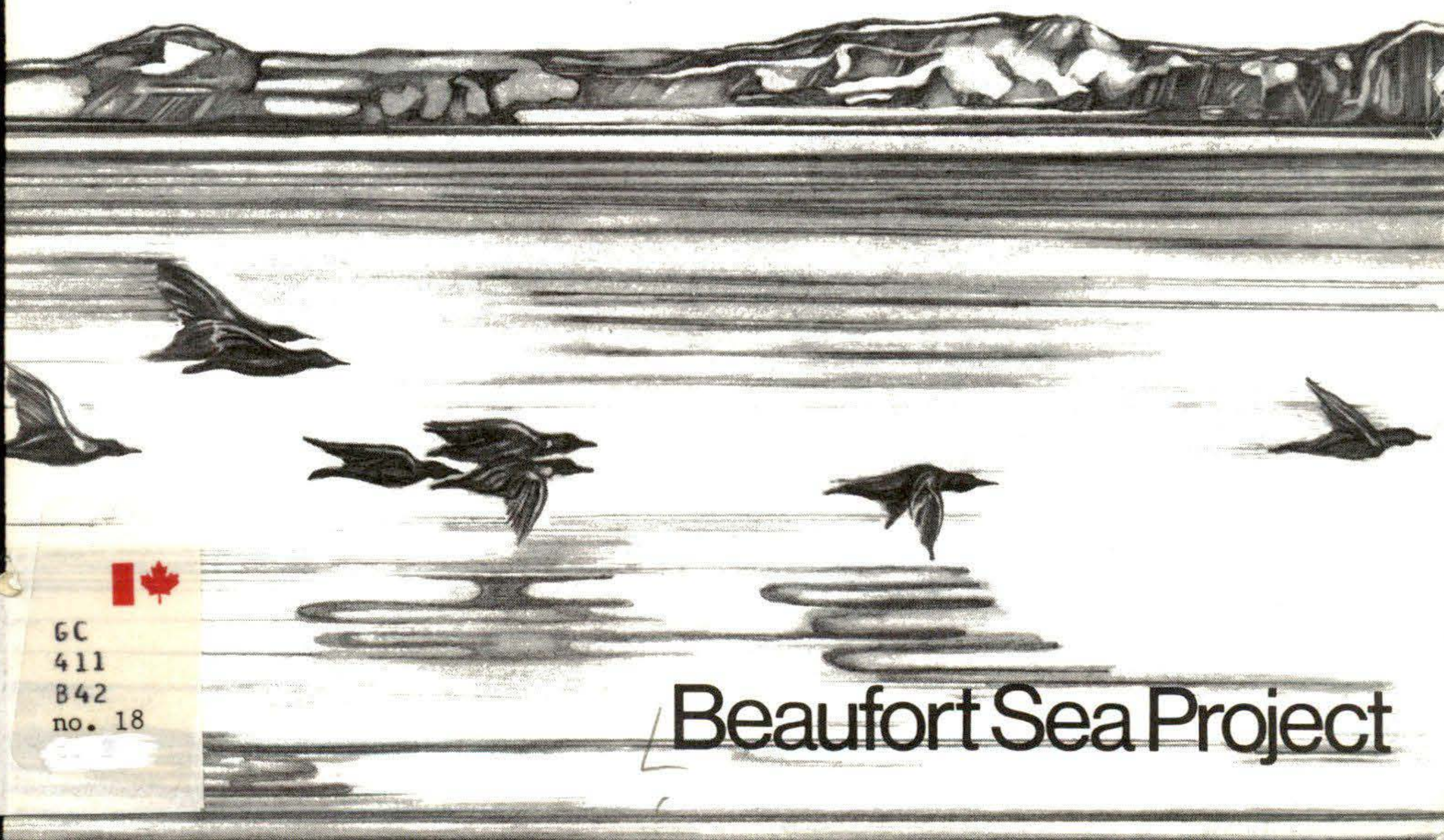
Physical Oceanography of the Southeastern Beaufort Sea

R.H. HERLINVEAUX, B.R. de LANGE BOOM

Technical Report No. 18



Beaufort Sea Project

THE PHYSICAL OCEANOGRAPHY
OF THE SOUTH-EASTERN BEAUFORT SEA

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Finally, the Polar Continental Shelf Project deserves thanks for supplying excellent logistic support and accommodation.

1. ABSTRACT

In the Beaufort Sea meteorological and ice conditions play a major role in the distribution of oceanographic properties. Field studies were conducted during the summer of 1974 ("worst ice conditions on record") as well as during the spring and summer of 1975 ("good ice conditions"). The discharge from the Mackenzie River dominates the surface waters of the southern Beaufort Sea, especially during bad ice years. The density distribution is salinity dominated throughout the system. The vertical profiles of salinity, temperature, turbidity and currents are described for summer and spring conditions. In both space and time the distribution of water properties is better known than the currents, although a qualitative description of the surface currents can be given for conditions of westerly or easterly winds together with the resulting temperature and salinity distribution. During the spring, tidally induced movements of the water column were observed only at mid-depth off Kugmallit Bay, and these movements are not considered to be a major factor in the study area. The movement of Mackenzie River water in the Beaufort Sea is predictable to some degree and can be followed by satellite imagery. Although the behaviour of oil is not identical to that of water, the flow of surface water could involve the movement of either crude oil from a blowout or other pollutants.

2. INTRODUCTION

The physical-oceanographic results described in this report are one product from a group of baseline environmental studies known as the Beaufort Sea Project, financed jointly by the Canadian Federal Government and the Petroleum Industry in the area shown in Figures 1 and 2. The objectives of the program were to provide regulatory agencies within Government with the necessary background information required to set realistic conditions upon the conduct of exploratory drilling in the Beaufort Sea.

Certain general oceanographic features which are usually associated with estuarine and coastal seaways were expected to be evident in the Beaufort Sea and are outlined below.

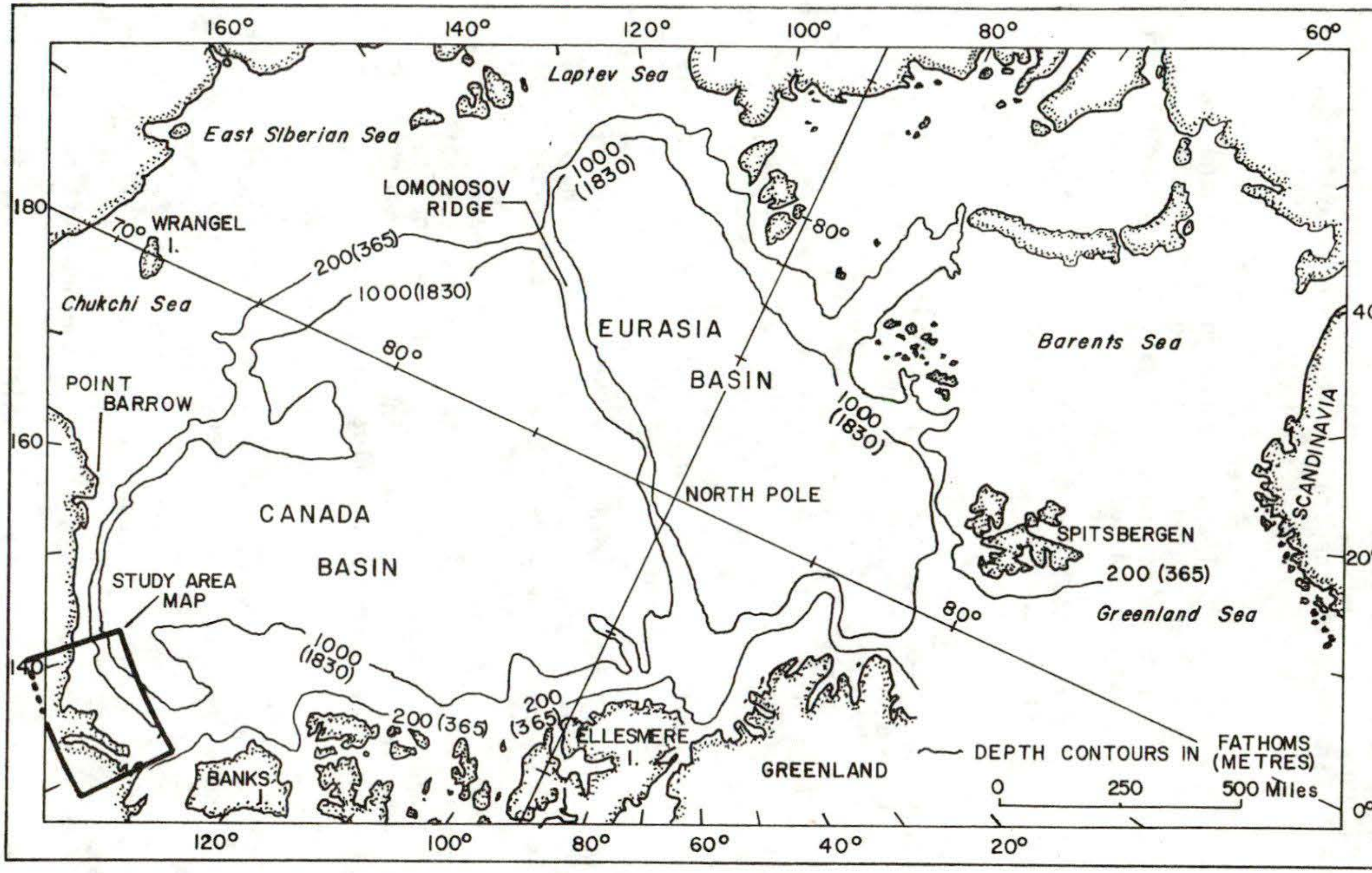

Figure 1. The Arctic Ocean and the major basins relative to the study area.

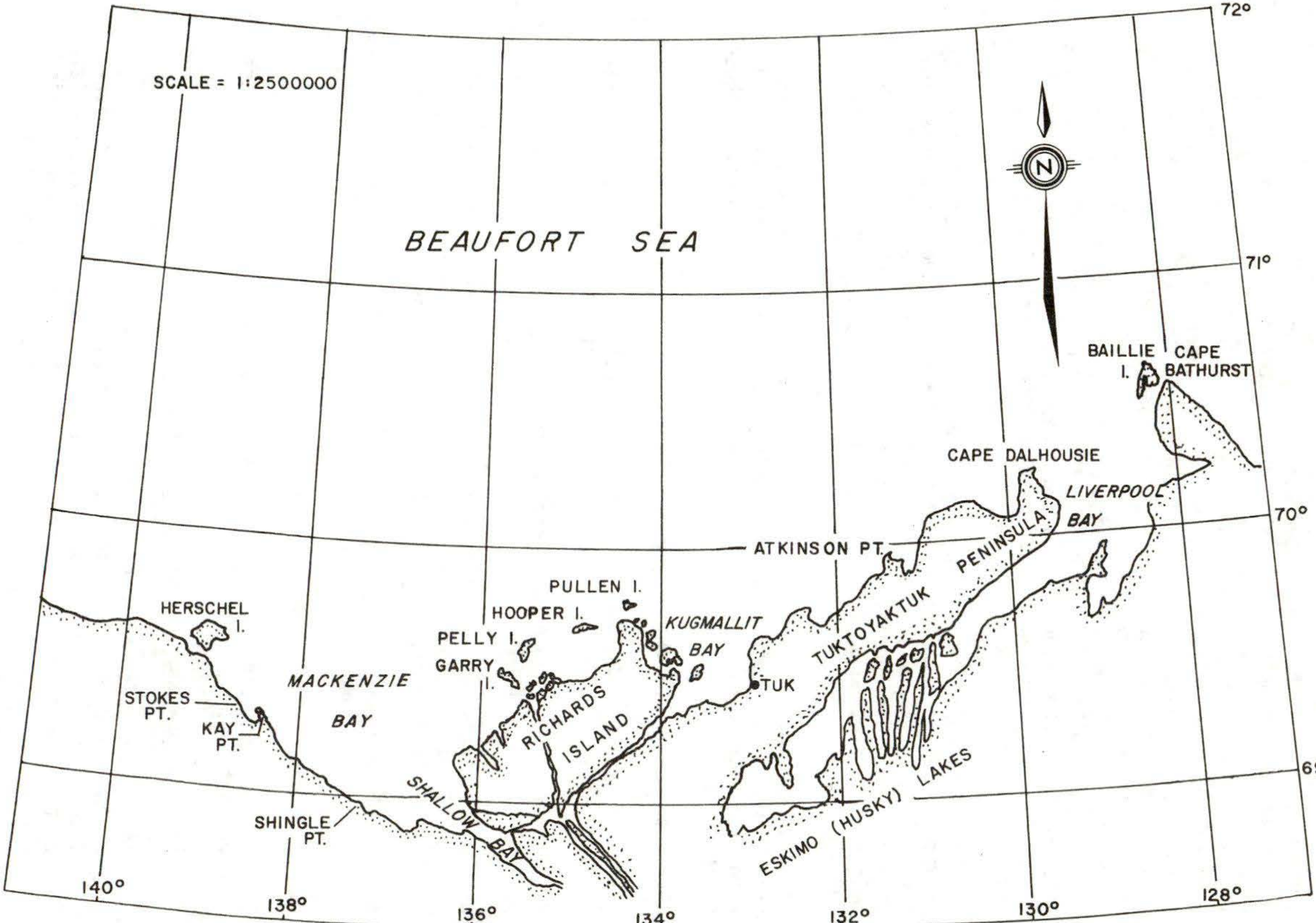

Figure 2. The study area in the southeastern Beaufort Sea.

The water structure in the southern Beaufort Sea is highly stratified in summer due to the shallow and brackish upper layer maintained by the Mackenzie River discharge. This brackish water moves persistently seaward mixing with the saline waters from below, as in an estuary. As a result of this mixing there is an onshore movement of saline water to replace that removed by the seaward-flowing upper layer. The brackish water moves eastward due to the Coriolis effect associated with the earth's rotation. Meteorological conditions, of which winds are a major part, modify or even reverse the net surface and subsurface movement noted above. Oil, whether floating on the surface or emulsified in the water column, will be influenced by the water currents; also water movement governs the nutrient levels and directly or indirectly influences the concentrations of fish food (plankton) preferentially in certain areas.

Heat accumulates in the surface layer during summer because of stability in the stratified water column and in general, water movement determines how much heat will be introduced, retained or removed from the SE Beaufort Sea. Consequently, the amount of heat in the area affects the melting and freezing of ice and has a direct effect on moderating the local climate.

Although some of the general oceanographic features in the study area were known, it was evident there remained much that was not understood. A physical oceanographic study was undertaken in order to minimize these deficiencies.

The specific aims of this study were:

1. To investigate the water column for natural variability in temperature, salinity, turbidity and water movements.

2. To investigate water movements in the surface layer, and their relationship to winds and to ice conditions.

3. To investigate whether either convergent or divergent flow exists in the vicinity of Mackenzie Bay and Tuktoyaktuk Peninsula and the possible relationship of such flow to ice congestion.

4. To relate water movements to satellite observations of the river discharge plume and ice movements.

5. To obtain statistics on surface waves.

6. To determine movements of ice islands and fragments in the southern Beaufort Sea.

2.1 Physical Oceanography of the Arctic Ocean

The Arctic Ocean differs from most other seas in that most of its surface is covered with ice, which acts as a lid, tending to isolate the water from the atmosphere. This isolation is not complete because, even in winter, the ice never forms one solid and continuous cover. It is always moving and leads are opening and closing throughout the year. Thus there is a continuous exchange of momentum, heat and moisture with the atmosphere, although much reduced from what would take place if the ice cover were to be removed. The details of the heat budget of the Arctic Ocean are not well understood and there is some concern that if the ice cover was somehow reduced the process may be irreversible, resulting in a major impact on global weather.

Temperature and salinity depth distributions collected from the Arctic Ocean over more than 70 years show no significant variation with time. There are repeated variations with geographic position and expected regular seasonal variations in the surface waters which indicate that the physical processes within the Arctic Basin are in a state of equilibrium.

The Arctic Ocean can be subdivided vertically into three major water masses, according to their temperatures; Arctic surface water, Atlantic water and Arctic bottom water (Figure 3), (Coachman and Barnes, 1961; Kusunoki, 1962; Coachman, 1963). The boundaries at depth between these water masses are somewhat arbitrary since the water masses gradually merge into each other.

Of all the Arctic water masses, the Arctic surface water shows the greatest variability in its properties. This water extends in depth from the surface to about 150 m in the Eurasia Basin and to about 250 m in the Canada Basin (Figure 1). Further, the Arctic surface water can be subdivided into three regions which may be called the surface layer, the subsurface layer and the lower layer (Pickard, 1963). The surface layer extending in depth from 0 to 25 - 50 m, is cold, relatively dilute and has the greatest variability. This layer is nearly isohaline with salinities in the range 28.5 to 33.5°/₀₀, temperatures less than 0°C, and is generally near the freezing point. (The freezing point of salt water is nearly a linear function of salinity, with a value of -1.5°C at 28°/₀₀, decreasing to -1.9°C at 35°/₀₀.)

