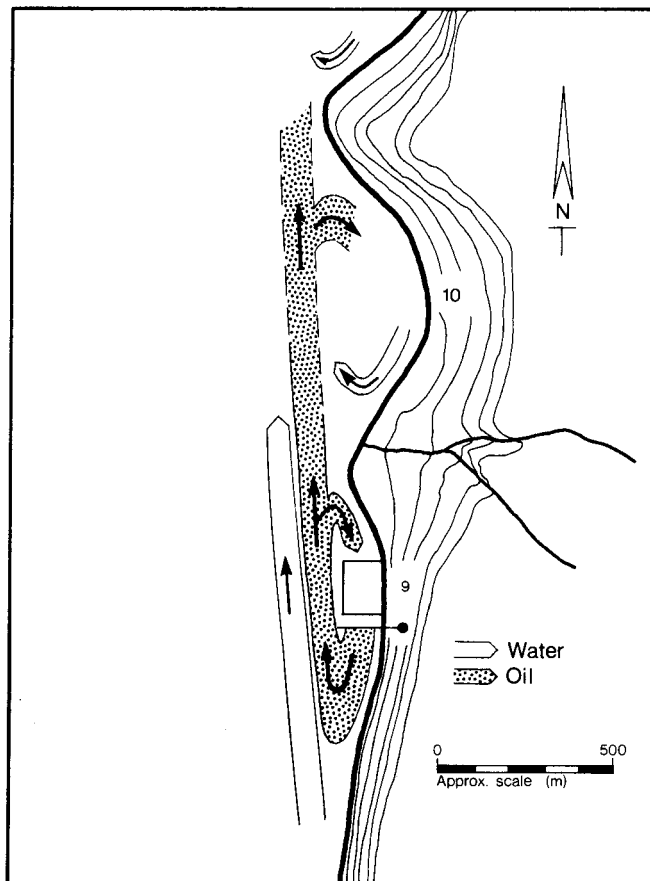


FIG. 17. Dispersed oil location and trajectory — 1800, 27 August 1981.

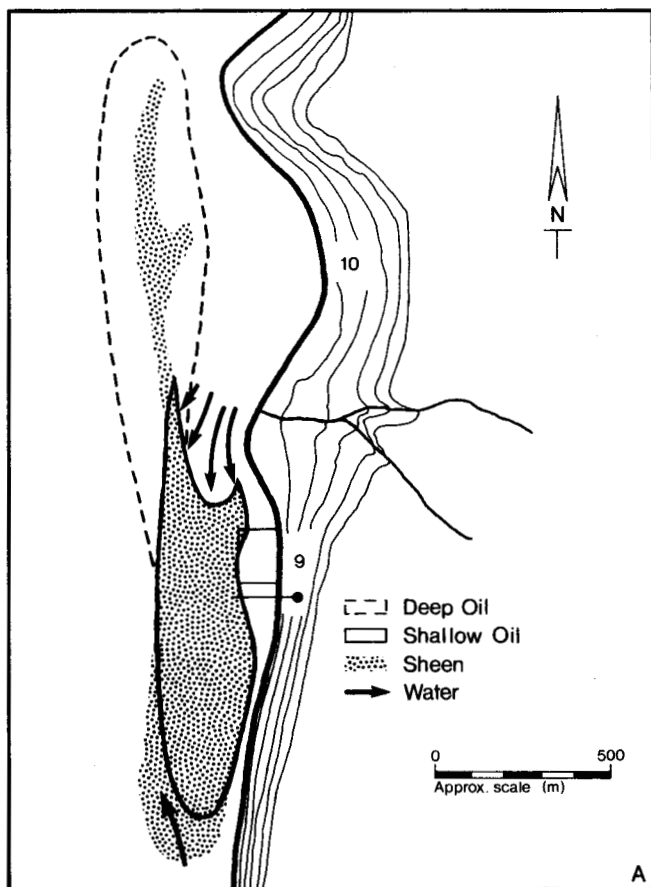


FIG. 18. Dispersed oil distribution during the night of 27 August. The oil distributions are interpolated based on late evening and early morning observations, wind and tide observations and on previously observed circulation patterns. A. 2130.