The subsurface layer extends in depth from 25 - 50 m to 100 - 150 m and is usually nearly isothermal with temperatures in the range -1.9 to -1.3°C. Its salinity increases markedly with depth, since the main halocline occurs in this layer. At a depth of 100 m, in the Eurasia Basin, all salinities are in excess of 33°/₀₀, while some exceed 34°/₀₀. Its temperatures fall in the range -1.8 to 0.1°C in summer and -1.9 to -1.3°C in winter. In the Canada Basin the subsurface layer extends somewhat deeper (to 150 m) compared to the Eurasia Basin and has generally lower salinities. The main halocline is correspondingly deeper so that salinities usually do not exceed 33°/₀₀ until a depth of about 150 m is reached. The temperature structure is also different in the Canada Basin, frequently showing a slight maximum (0.5 to 1.0°C warmer than water above or below) at 75 to 100 m, with a minimum of -1.4 to -1.5°C at 150 m. This maximum is attributed to summer Bering Sea water that is advected around the Beaufort Sea Gyre, the temperature maximum being eroded by vertical diffusion as it progresses (Coachman and Barnes, 1961). The mixing of winter Bering Sea water with bottom

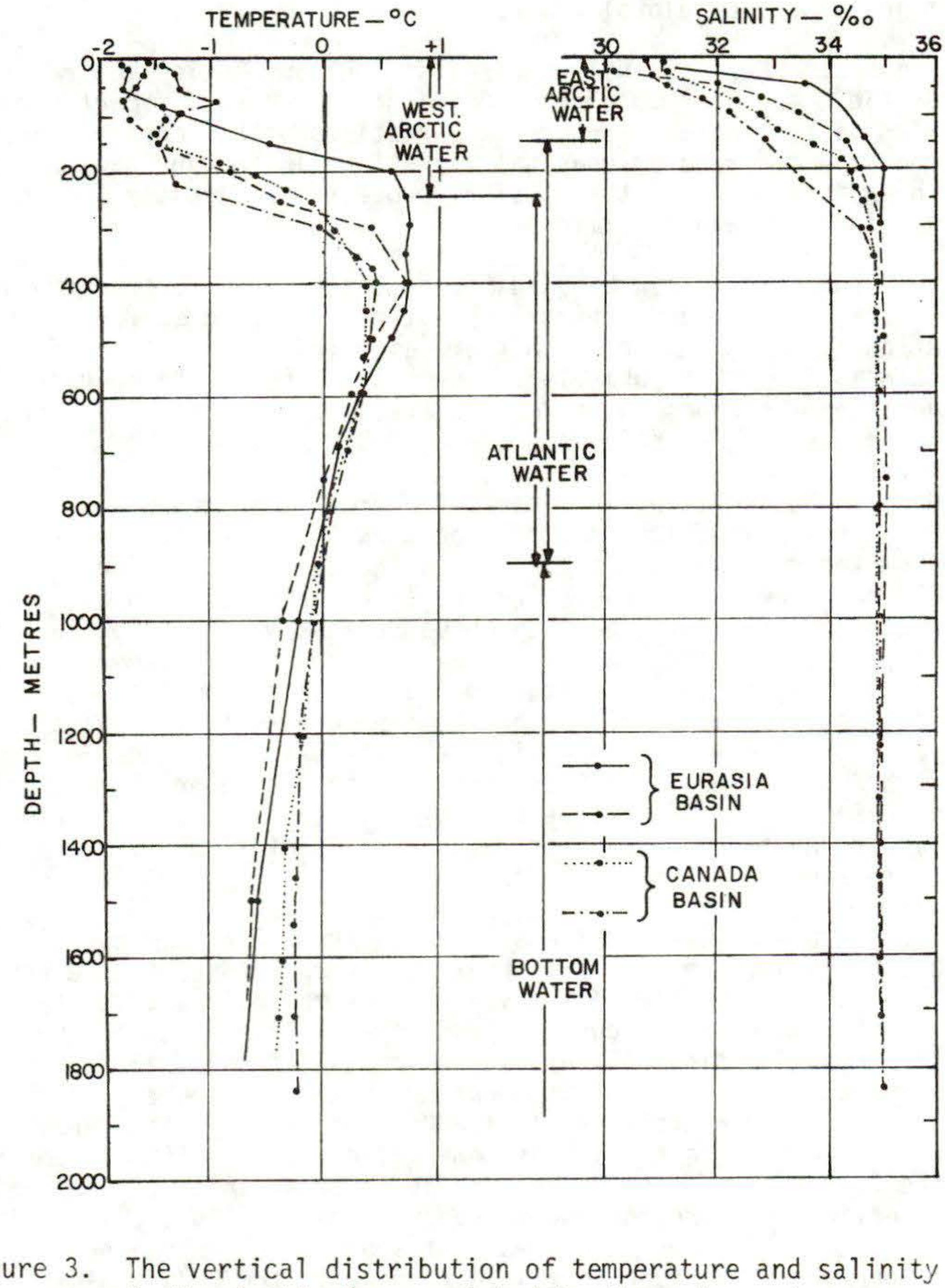

Figure 3. The vertical distribution of temperature and salinity in the Arctic Ocean related to the major water masses (after Coachman and Barnes, 1961).

shelf water is suggested as the mechanism for maintaining the temperature minimum. The formation of the subsurface layer in the Eurasia Basin appears to take place in regions where submarine canyons indent the continental shelf. These canyons act like estuaries allowing saline Atlantic water to move inshore where it mixes with surface water moving offshore, reducing its salinity and temperature (Coachman and Barnes, 1962).

The lower layer extending from a depth of 150 m in the Canada Basin (100 m in the Eurasia Basin) down to the Atlantic water has properties intermediate between those of the subsurface layer and the Atlantic water. These properties result from the mixing between these two layers so that the lower layer supports the main thermocline.

Variations observed in temperature and salinity throughout the Arctic surface water can be traced to two causes; seasonal weather changes and changes with geographic location of oceanic source waters and water-modifying processes. Seasonal weather changes result in changes in salinity and temperature as the sea ice melts and freezes and river discharge rates vary. The resulting changes in the stability of the water column determine the extent to which mixing takes place in the surface layer. In winter, freezing plus mechanical mixing due to wind-water to ice-water shears can produce an isohaline and isothermal surface layer 50 m deep. In summer, fresh water and heat added to the surface layer can produce a seasonal halocline and thermocline at depths usually between 5 m and 20 m.

The change from the continental slope to the continental shelf occurs at about 200 m; hence the nearshore waters are generally part of the Arctic surface water. The shallower depths and closer proximity to sources of fresh river water lead to greater variations in water properties than are found over the deeper basins. At the surface, salinities may at times drop as low as 0°/₀₀ or temperatures rise to more than 10°C, although these occurrences are quite localized.

Lying below the Arctic surface water is the Atlantic water, occupying depths from about 150 - 250 m down to 900 m. The most prominent characteristic of this water of Atlantic origin is the presence of temperatures above 0°C (exceeding 2.5°C near Spitsbergen) while salinities fall mainly in the range 34.8 to 35.0°/₀₀. Without going into detail about the circulation of this water mass (to be discussed later), the Atlantic water enters the Arctic Ocean near Spitsbergen with a temperature maximum that can exceed 2.0°C at a depth of 150 to 200 m (with 1.0°C to 2.0°C variations from season to season and year to year) and has characteristic salinities in the range 34.95 to 35.10°/₀₀ which change little with time. As this water follows the continental slope eastward, it rapidly loses heat so that on reaching the Laptev Sea the temperature maximum is only about 1.0°C and is found at depths between 200 and 250 m. By the time this water reaches the central Beaufort Sea and north of the Chukchi Sea the maximum temperature has decreased to about 0.5°C and is at depth ranging between 400 and 500 m. At locations most remote from its source (northwest of Ellesmere Island or northwest of Point Barrow) the maximum is at a depth slightly below 500 m. This deepening of the temperature maximum can be attributed to the greater heat loss upward since the temperature gradients are greater above the Atlantic water than below it (Coachman and Barnes, 1963). Measurements also indicate that larger current shears occur in the pycnocline (at 150 m) than below it (Newton and Coachman, 1973), leading to greater mechanical mixing from above than from below the Atlantic water. Coincidental with the loss of heat, the salinities also decrease, falling in the range 34.80 to 34.93°/₀₀.

Arctic bottom water fills the basins of the Arctic Ocean below about 900 m and represents roughly 60% of the total water volume. The characteristics of this water mass are temperatures below 0°C and salinities with a very narrow range (34.90 to 34.99°/₀₀). In any particular location, the increase in salinity with depth is even less while its temperature decreases continuously with depth (to a minimum of -0.4°C at 2000 m in the Canada Basin). At any given depth, the measured range of temperature is about 0.2°C, with the Eurasia Basin showing slightly greater range than the Canada Basin. The two basins are separated by the Lomonosov Ridge (Figure 1) which has an estimated sill depth of 1200 to 1400 m (Coachman, 1963). Temperatures in the Eurasia Basin are about 0.5°C colder below sill depth since this water cannot penetrate the Canada Basin over the Lomonosov Ridge. Below 2500 m temperatures increase by about 0.2°C to the bottom, attributed to heating by adiabatic compression of the water as it sinks. The major source of the bottom water appears to be the Norwegian Sea where Atlantic water is cooled in winter to form the densest water of the Norwegian Current, and which flows into the basins of the Arctic. Small amounts of bottom water may be formed locally in conjunction with the submarine canyons of the Eurasia Basin.

It should be mentioned that, although no direct references have been made here, our knowledge of the Arctic Ocean is based in part on the work of scientists from the Soviet Union. The U.S.S.R. has been engaged in intensive Arctic research since the 1930's.

2.2 Water and Ice Motions

The circulation of the Arctic Ocean is much less well known than the distribution of water masses, due in part to the great variability of currents. Our present knowledge is based on the results of studies conducted from drifting ice islands, ice floes and ships. The mean circulation is slow (5 cm/sec or less) but much higher velocities can occur over short periods.

The mean circulation of the Arctic surface water consists of two main features; the Beaufort Gyre and the Transpolar Drift Stream (Figure 4b). The Beaufort Sea Gyre consists of a clockwise circulation centred at 80°N and 140°W over the Canada Basin and coincides with the mean atmospheric pressure anticyclone. Velocities are in the range of 1-5 cm/sec around most of the gyre with velocities of about 10 cm/sec north of Alaska. The Transpolar Drift Stream carried water and ice from the Asian shore past the North Pole to the east

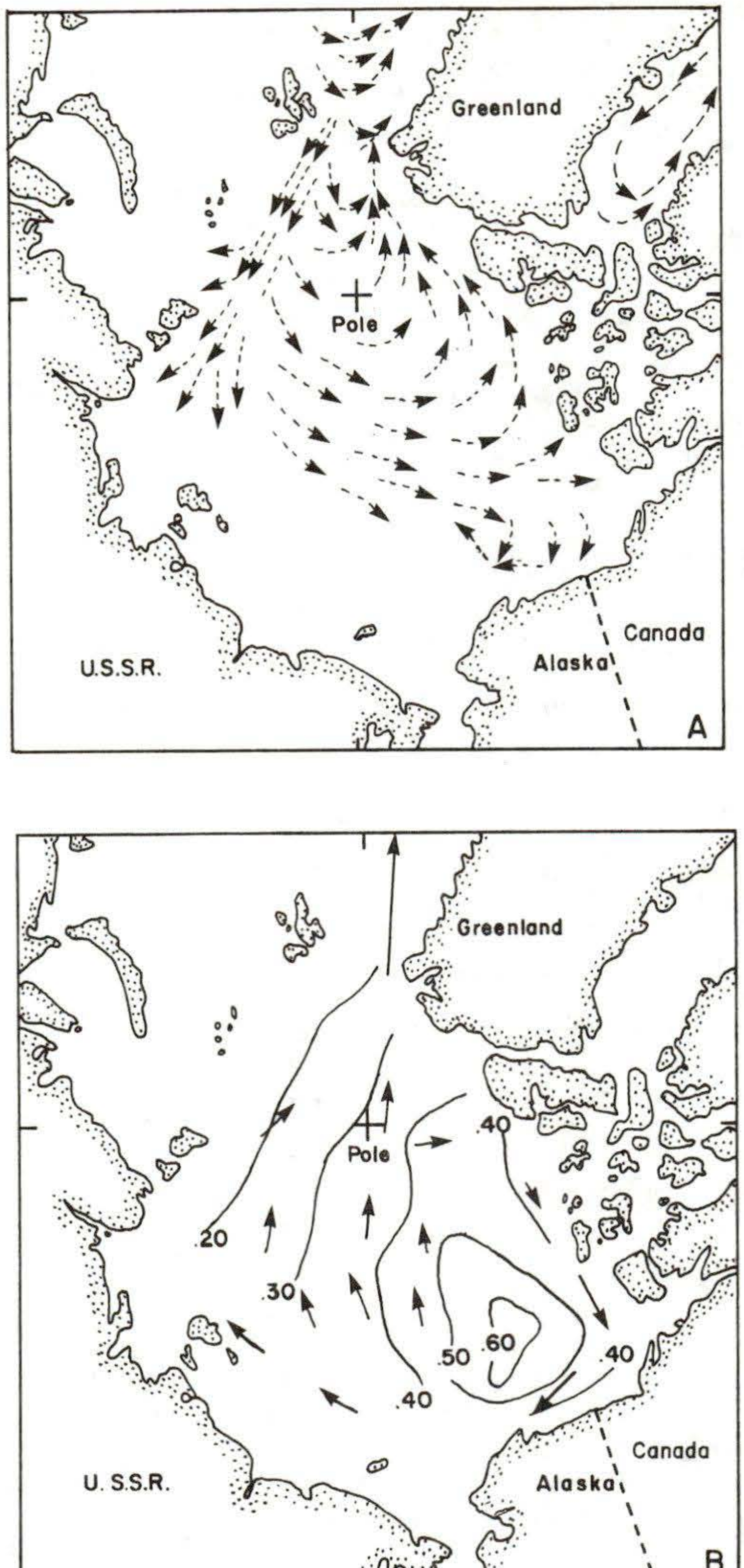

Figure 4. The general circulation in the Arctic Ocean:
(a) the Atlantic water; and,
(b) the Arctic surface water with the dynamic topography from 0/1200 db in dyn. m. (after Sater, 1969).

Greenland Current. The stream is continuous with the western part of the Beaufort Gyre and is responsible for the removal of ice and surface water from the Arctic Ocean. This information was derived from drifting stations on ships and ice and from calculation of geostrophic currents (Coachman and Barnes, 1961).

The largest currents are associated with transient phenomena. Coachman (1969) reported velocity fluctuations of ± 17 cm/sec at inertial or semi-diurnal tidal periods. Newton, Aagaard and Coachman (1974) and Hunkins (1974) have attributed the transient current maxima in the pycnocline to subsurface eddies of diameter 10 to 30 km. Velocities as high as 40 cm/sec have been observed at 150 m depth. The kinetic energy associated with these eddies in the area studied appears to be a major portion of the total kinetic energy. Thus eddies may be important in the exchange of momentum, heat and salt among the various water masses.

Newton and Coachman (1973) reported on water movement in the water column down to 850 metres. They indicated the existence of surges of relatively strong currents in the profile (8 cm/sec) which persisted in one direction for periods of days then after a relatively short period of time would reverse and flow in a completely different direction. These movements are barotropic currents resulting from the slope of the water surface.

The circulation of the coastal areas of the Arctic Ocean has been studied less than the circulation occurring over the deep basins. It has been suggested the Beaufort Gyre does not extend further shoreward than the edge of the continental shelf. However, from observations of ice drift it appears that the gyre may encroach onto the shelf at times. Based on the mean annual surface wind, Wilson (1974) indicates there should be a coastal current setting to the east along the Alaskan north shore and into Mackenzie Bay while a west setting current should be found off the Tuktoyaktuk Peninsula. Such currents can be observed but insufficient data exists to calculate a mean current, as has been done for the Arctic Ocean. An easterly current of relatively warm water derived from the Bering Sea has been observed along the north coast of Alaska in the summer (Hufford, 1973; Paquette and Bourke, 1974; Mountain, 1974; Hufford, 1975). Data are insufficient either to prove or disprove its existence during the remainder of the year. Preliminary results indicate an easterly setting current is also found near the bottom on the shelf north of the Mackenzie River delta in late spring and in the summer (S. Huggett, personal communication). Whether this current is seasonal or what drives the current have yet to be determined. Cameron (1953) and Healey (1971) found the wind to be important in determining the motion of the relatively fresh surface layer in summer. Velocities over 60 cm/sec, both easterly and westerly, have been observed in the surface waters (M. MacNeill, personal communication). Cameron (1953) also found that easterly winds caused upwelling in the Mackenzie River delta region, and upwelling was reported by Hufford (1974) for the Alaska north coast.

Our knowledge of tidal currents in the Arctic is very limited. Part of the problem lies in the fact that the inertial period is very close to the semi-diurnal tidal period in these latitudes. This makes it difficult to separate the two motions. There are few direct current measurements. In the area of the Beaufort Sea shelf, the vertical rise and fall of the water surface due to tides is often overshadowed by wind effects such as storm surges.

The circulation of the Atlantic water (Figure 4a) has been derived from the temperature and salinity distribution by means of the "core-layer method" (Coachman and Barnes, 1963) and agrees with the results of Russian workers. Direct current measurements by scientists from the U.S. and the U.S.S.R. indicate agreement with the general pattern, although insufficient data exists to determine a mean circulation from the direct measurements. The circulation is cyclonic (counter-clockwise) except for a small anticyclonic gyre north of Alaska. Velocities are in the range 1 to 10 cm/sec (Coachman and Barnes, 1963).

The narrow range of temperature and salinity values preclude using the "core-layer method" to determine the circulation of the Arctic bottom water. All that can be deduced is that the bottom water is mostly formed in the Norwegian Sea and then moves into the Eurasia Basin, crossing the Lomonosov Ridge to enter the Canada Basin. From the high oxygen values found throughout the water column in the Arctic Ocean (generally greater than 70% saturation (Kusunoki, 1962)), it is apparent that there must be renewal of the waters in the Arctic Basin. The difficulty of determining residence times for the water masses is due to uncertainty about the rate of oxygen depletion.

In the Arctic Basin runoff exceeds evaporation and precipitation. This excess fresh water is removed both as ice and as lower-salinity surface water via the east Greenland Current (Coachman, 1963). Our present knowledge indicates saline water enters the Arctic Basin via Bering Strait and the Norwegian and Greenland Seas, while there is an outflow through the Greenland Sea and the Canadian Archipelago. The circulation through the Archipelago is not well known, particularly its variation with time.

The mean ice-motion pattern is similar to that associated with the mean atmospheric pressure field (Coachman, 1969). The surface water circulation also shows this similarity. Mean ice-drift speeds are in the range 1 to 5 cm/sec. Higher average drift speeds over short periods have been observed; 39 cm/sec for ice island T-3 (Kusunoki, 1962) and 22 cm/sec for sea ice (Newton and Coachman, 1973). Plots of ice drift show large changes of direction over periods of less than a day; even 180° reversals of drift can be seen. Such large drift speeds or changes in direction are usually associated with the wind. Under average conditions, ice drifts at about 2% of the wind speed and approximately 30° to the right of the wind due to the Coriolis effect. Where ice concentrations are very low the response can be greater than 2%, while closely packed ice conditions result in values closer to 1% (Newton and Coachman, 1973). The ice may also move directly in line with the wind. Ice motion is determined by the combination of several forces; wind (through air-ice stress), currents (through ice-water stress), internal ice stress (resistance of the ice pack to motion within itself), the Coriolis effect and pressure gradients (due to the tilt of the sea surface). The relative magnitudes of these forces can change both in time and in space, leading to apparent differences in the response of the ice to the wind.

3. HISTORICAL REVIEW

3.1 Physical Oceanographic Studies in the Southeastern Beaufort Sea

Prior to 1951, there was little oceanographic data collected in the southeastern Beaufort Sea. Some of the early expeditions which obtained oceanographic data included the Canadian Arctic Expedition of 1913 to 1918 under V. Stefannson, the patrol of the R.C.M.P. vessel *St. Roche* from 1935 to 1937 under Sergeant H.A. Larsen (Tully, 1952), and the cruises of the icebreaker U.S.S. *Burton Island* in 1950 and 1951. The first detailed physical-oceanographic study took place in 1951 and 1952 using the C.G.M.V. Cancolim II and was reported by Cameron (1952, 1953). As well as increasing the knowledge of the bottom topography in the southeastern Beaufort Sea, a better understanding of water characteristics and motions was obtained.

In subsequent years, Canadian and United States icebreakers obtained salinity, temperature and oxygen data as well as bottom samples. Similar observations were made from Ice Island T-3 when it drifted from east to west off the Mackenzie Delta. Although these observations added to our knowledge of the water properties of the Arctic Ocean, most of the stations were taken beyond the edge of the continental shelf, and are of little direct interest to the present study. In 1970, as part of the Hudson 70 Program, physical, biological and geological data were collected on the shelf from the C.S.S. Hudson. Healey (1971) reported observations taken the same summer from the C.S.S. Richardson in the nearshore waters, including some near-surface current measurements.

The data were largely collected during the open water season (summer). Only two sets of winter measurements have been reported for the study area. Barber (1968) reports the results of measurements in Tuktoyaktuk Harbour and Kugmallit Bay taken between 1962 and 1963 during winter, spring and summer. A helicopter was used to obtain physical and biological data in the early spring of 1972 (Vilks, 1973). Data collected as part of the Beaufort Sea Project will be discussed later.

3.2 Results of Previous Studies

Cameron (1953) described the vertical distribution of temperature and salinity in summer when the discharge from the Mackenzie River results in a thin layer of low-salinity water, separated from the underlying higher salinity water by an intense halocline (Figure 5). This halocline decreases in intensity both northward and from east to west, depending on the distance from Mackenzie Bay. Marked heating can occur within the stable, low-salinity surface water. In contrast to the salinity, the temperature decreases with depth to a minimum which is characteristic of the degree of cooling during the previous winter; it may be evident at depths from 10 to 50 metres, depending on location and depth of the water column. Temperature inversions can occur in the surface layer, associated with periods of cool northerly winds when the surface layer can be chilled rapidly; they can also occur near melting ice and are indicative of the horizontal advection of waters with different characteristics. Temperature inversions occur below the surface layer and are believed to result from horizontal water movements alone.

Winds play a major part in the movements and distribution of low-salinity surface water. Cameron (1953) described the surface distribution of low salinity waters during or after periods of easterly and westerly winds. During westerly to calm conditions the low-salinity water moves out and along the coast to the eastward; during easterly winds the low-salinity surface water is moved offshore, and is replaced by higher-salinity subsurface waters which upwell along the coast. Figures 6 and 7 depict schematically two different water distributions under onshore and offshore winds.

Vilks (1973) took winter observations through the ice over the continental slope and found that higher-salinity water (which during the summer was well offshore) had intruded inshore. However, his observations were not near enough to shore to detect the Mackenzie River water along the Tuktoyaktuk Peninsula.

During the summer of 1970, Healey (1971) observed temperatures and salinities in Kugmallit Bay. Surface currents in the general area were also measured. The current measurements confirmed Cameron's model of surface-water movements, i.e., that surface currents are strongly influenced by the wind. It was also apparent that the very shallowest water layer, a fraction of a metre or so in thickness, follows the wind more closely than does the water just below. In addition, in Kugmallit Bay this "deeper" water appears to be influenced somewhat by the tide.

It is clear that the Mackenzie River water and the change in its discharge rate strongly influences the surface water motions in the southeastern Beaufort Sea during all seasons. These motions can be further affected to some degree by the wind, tide and the state of the sea ice.

4. STUDY AREA

4.1 Geographic Location

The area of main concern is shown in Figures 1 and 2 which coincides in part with oil exploration permits. Also of concern are regions to the east and west through which surface waters which originate in

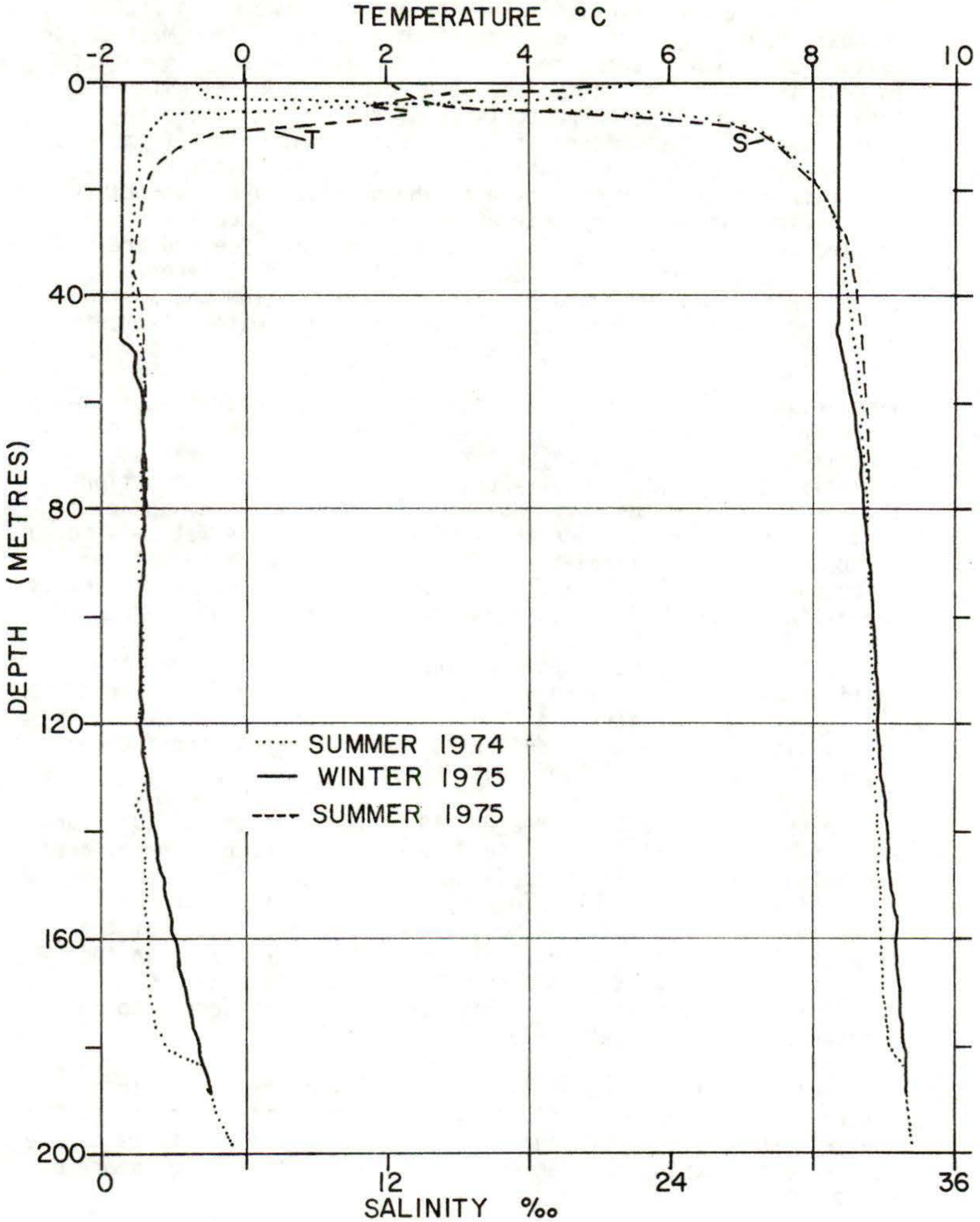

Figure 5. Comparison of typical summer and winter temperature and salinity profiles in Mackenzie Bay.

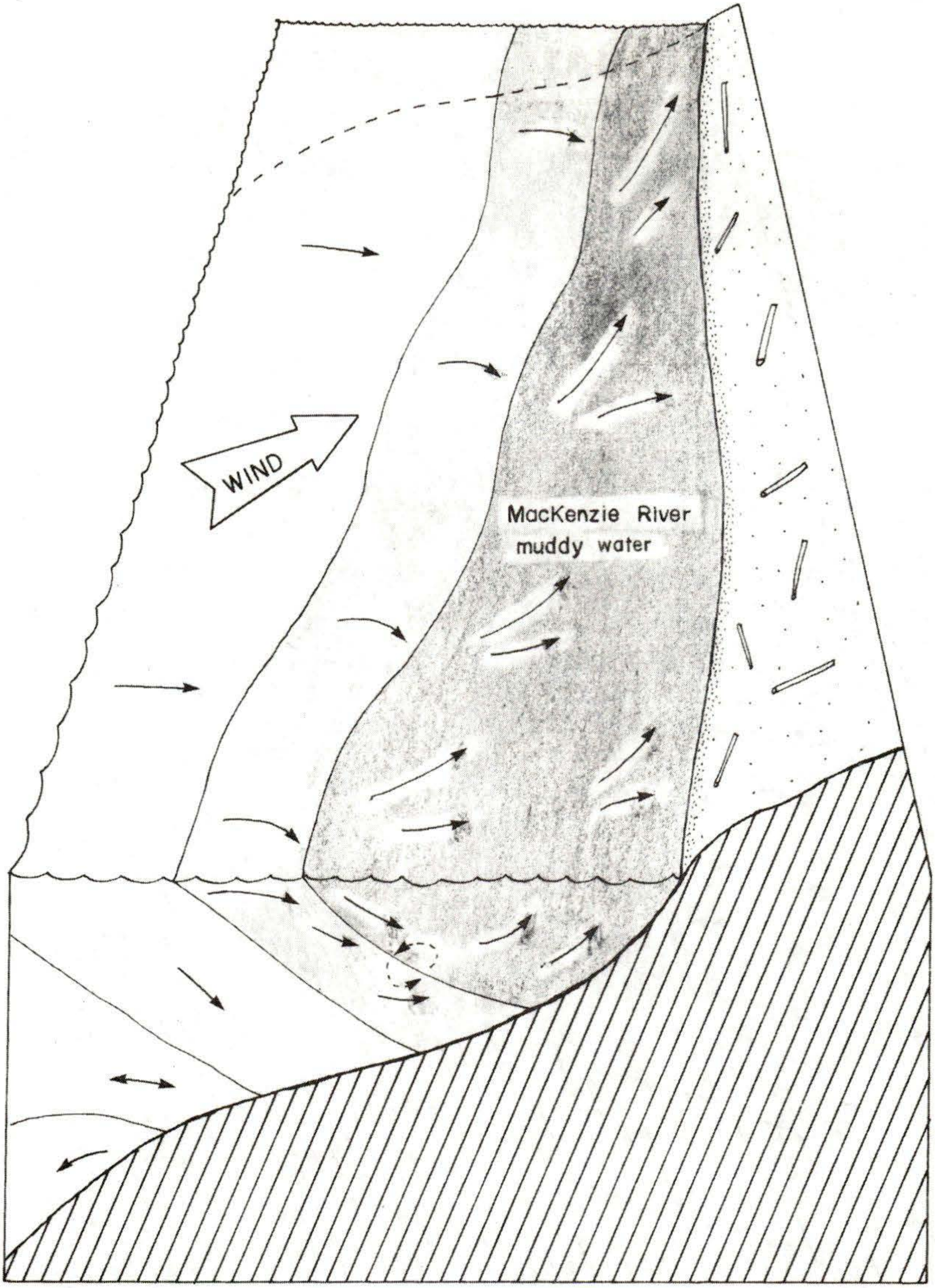

Figure 6. The general motion of water under the influence of onshore winds.

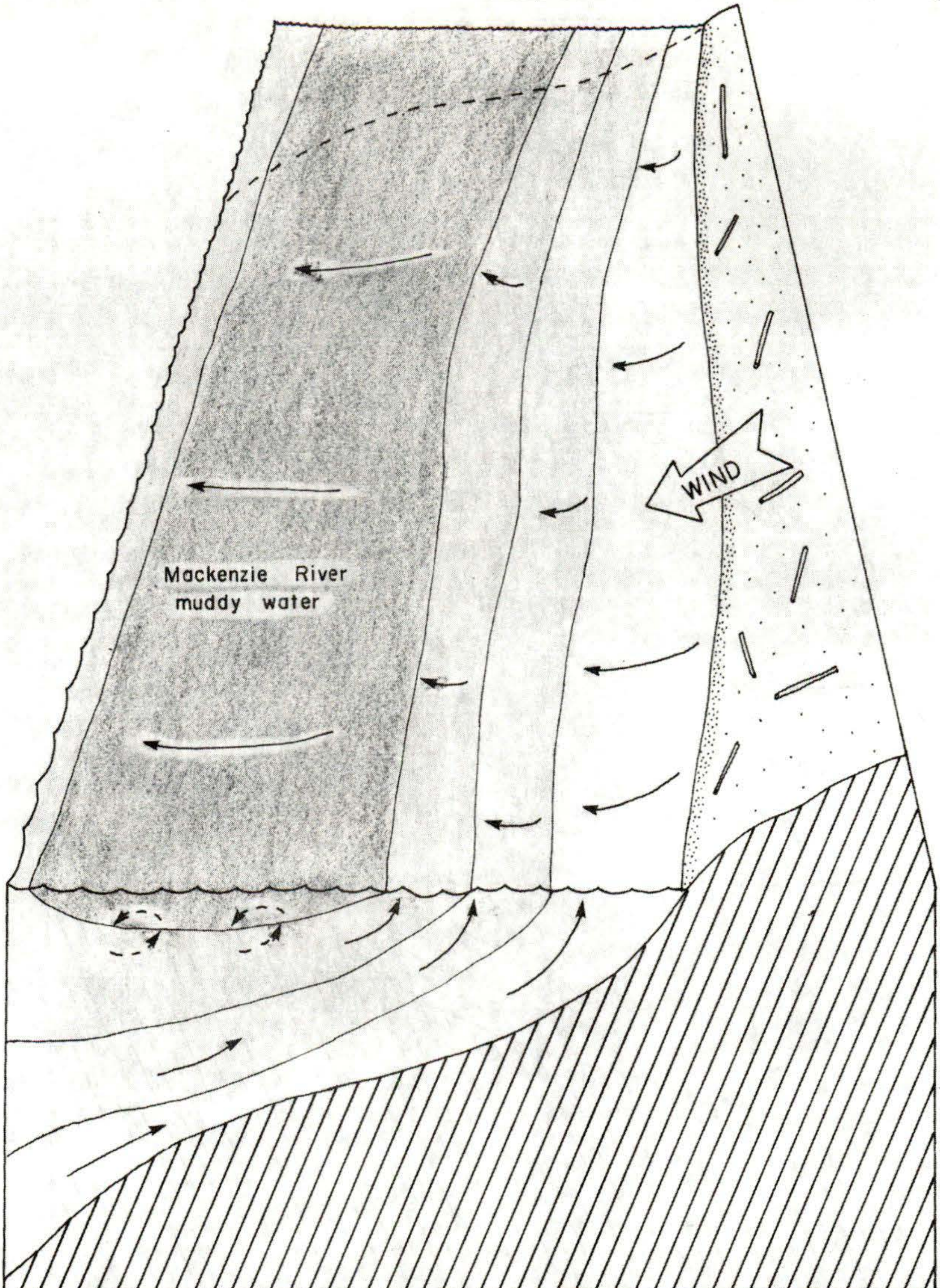

Figure 7. The general motion of water under the influence of offshore winds.

in this area may move. The area of interest therefore extends from west of Herschel Island, into Amundsen Gulf and northward off the continental shelf to north of 71°N.

4.2 Bottom Topography

The bottom topography is shown in Figure 8; the main feature is Herschel Canyon which extends southward from deep water north of Herschel Island into Mackenzie Bay and toward the mouth of the Mackenzie River. A small deep basin is located to the southeast of Herschel Island and to the west of Herschel Canyon; to the east of the Canyon lies the Mackenzie River delta fan. A smaller canyon is located north of Kugmallit Bay, largely parallel to Herschel Canyon.

Along Richards Island and the Tuktoyaktuk Peninsula, the continental shelf, defined to be inshore of the 200 metre contour, extends seaward to a distance of 110 to 150 km. In the Mackenzie Bay region, the nearshore water is very shallow, deepening very gradually, with the 10-m isobath lying as far as 35 km offshore. Only ice scours and underwater pingos mar the flatness of the continental shelf.