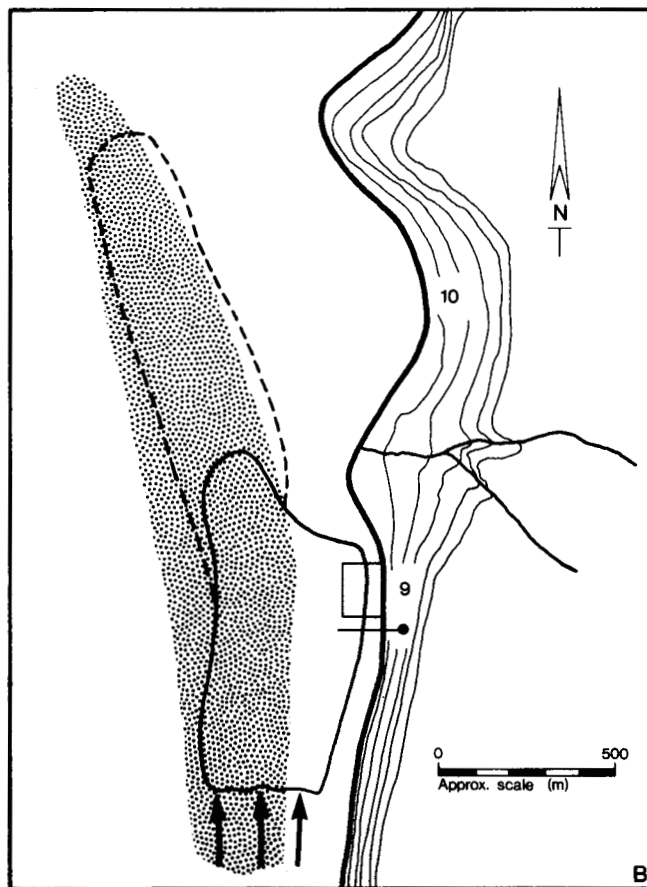


FIG. 18B. 2300.

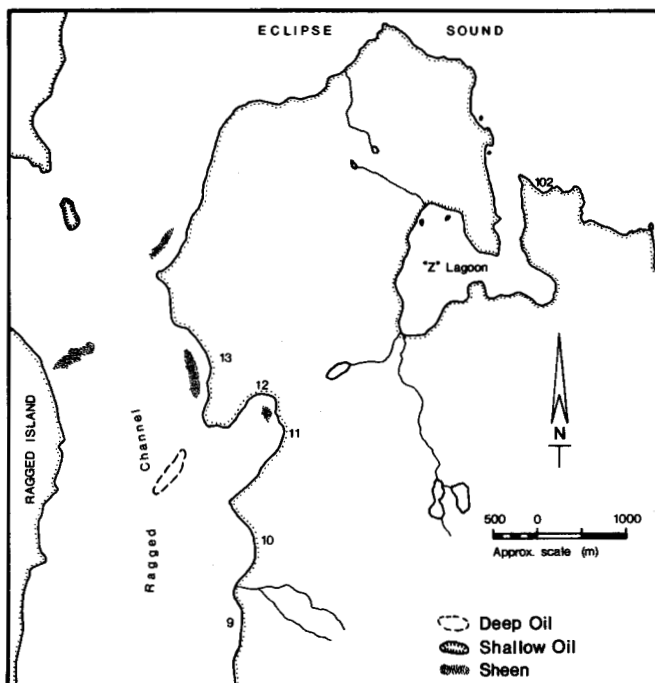


FIG. 19. Dispersed oil distribution — 0800, 28 August 1981.

standing about 0.5 km west of Bays 11 and 12 (Fig. 19). Since this water mass appeared to be moving toward centre channel, it is not unreasonable to assume it became entrained in the general counter-clockwise rotation.

The appearance of oil in Bay 7 on the following day is in keeping with transit times observed with mid-depth drogues under similar conditions. It is likely that some surface sheen was blown into Bays 11 and 12 overnight.

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