4.3 Land Drainage

The Mackenzie River water moves into the Beaufort Sea through several passages shown in Figure 9. Figure 10 shows the discharge values for the gauging station at Norman Wells (600 km up-river); from there to the open ocean the runoff is enhanced somewhat. The river enters the Beaufort Sea through many channels – into Shallow Bay (which is part of Mackenzie Bay), through the islands of the delta and into Kugmallit Bay – rather than as a "point source". The discharge waters from the Mackenzie River constitute the major source of brackish water on the north coast of Canada. Other sources are minor and are of significance only in the immediate vicinity of river mouths.

The spring freshet of the Mackenzie River starts in early May and reaches a peak flow of approximately 2.3×10^4 m^3/sec from the middle of May to the beginning of June. From then to August the discharge can fluctuate by about 5×10^3 m^3/sec in a period of five days. The fluctuations are probably caused by the passage of weather systems over the various drainage areas of the Mackenzie River system. By December the discharge is reduced to the winter minimum of approximately 2.5×10^3 m^3/sec.

4.4 Winds

During the summer months winds generally blow from the northwest and southeast quadrants about equal amounts of time. The strongest winds are generally westerly; modified as they blow along the western slope of Mackenzie Bay because of the orographic effects of the mountains. During the summer of 1974, however, these general features altered in that winds from the northwest quadrant predominated over those from the southeast quadrant. At times in early or late summer, diurnal winds are significant; these result in alternate

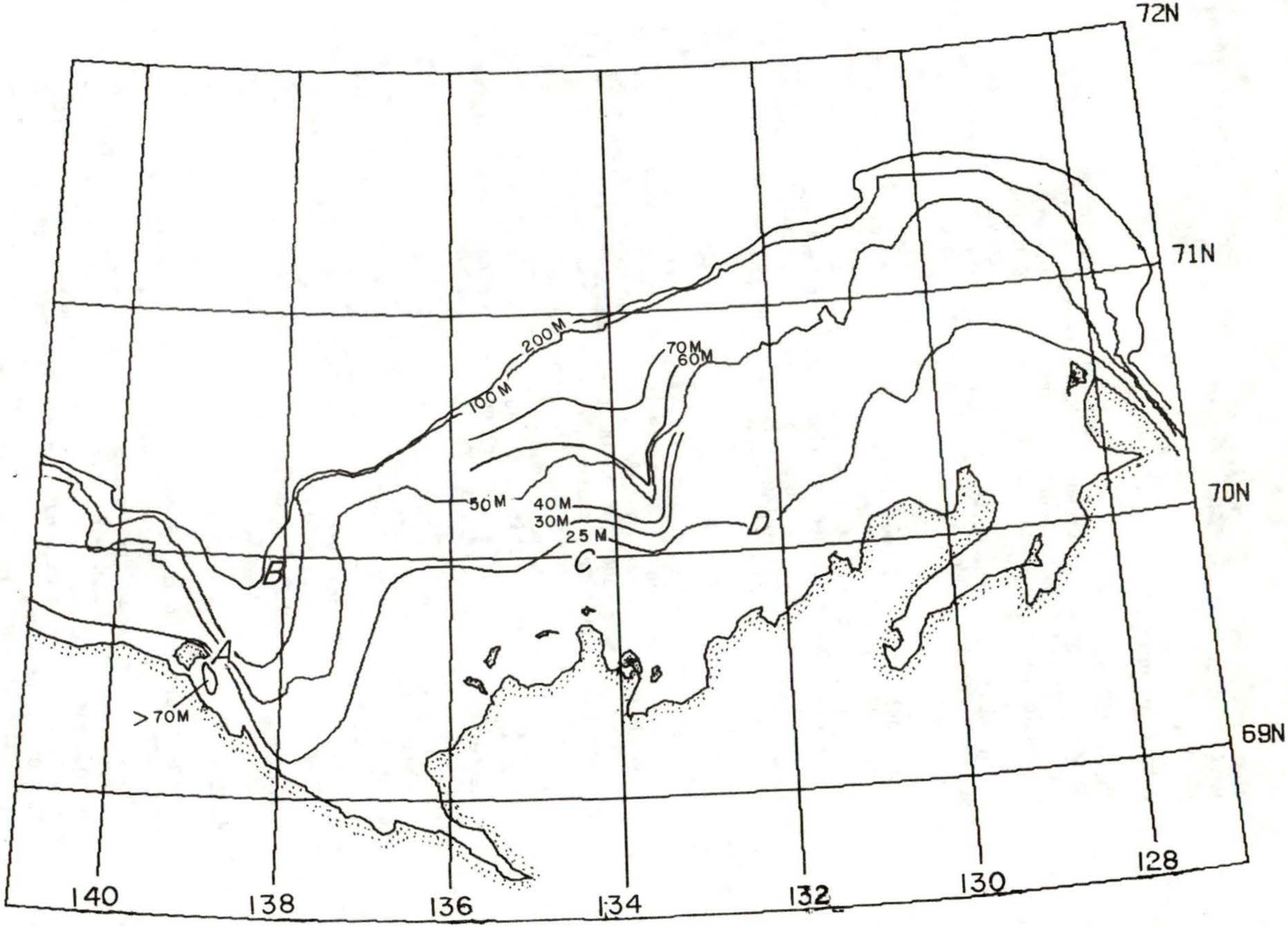

Figure 8. The bottom topography of the southeastern Beaufort Sea with letters indicating the grouping of stations by regions.

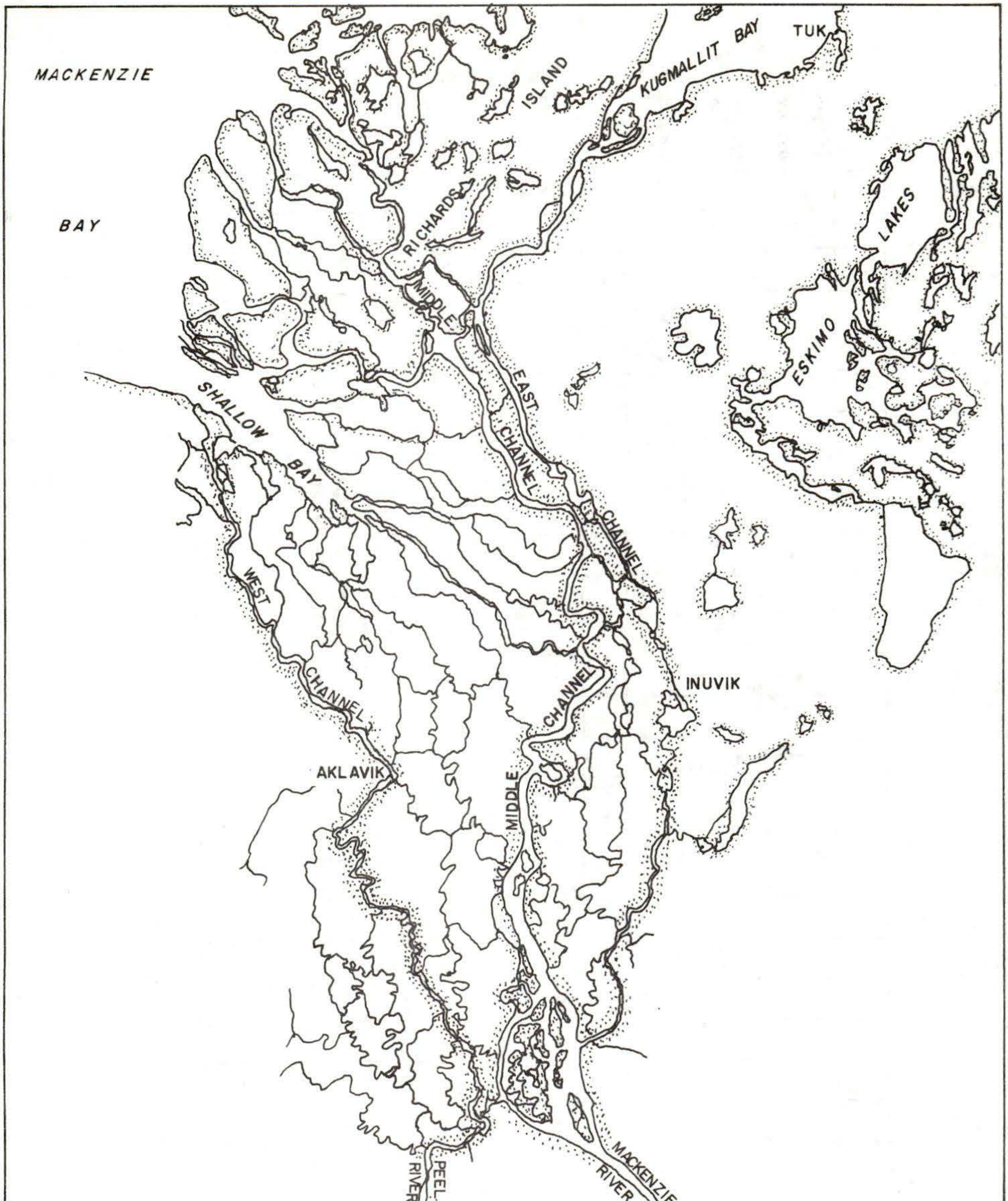

Figure 9. The channels of the Mackenzie River Delta.

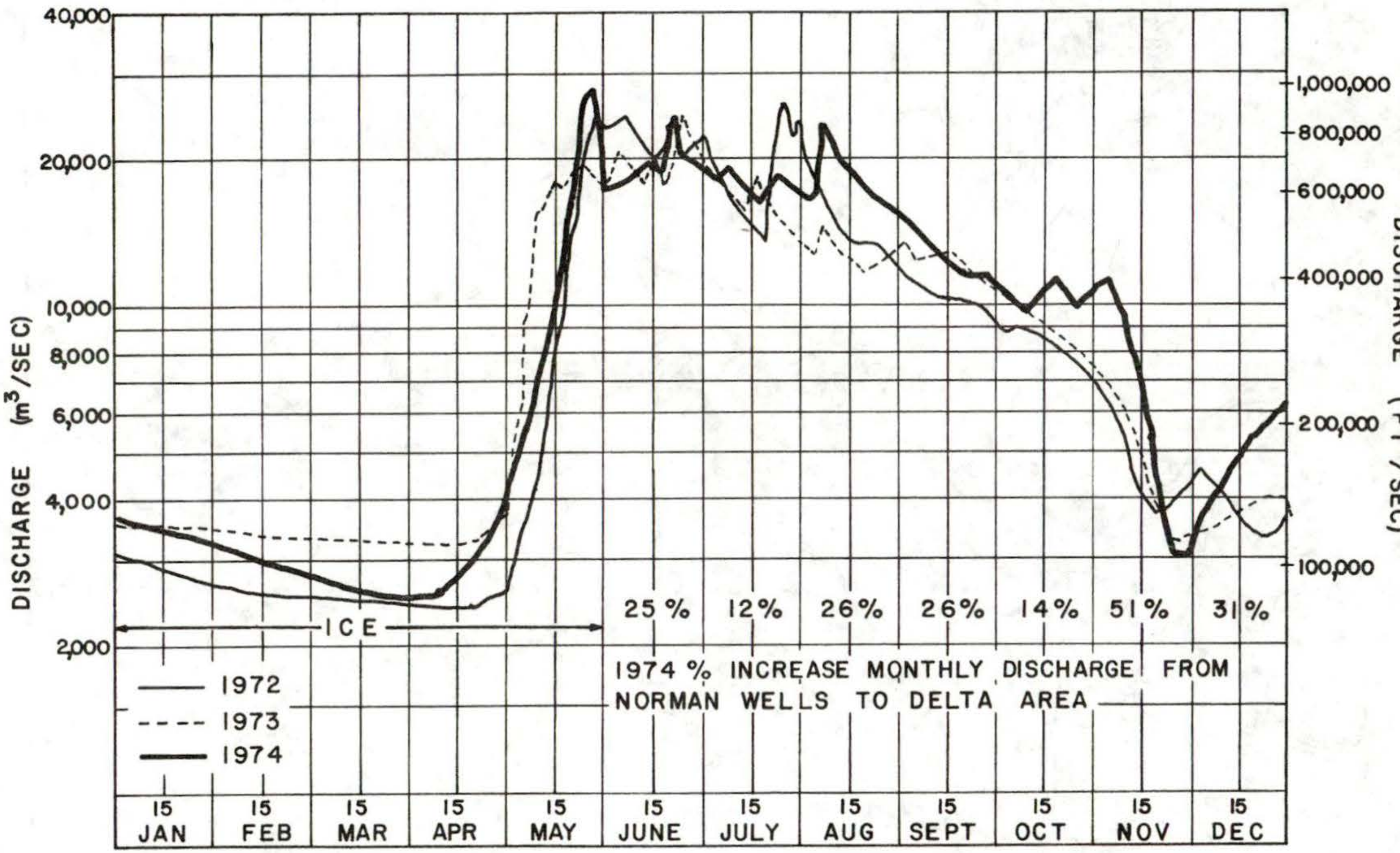

Figure 10. The Mackenzie River discharge measured at Norman Wells for the years 1972, 1973 and 1974.

onshore (daytime) and offshore (nighttime) local air movements.

The large extent of shallow water in the southeastern Beaufort Sea produced ideal oceanographic conditions for the occurrence of storm surges. Such surges occur in the presence of strong winds and may change the sea level in coastal embayments by more than 2 m, in contrast to the general tidal range of 0.5 m in the area. Human fatalities, damaged facilities and significant erosion of coastal features are by-products of these surges. A companion report on Storm Surges detail this phenomena (F. Henry, 1975).

We emphasize that the southeastern Beaufort Sea region has a climatology and oceanography extremely variable in both time and space; hence, the "means" or "typical" conditions often noted in the literature must be regarded with caution. For example, the rather "heavy" ice conditions along the north coast of Alaska during the summer of 1975 occurred at a time of "light" ice conditions in the southeastern Beaufort Sea and the Canadian Archipelago.

5. DATA COLLECTION AND REDUCTION

5.1 The Observation Platform

During the summer of 1974 salinity, temperature, turbidity and current profiles were measured from the M.V. Theta at 63 stations (Figure 11). Meteorological observations were also made, and a record was kept of the ship's drift by means of the Decca navigational equipment. A surface wave-measuring buoy was moored in the entrance to Kugmallit Bay for a period of about nine days in summer 1974.

During the spring of 1975 similar oceanographic and meteorological observations were carried out through the ice cover at 41 locations (Figure 12) where a Bell 205 helicopter was used for transportation over the ice. Positions were determined by Decca. Ice drift measurements were also carried out by placing radio beacons on the ice and tracking them with a Bell 206 helicopter fitted with a Decca receiver. Time-series of measurements of water properties and velocities were carried out on the ice at positions A, B, and C, (Figure 12), by means of a CTD, a transmissometer and a Savonius rotor current meter; the measurements were undertaken within a specially-designed portable shelter.

In the summer of 1975, 48 oceanographic stations plus meteorological observations were taken from the M.V. Pandora II. These station positions are shown in Figure 13. Station 48 was a 24-hour time series. A wave measuring buoy was moored off Pelly Island (Location B in Figure 13), just north of the Mackenzie River Delta, for 30 days.

Standard oceanographic procedures were used; more detailed descriptions of the ships, equipment and methods used during 1974 and 1975 to obtain data are provided in Appendix B.

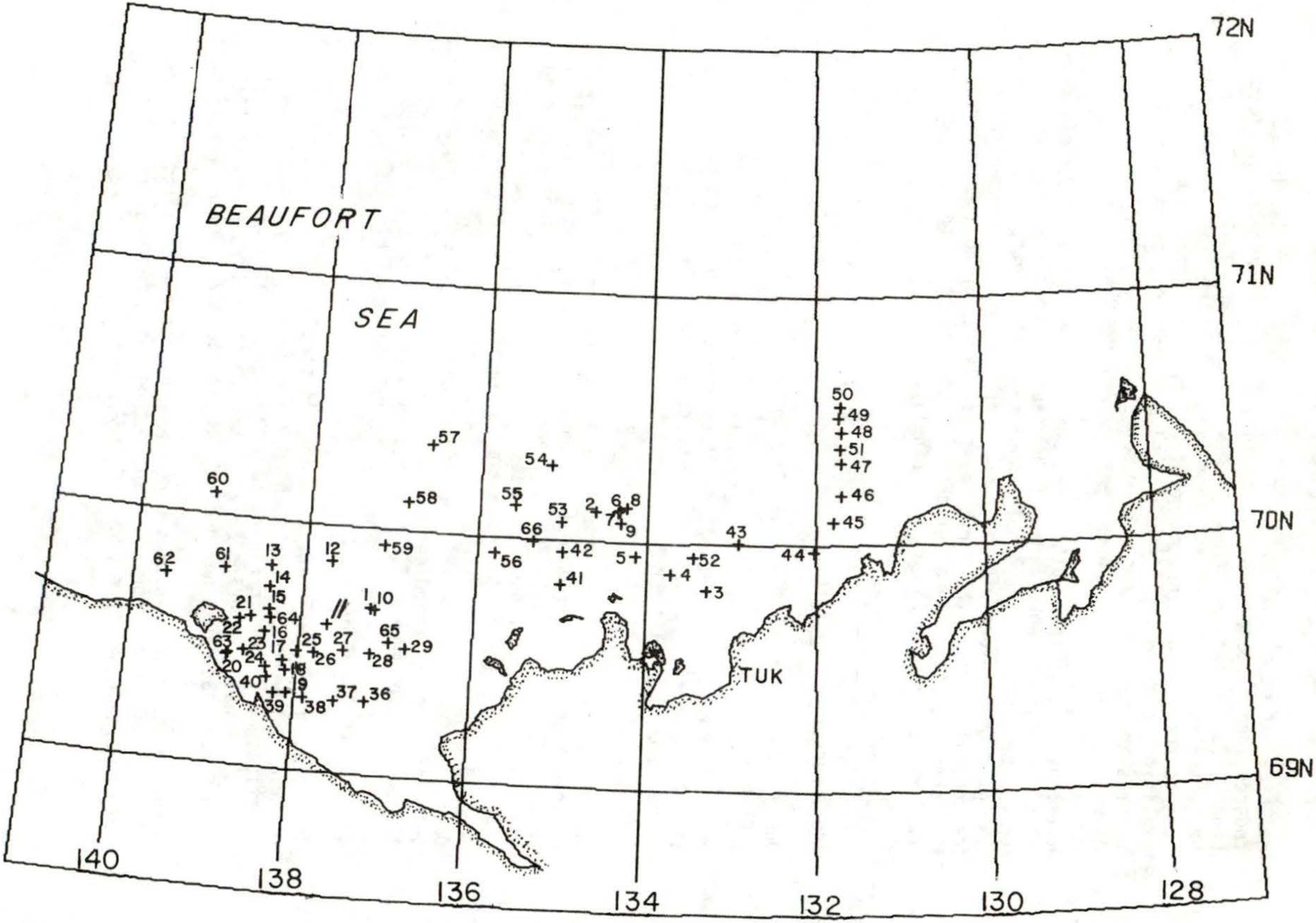

Figure 11. Oceanographic stations, 1974 summer (stations 30 to 35 were for bottom samples only and were not plotted).

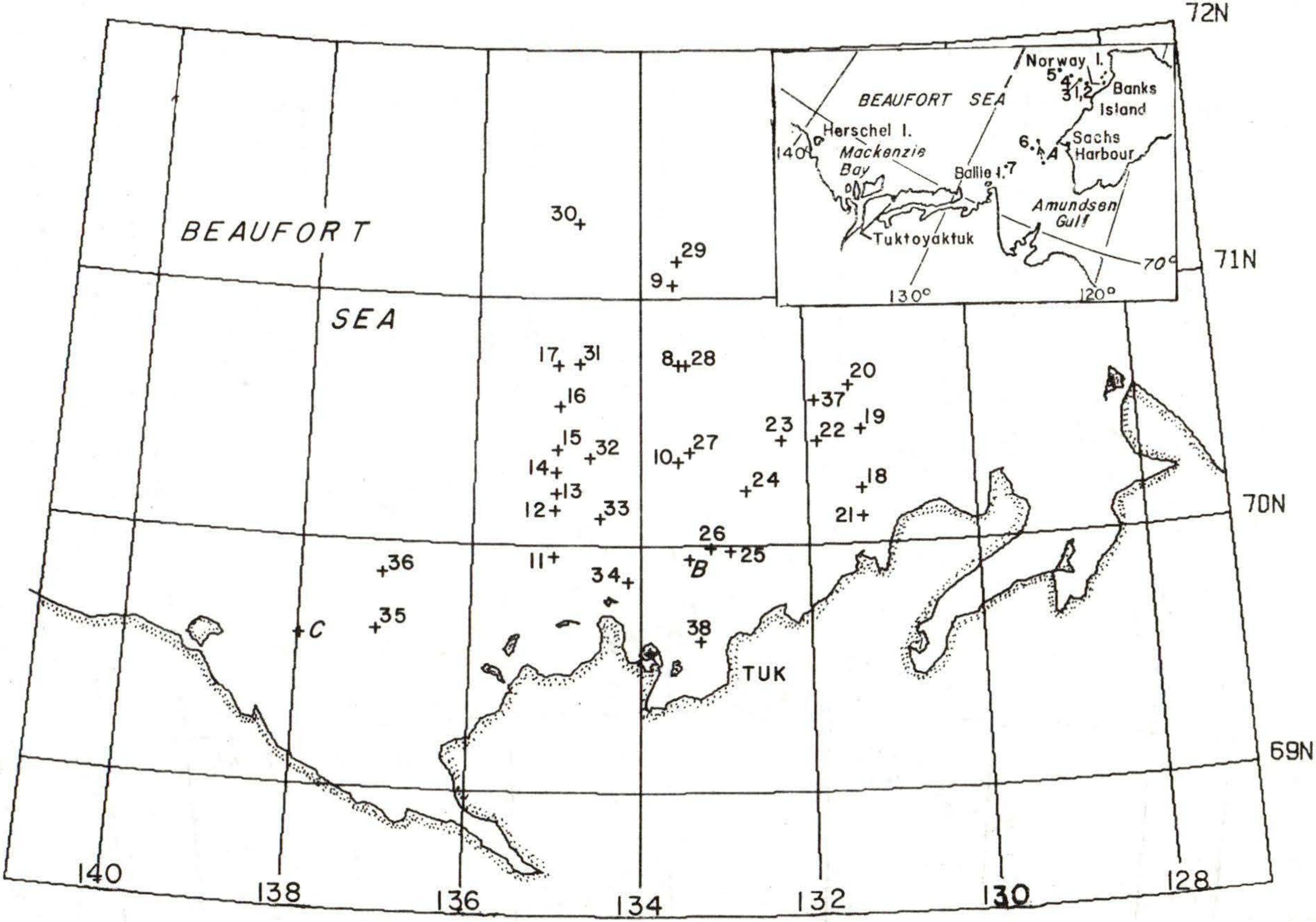

Figure 12. Oceanographic stations, 1975 spring with the ice camps indicated by letters.

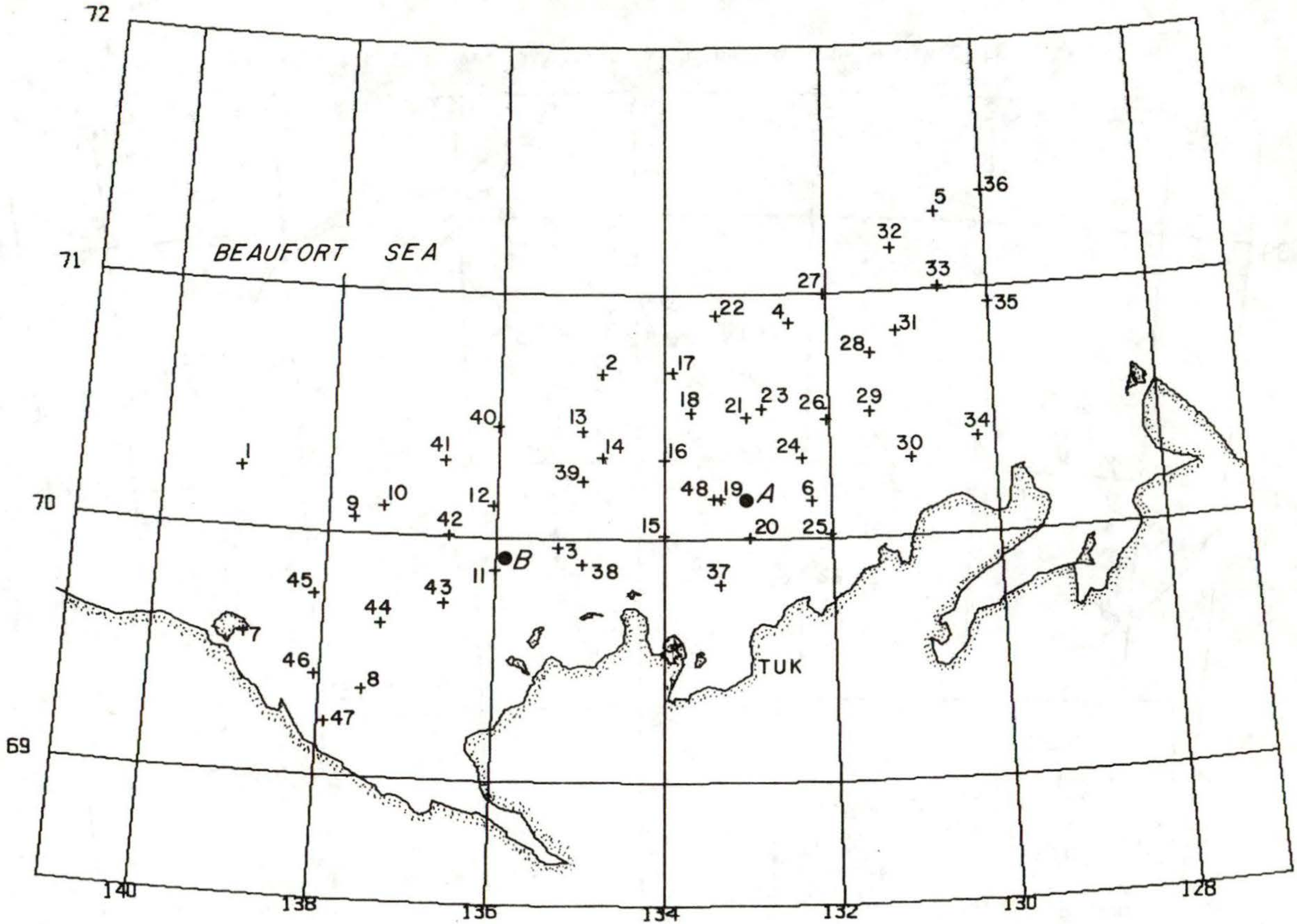

Figure 13. Oceanographic stations, 1975 summer (A indicates position of Canmar barge and B indicates position of wave buoy).

5.2 Data Summary

We intend to publish all data collected during 1974 and 1975 in the following collections:

1) Salinity, temperature, turbidity and meteorological observations in the southern Beaufort Sea - Summer 1974, Spring and Summer 1975.

2) Water movements at surface and at depth observed from recorded ship's drift, ice drift and current meter observations in the southern Beaufort Sea - Summer 1974, Spring and Summer 1975.

3) Wave records in the southern Beaufort Sea - Summer 1974 and Summer 1975.

6. RESULTS

6.1 General Conditions in the Study Area

6.1.1 Summer 1974

The summer of 1974 was characterized by the worst summer ice conditions for ships for 20 years of records in the southeastern Beaufort Sea. As a result, the oceanographic cruise, which was originally planned to extend from Herschel Island to Cape Bathurst and offshore to the edge of the continental shelf was confined to a relatively narrow band of open water along the coast between Herschel Island and Atkinson Point.

From the middle to the end of July the ice front of the multiyear ice lurked near the 10-metre depth contour. By mid-August the front had moved outward in an expanding arc from Herschel Island to 70° north and then into Atkinson Point. By August 19 the ice had returned onshore in some areas. In September it again moved northward; this was followed by a limited southward movement. North of the front there existed large areas of first-year ice, apparently in various states of decay. These ice conditions coincided with a lack of persistent winds from the east and south which usually blow in summer; such winds force the ice offshore to a distance of about 200 km north of Tuktoyaktuk for at least some period in a light ice year. The north-to-west winds held the ice onshore, and as a result restricted the movements of the M.V. Theta, which has little ice-breaking capability. The desired synoptic coverage, which normally could have been obtained in a few days, was not possible because of the ice conditions. Anchoring within the moving multi-year ice was nearly impossible, however, some observations were made; (Figure 11 shows the oceanographic stations occupied). The resulting data are considered to be representative of a heavy ice year.

6.1.2 Spring 1975

The spring of 1975 was characterized by considerable ice movement and by numbers of open leads; easterly winds blowing out of Amundsen Gulf were assumed to be a major factor in bringing about these conditions.

We planned to set up observational ice camps in the early spring on shore-fast ice to the west and southwest of Banks Island. Such ice however, was difficult to find, since large areas of ice off Sachs Harbour was moving as rapidly as 19 km per day. Air temperatures in March dropped to -40°C and constituted an appreciable hindrance to observations; also fuel supplies were low because of the resupply problems encountered during the previous summer. Hence, the extensive observational program originally planned for the western coast of Banks Island was confined to the following: a section of oceanographic stations off Norway Island, a $2\frac{1}{2}$-day time series on drift ice south of Sachs Harbour, and two stations at the mouth of Amundsen Gulf.

During April and May, several ice camps were to be set up on landfast ice between Baillie Island and Herschel Island. Ice, open water and warmer weather resulted in fog which restricted the planned observational program of time series and synoptic coverage. However, two time series were accomplished: one off Kugmallit Bay and one on the western edge of Herschel Canyon (Stations B and C in Figure 12). The synoptic coverage obtained is also shown in Figure 12.

6.1.3 Summer 1975

The summer of 1975 was more favourable than 1974 for shipboard oceanographic work with the sea ice giving little trouble in the survey area. To the north of Tuktoyaktuk the main pack ice remained north of 71°N while off Herschel Island it remained 70°N, allowing the two research ships to work to the edge of the continental shelf. Later in August westerly storms did bring ice further south but it consisted of individual floes which were less troublesome than the polar pack. The surface of the open water became rough during periods of wind.

Better oceanographic coverage was obtained in 1975 than in 1974 despite the late ship's entrance into the working area which was hindered by ice along the north coast of Alaska. A small patch of ice off Pelly Island delayed the mooring of of the wave buoy. CTS casts were taken at 46 stations and a 24-hour time series was also taken at one of the Canmar drill sites* (Figure 13, position A). Waves were recorded successfully at position B in Figure 13.

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* Proposed site for exploratory drilling by the Canadian Marine Drilling Co. in 1976.

6.2 Data Comparisons: Water Properties

6.2.1 Comparison of Oceanographic Observations Taken in the Same General Area but in Different Years

The oceanographic stations were grouped into regions A, B, C and D shown in Figure 8 to best illustrate the differences that can occur from year to year in the same general area. Not all positions were occupied each year, therefore, year to year comparisons cannot be made at all locations. Markham (1975) classified the years 1955 to 1975 into the type of ice years: Good (G), Fair (F), and Poor (P). F.G. Barber (Private communication) classified the year 1951 - 52: Good(G) and Fair (F). The data used here are also classified: 1951 (G), 1952 (F), 1958 (G), 1960 (G), 1970 (G), 1974 (P) and 1975 (G).

Figure 14 shows temperatures and salinities observed at position A (Figure 8) in Mackenzie Bay, where the salinities were the lowest in 1974, but the temperatures were intermediate to those observed in 1951 (the warmest) and 1952, but much closer to those of the latter years. The differences may be linked to upwelling in 1952 which could have occurred because of easterly winds during the sampling periods. Temporarily lower surface temperatures would be expected because of the presence of colder, upwelled subsurface waters.

Figure 15 shows the temperatures and salinities vs depth taken at Position B, northeast of Herschel Island, (Figure 8) during the years 1951, 1952, 1958 and 1974.

The water temperatures vs depth at Position B indicate the year 1974 was the coldest of the four years in which studies took place, and also that there was more fresh water present in the surface layer than was the case during the other three years.

Figure 16 shows that at Position C (Figure 8) north of Richards Island, the salinity profile in 1974 indicates the presence of water with a considerably lower salinity in the upper 10 metres in 1974 than was the case in other years shown. The temperatures were also lower in the surface layer in 1974 than they were in the other years.

Figure 17 shows that at Position D (Figure 8), northeast of Kugmallit Bay, the temperatures were markedly colder, and the salinities lower, in 1974 than in 1952 and 1960

6.2.2 Comparison of Time Series Taken in 1952, 1974 and 1975

Three oceanographic stations (#1, #10 and #65 in Figure 11) were occupied within a common area in Mackenzie Bay over the period August 11 to September 2, 1974; the results are shown in Figure 18. The halocline depth increased somewhat

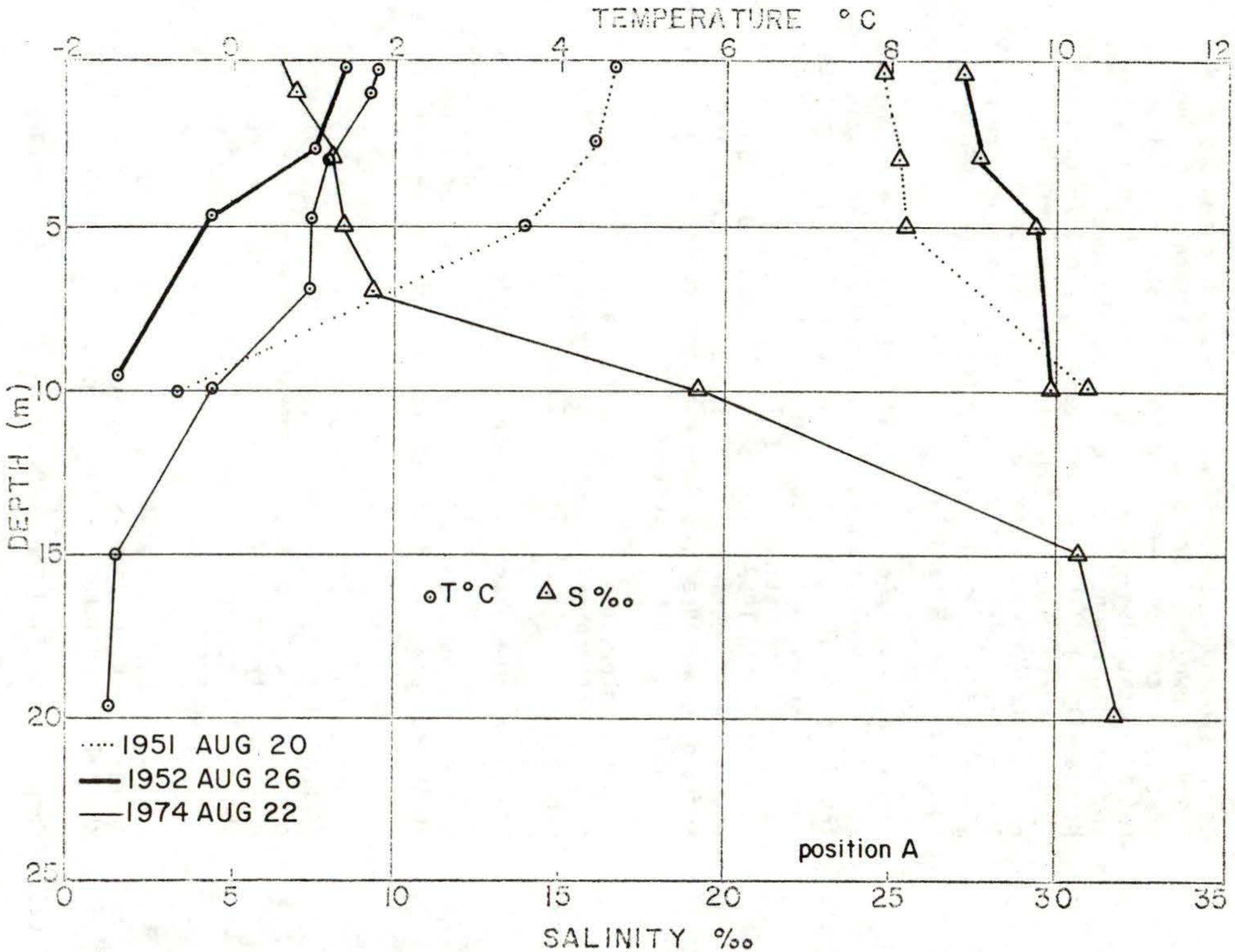


Figure 14. A comparison of vertical profiles of salinity and temperature from various years in region A (see Figure 8).

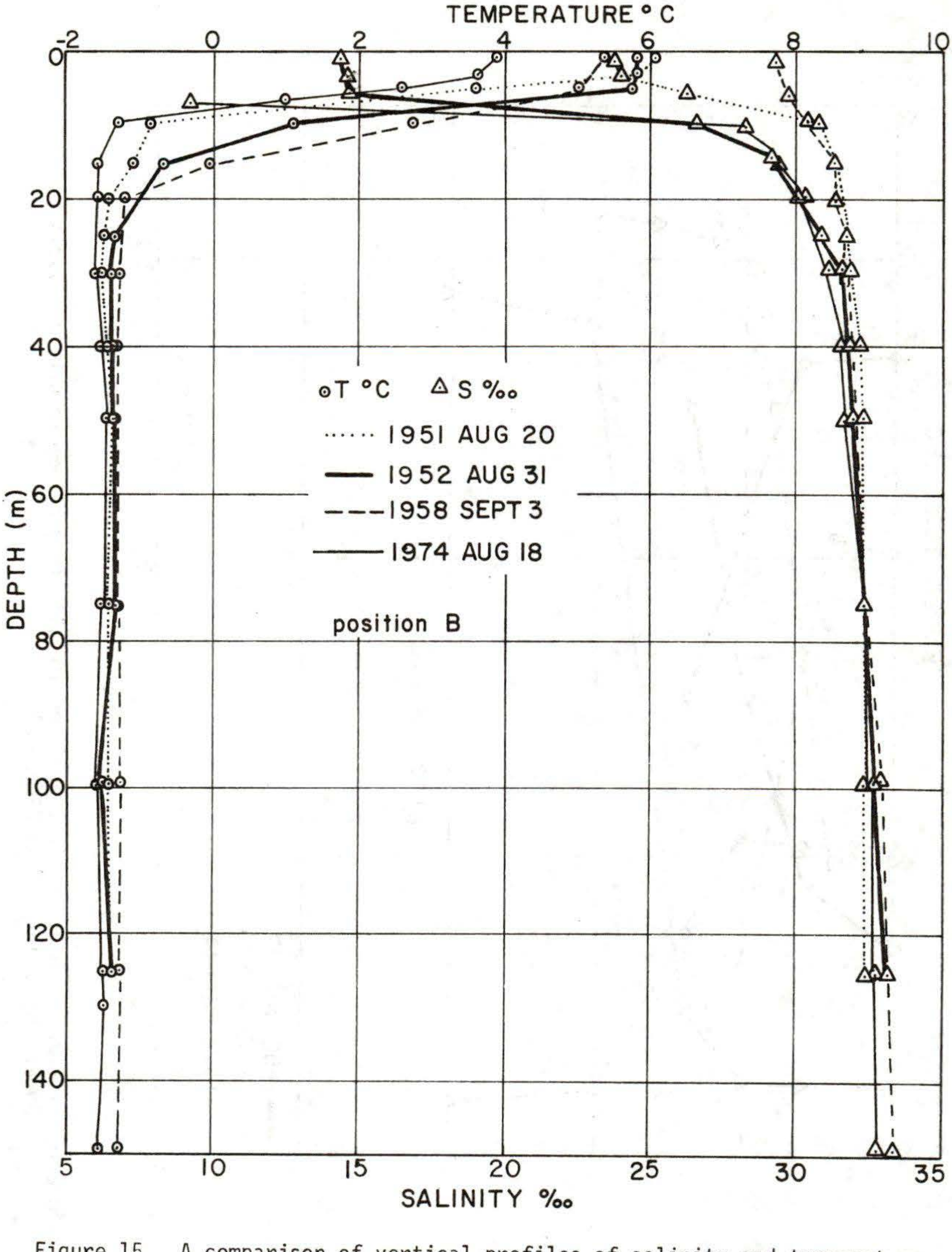


Figure 15. A comparison of vertical profiles of salinity and temperature from various years in region B (see Figure 8).

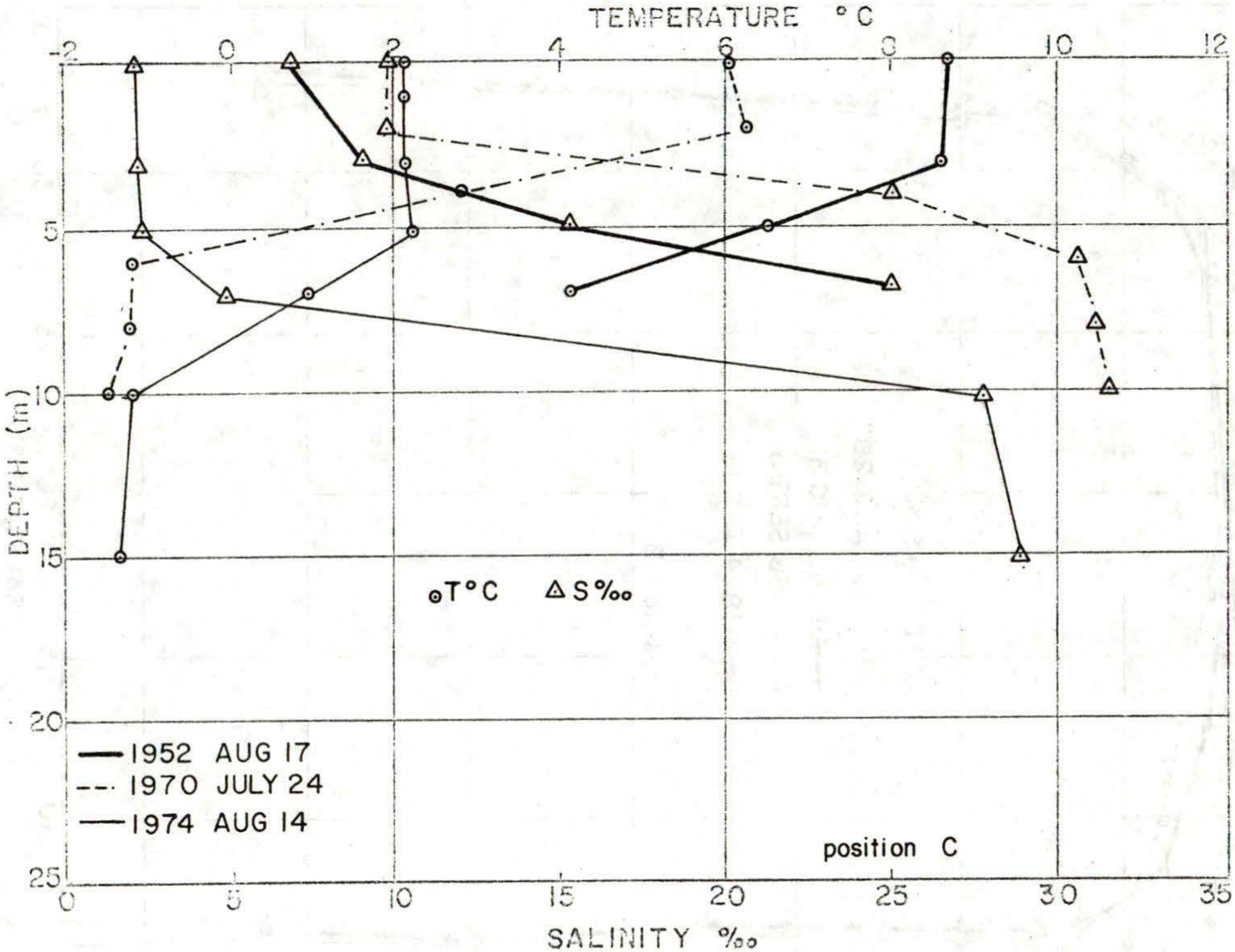


Figure 16. A comparison of vertical profiles of salinity and temperature from various years in region C (see Figure 8).

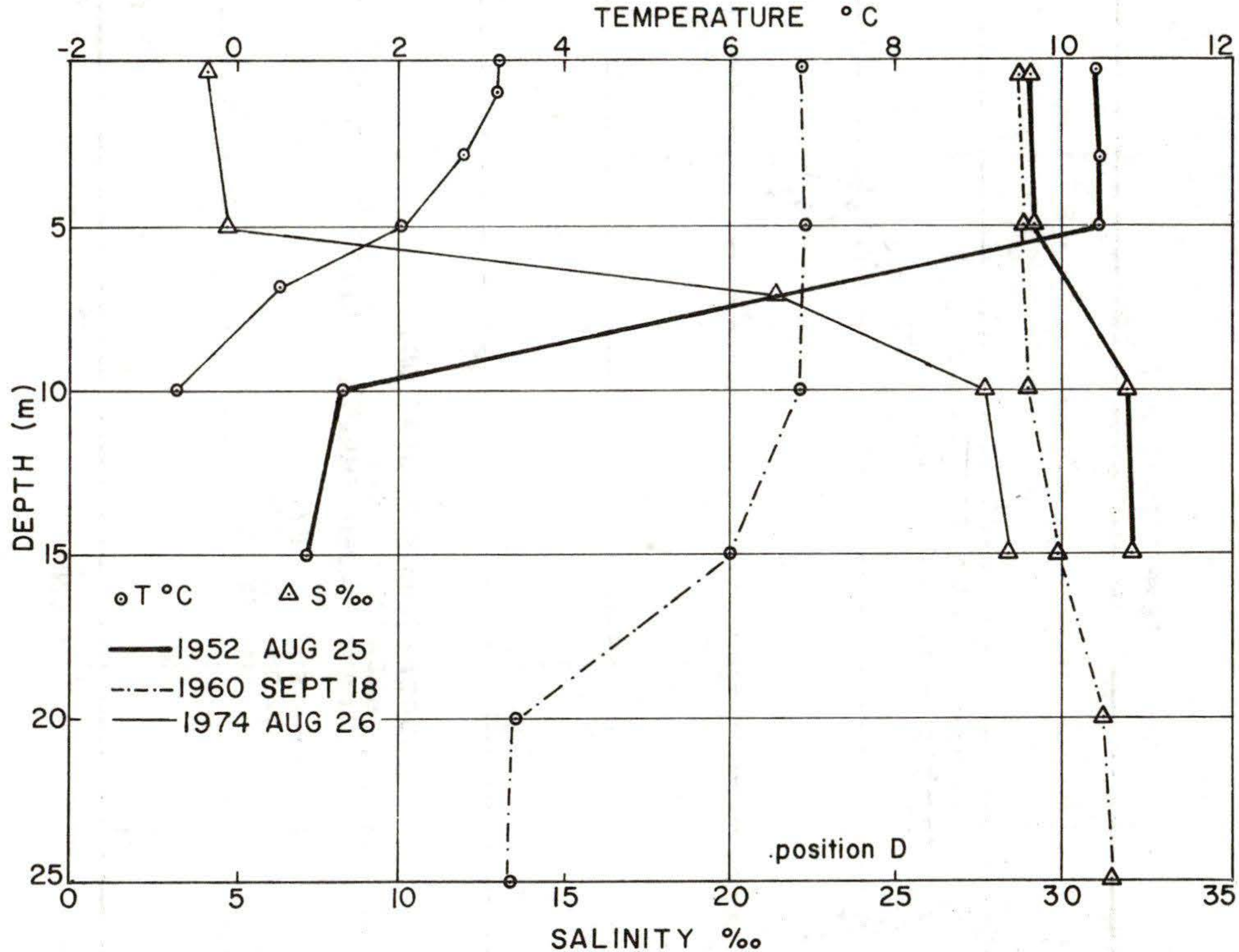


Figure 17. A comparison of vertical profiles of salinity and temperature from various years in Region D (see Figure 8).

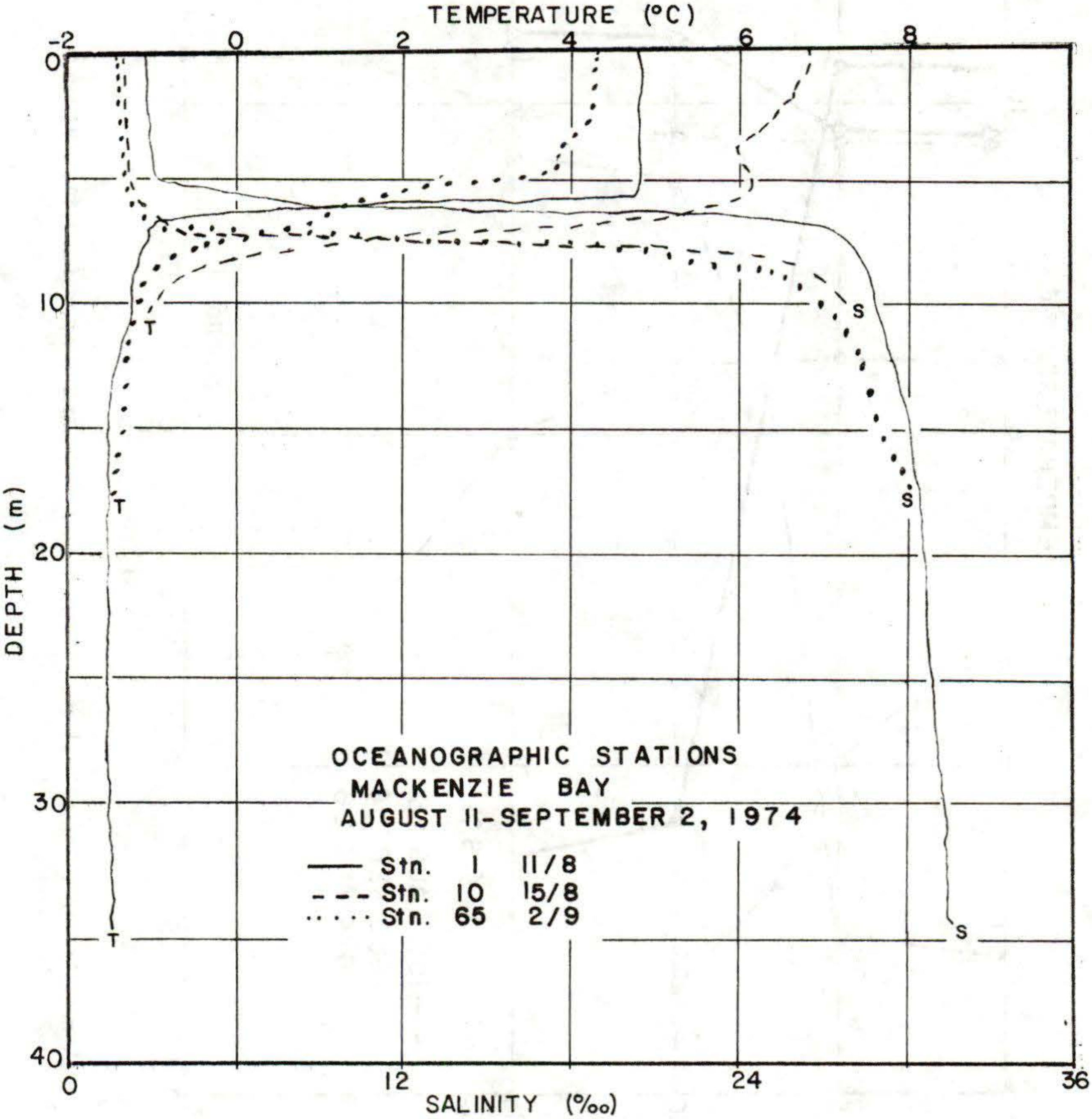


Figure 18. A comparison of vertical profiles of salinity and temperature from Mackenzie Bay over the summer of 1974.

during the period; temperatures were highest in the middle of August but had decreased noticeably by September 2nd. These facts suggest that low-salinity water was still accumulating in the area throughout the observation period, but reached its maximum temperature near the middle of August. Composites of the five available time series are shown in Figures 19, 20 and 21. One series was taken in 1952 from the M.V. Cancolim (Cameron, 1953) and the other in 1974 from M.V. Theta. There is a large difference between the maximum depths sampled in the two cases (15 m vs 60 m); however, it is evident that the surface layer was much fresher in 1974 than in 1952; the ranges of variation in the surface salinity (0.7°/₀₀) was about the same in both years. The range of variation in the surface temperature was between 5.0° and 8.0°C while in 1952 it was slightly less (between 7.0° and 8.3°C).

Composites of the spring 1975 time series (Ice Camps B and C in Figure 12) are shown in Figures 20 and 21. As would be expected, there was far less variation in the surface layer, both in temperature and salinity, during this time than during the summer of 1974, in Figure 19. At times, a less intense halocline was apparent at 40 m below the surface halocline. In some individual salinity profiles this halocline was observed, however it was not noticeable in all areas and was probably associated with intruding subsurface water and the winter halocline.

Time series of salinity and temperature vs depth (hourly profiles) which were taken in the summer of 1974 and in the spring of 1975 indicate that during an hour, temperature changes as great as 0.4°C (summer) or 0.1°C (spring) can take place below the thermocline. Generally, however, the temperature variations are smaller. Similarly, salinity changes of 0.15°/₀₀ (summer) or 0.8°/₀₀ (spring) can take place beneath the halocline during an hour. Generally, the temperature shows less variation as a function of time than does salinity. This presumably can be attributed both to the rather small range differences in temperatures throughout the deeper water and to the larger vertical diffusion rate for temperature.

In the summer of 1975 the time series north of Kugmallit Bay is shown in Figure 20 (bottom). The range of surface salinities was 3.0°/₀₀ with the biggest range of 8.0°/₀₀ at depths of 3 to 4 metres, and smallest range of 1.0°/₀₀ at a depth of 25 metres. The surface temperature ranged over 1.0°C with the greatest range occurring at depths of 7 to 8 metres 2.5°C. Temperature maxima and minima of greater than 1.5°C occurred in the upper 15 metres and are believed associated with subsurface water movements.

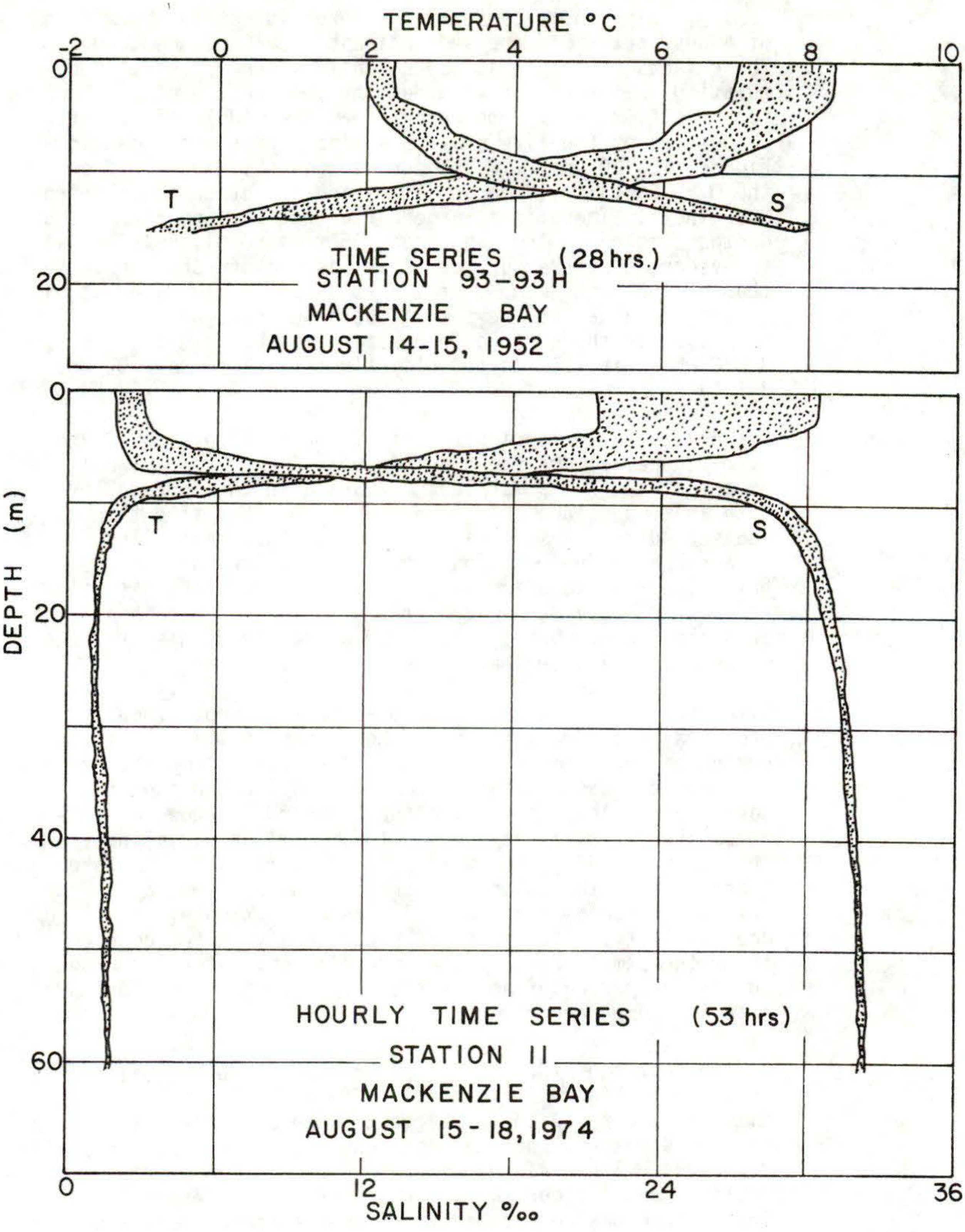


Figure 19. The variation observed in the vertical salinity and temperature profiles in Mackenzie Bay during summer, 1952 and 1974.

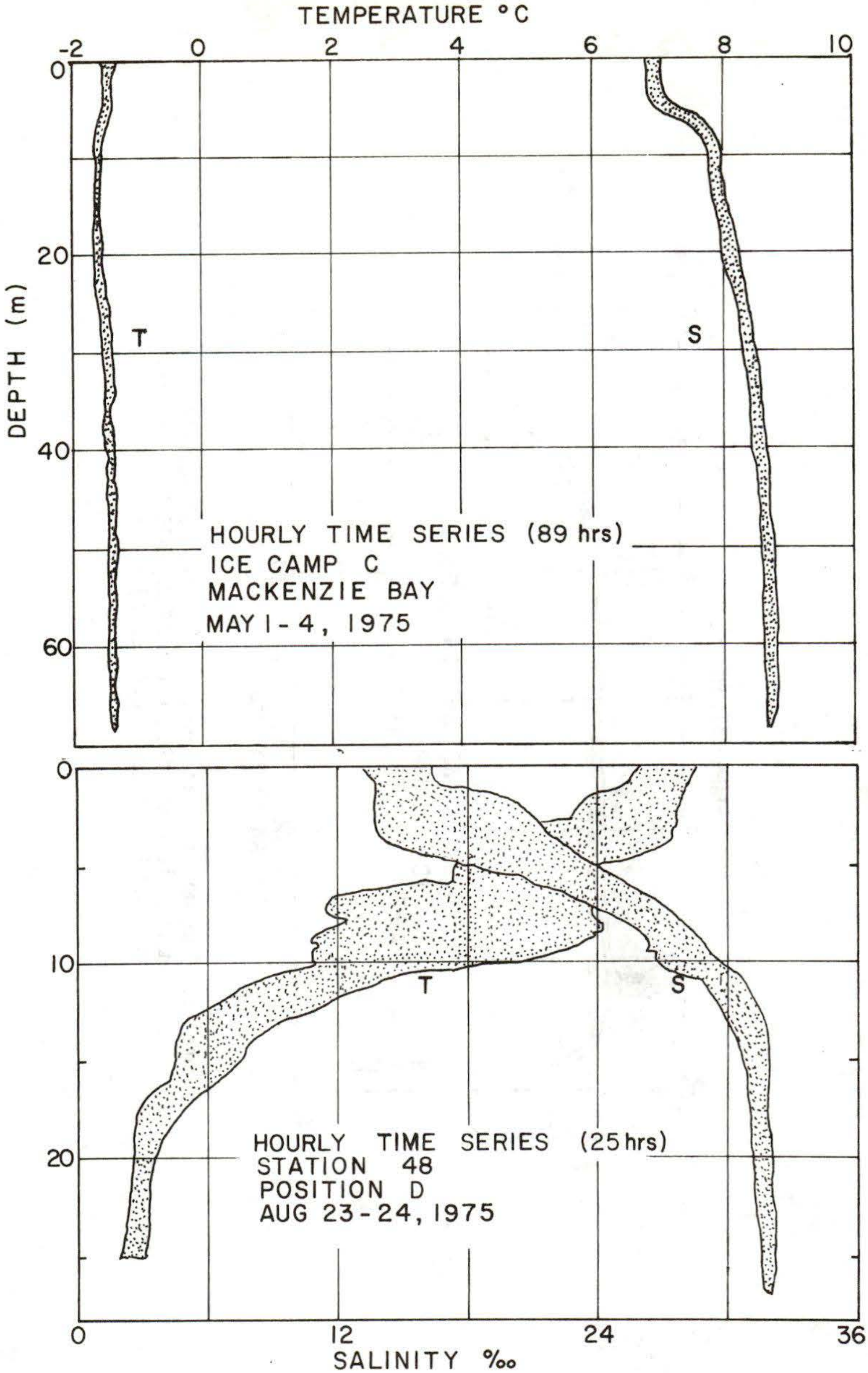


Figure 20. The variation observed in the vertical salinity and temperature profiles: (top) in Mackenzie Bay during the spring, 1975 (ice covered conditions); (bottom) north of Kugmallit Bay during summer, 1975 (open water).

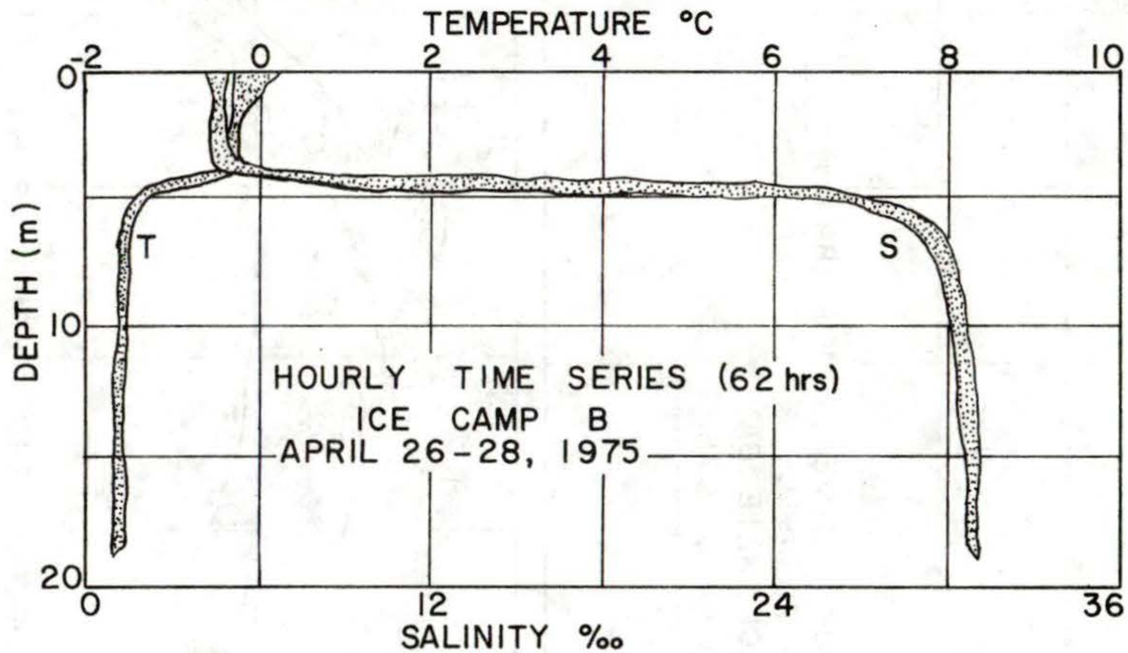


Figure 21. The variation observed in the vertical salinity and temperature profiles north of Kugmallit Bay during spring, 1975 (ice covered conditions).

6.2.3 Comparison of Vertical Cross Sections of Salinity and Temperature from Different Years

The vertical cross-sections of temperature and salinity shown in Figure 22 were taken during summer in 1951, 1952 and 1974. It is quite evident from these sections that conditions in the summer of 1974 were marked by a large volume of low-salinity water in the surface layer. The temperature sections also support the conclusion presented earlier that the temperatures were below those recorded during the earlier years.

6.2.4 Comparison of Vertical Sections of Turbidity in Various Areas of the Delta

Turbidity data taken in 1974 are shown in Figures 23 and 24 as vertical sections offshore. The section of Figure 23 runs offshore from Atkinson Point; that of Figure 24 is in two parts, both at the edge of Herschel Canyon. The sections have one common feature; a very turbid surface layer underlain by much clearer water. Off Atkinson Point (Figure 23) there was an appreciable increase in turbidity near the bottom; however at the edge of Herschel Canyon, (Figure 24), the turbidity increased only very slightly.

In spring 1975 the turbidity was again investigated to determine how much (if any) it had changed over the preceding summer. Figure 25 shows that the data from two summer 1974 stations, as well as those from two spring 1975 stations near the earlier ones. The turbidity had definitely lessened during the intervening period but the same general pattern is still evident; a turbid layer at the surface and a turbid layer near the bottom, with relatively clear water in between.

6.2.5 Heat Storage in the Upper Layer

The heat content was determined for the portion of the water column above the depth of the temperature minimum. The reference temperature used for each year was the lowest temperature encountered in the temperature-minimum layer beneath the thermocline. The calculated heat thus provides a measure of the heat gained by the water column since the formation of the minimum temperature during the previous winter.

Barber (1968) reports an estimated net heat content of the surface layer of 9.4 kg cal/cm^2 for the end of July 1963 in Tuktoyaktuk Harbour, decreasing to 2.5 kg cal/cm^2 by the following September 15. He used a reference temperature of 0.0°C because of the large amount of fresh water in the harbour.

During the summer of 1974, the greatest heat content observed during the time series taken occurred at Station 11 (Figure 11) in Mackenzie Bay - a value of 6.5 kg cal/cm^2 for August 17th.

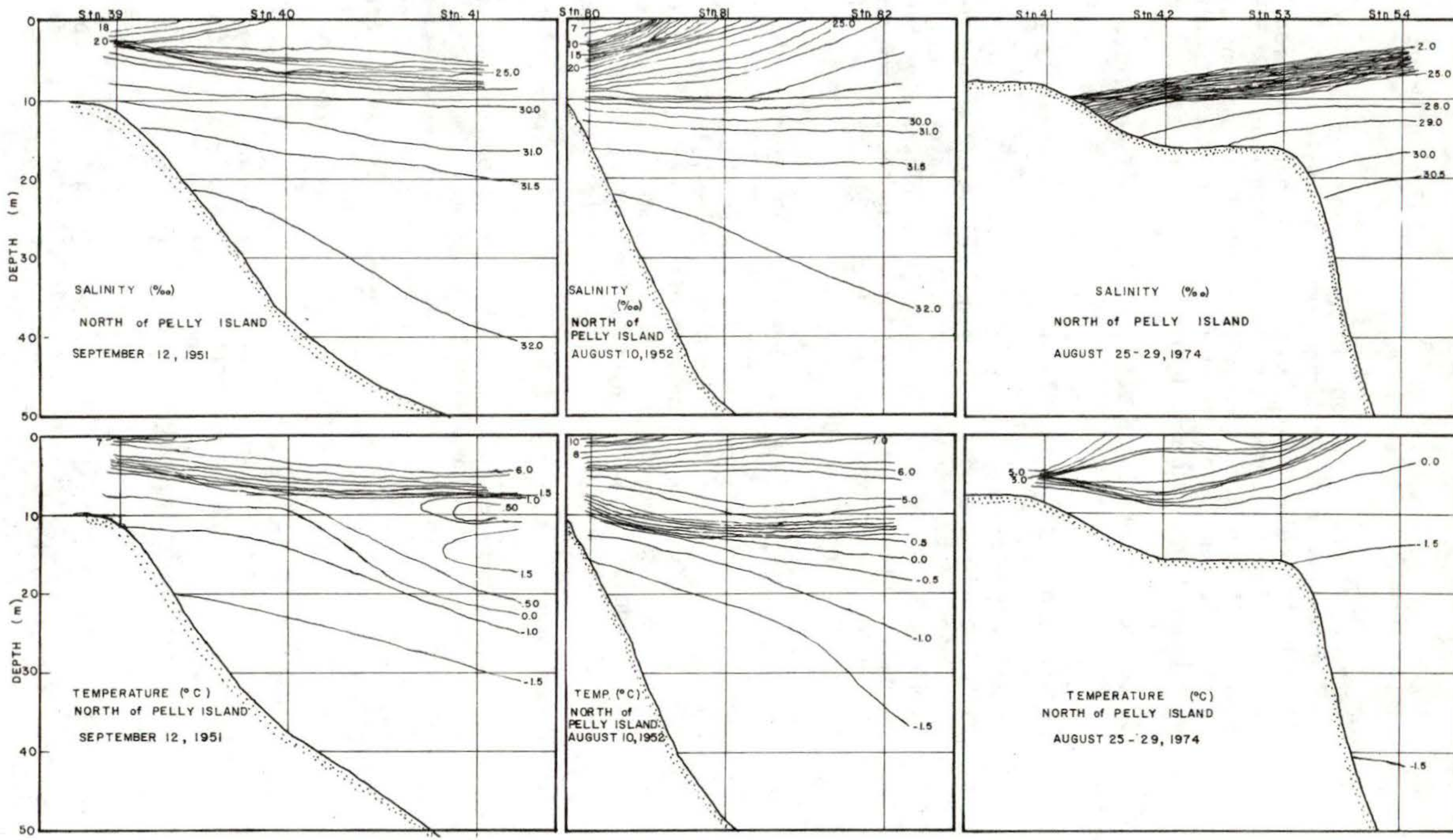


Figure 22. Vertical cross-sections of temperature (°C) and salinity (°/₀₀) north of Pelly Island during summer in 1951, 1952 and 1974.

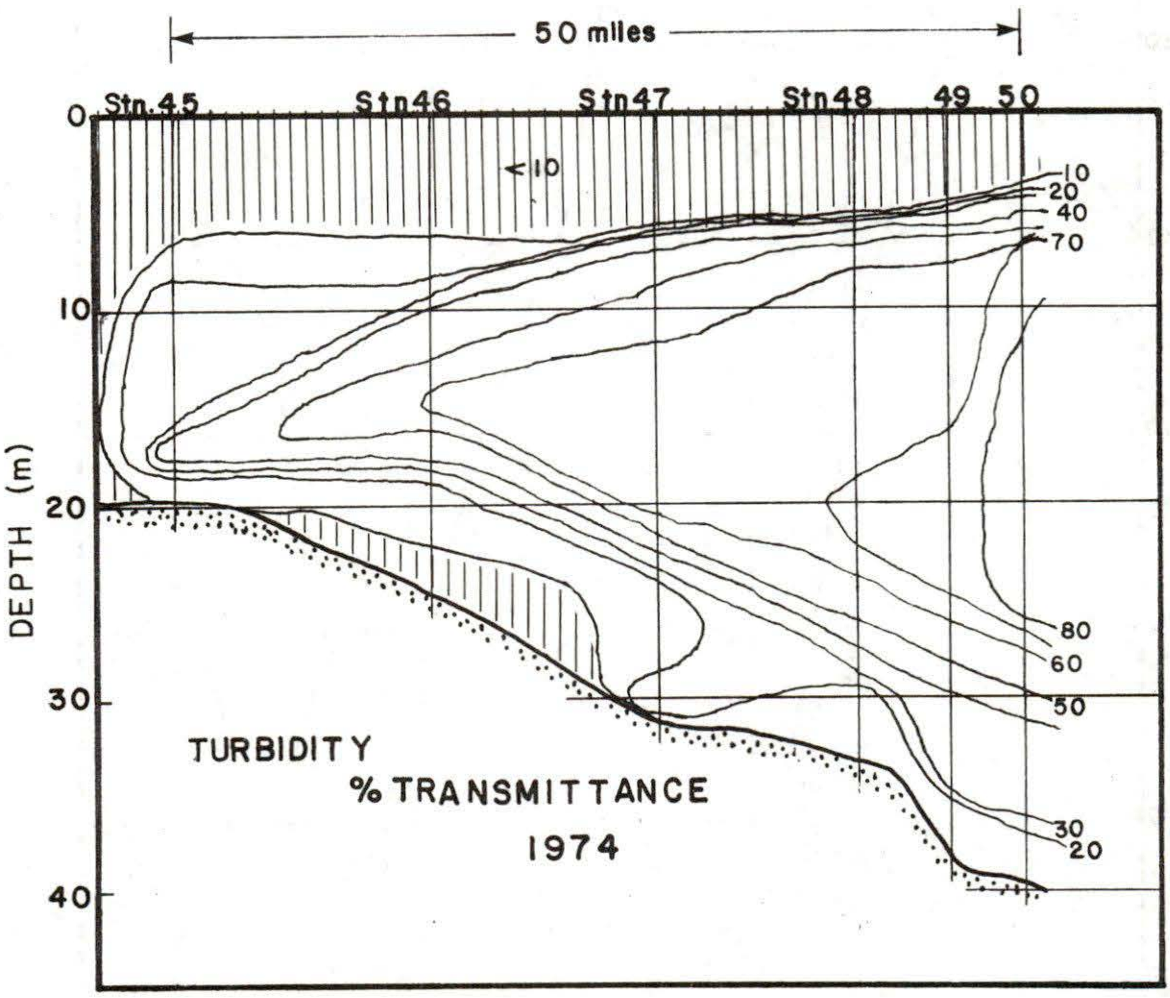


Figure 23. Vertical cross-section of turbidity north of Atkinson Point, summer 1974.

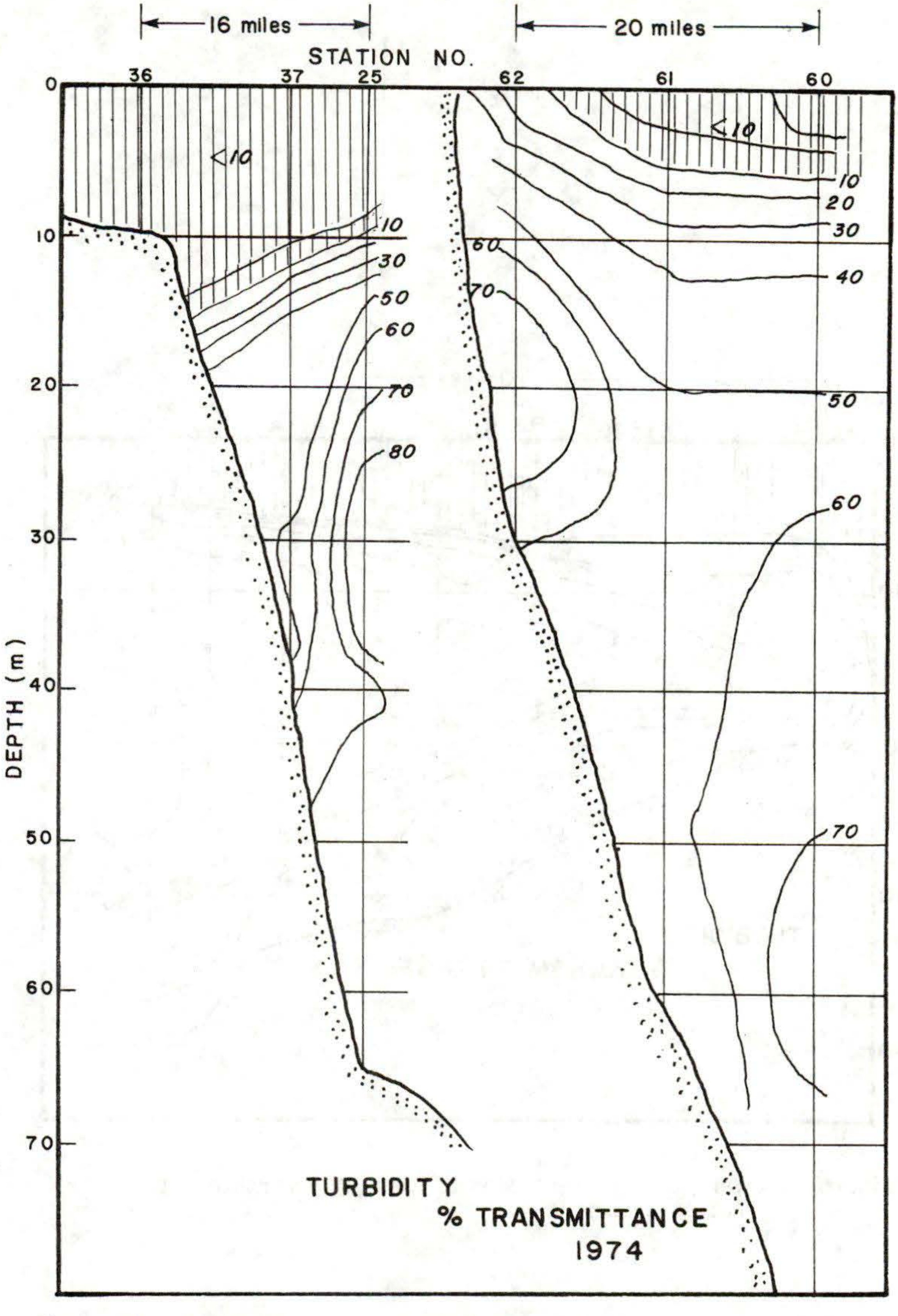


Figure 24. Vertical cross-sections of turbidity in Herschel Canyon area, summer 1974.

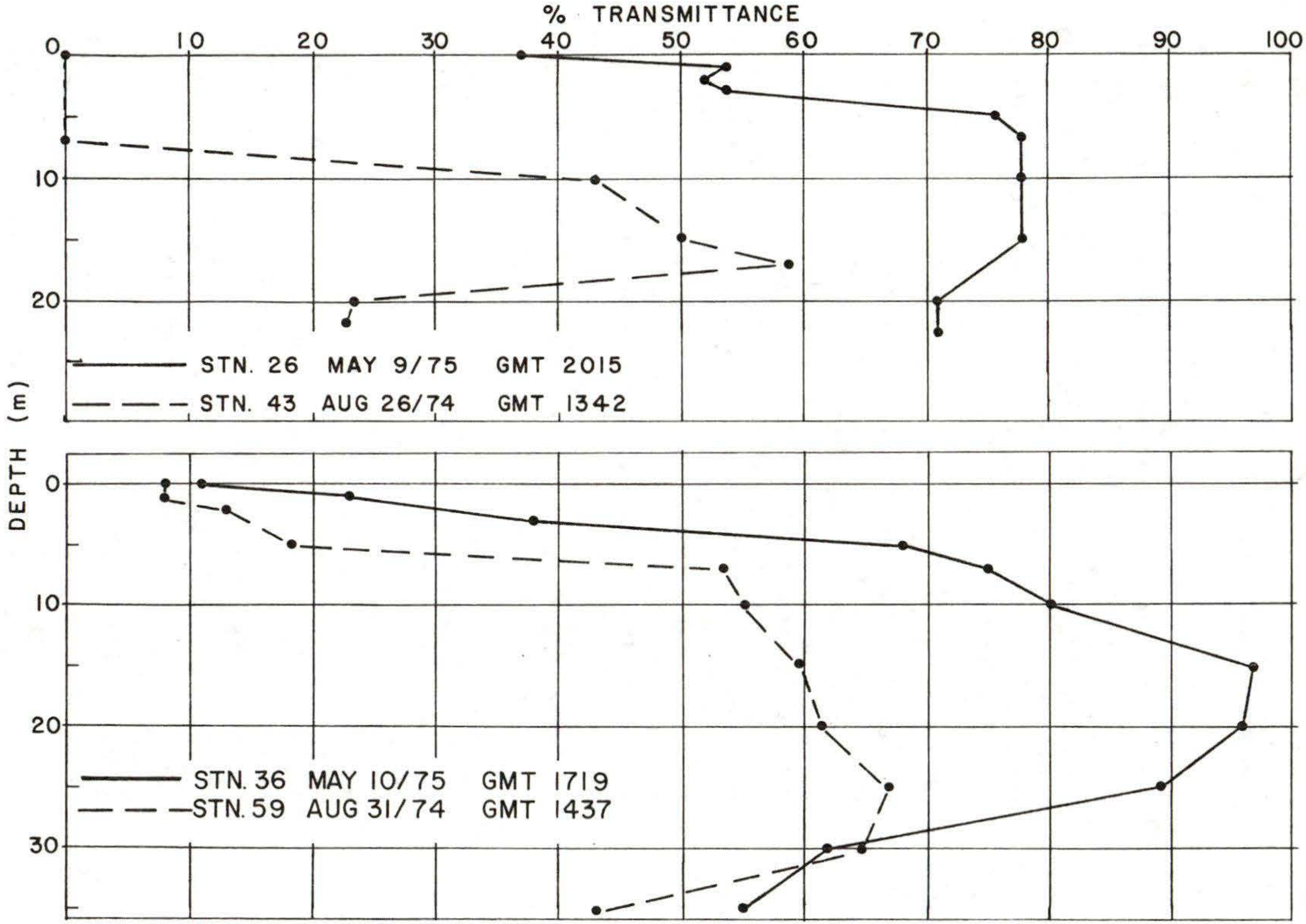


Figure 25. A comparison of spring and summer water transparency (turbidity) profiles.

The minimum heat content recorded at this station was 4.9 kg cal/cm^2 on August 16th. These values were calculated using a reference temperature of -1.68°C. The lower heat content in 1974 compared to that in 1963 was probably due to the presence, in 1974, both of cooler weather and of ice nearby.

As we expected there was less heat present in the spring of 1975. At Ice Camp B, in Kugmallit Bay (Figure 12) the heat content was 0.60 kg cal/cm^2 and 0.95 kg cal/cm^2 respectively relative to -1.71°C, the previous winter's minimum. Minimum and maximum heat content at Camp C were 0.19 kg cal/cm^2 and 0.41 kg cal/cm^2, using the same reference temperature. The greater heat at Camp B can be attributed to the presence of the fresh water from the Mackenzie River outflow, which was not present at Camp C.

6.2.6 Horizontal Distribution of Surface Salinities

Figures 26 and 27 show the surface salinities and polar ice-pack boundary during two periods in 1952 (characterized by east and west winds respectively), the summer of 1974, and the spring of 1975. During easterly winds (e.g. 1952) the high salinities experienced along the coast are presumed due to upwelling conditions (Cameron, 1953). Salinities during the other periods were lowest along the coast, increasing to seaward. The surface distribution of salinity indicates that if the pack ice is offshore, low-salinity water from the Mackenzie River generally moves to the east as a definite stream. If the pack ice is confined near the shore as it was in the summer of 1974, the river flow is confined and low-salinity surface water is seen to accumulate over the Mackenzie River Delta area. The absence of marked longitudinal flow is shown by the surface salinity distribution.

The surface distribution of Figures 26 and 27 also indicate, the degree to which the low-salinity water moves to the west with easterly winds. It proceeds from Shallow Bay as a tongue of muddy water. As the wind diminishes, and possibly swings to the northwest, the tongue will double back towards the delta. During light westerly winds, the recent low-salinity surface water moving out of Shallow Bay will turn to the east. Another surface feature which is markedly evident in Figure 26A is the bulge of low-salinity water situated northwest of Richards Island. This feature probably results from the high percentage of Mackenzie River water moving north through the islands in that vicinity. We can visualize this bulge taking on the features of a finger which can curve to the west or to the east depending upon wind direction at the time. The highest-salinity water intrudes into Mackenzie Bay via the Herschel Trench and into Kugmallit Bay. These high-salinity areas are a common feature and are believed to be associated with convergences in which the high-salinity water meets, and underrides the lighter low-salinity water. If any ice is in the same general area, it usually accompanies

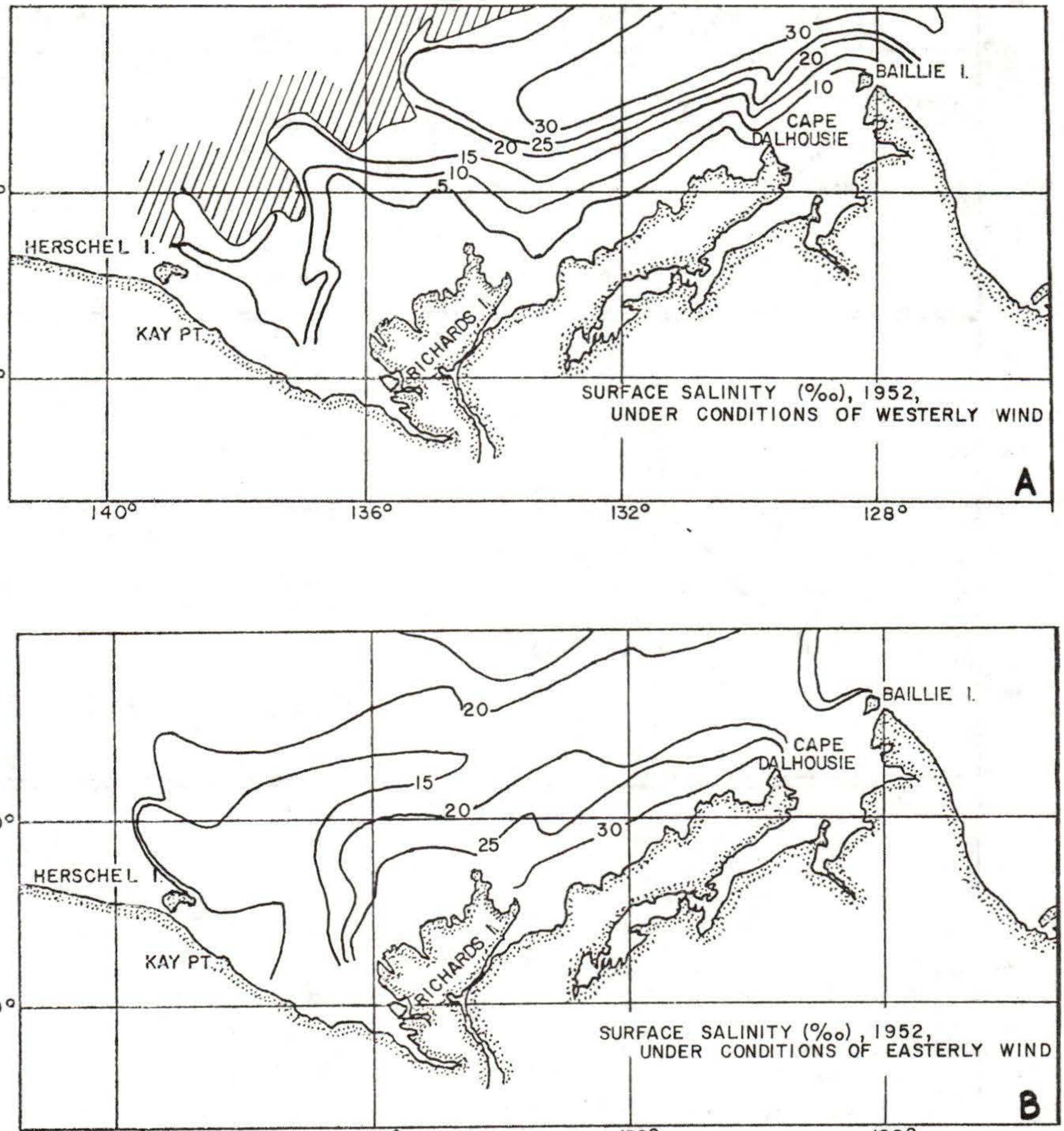


Figure 26. A comparison of surface salinity and polar pack (shaded) boundaries under conditions of easterly and westerly winds, summer 1952 (after Cameron, 1953).

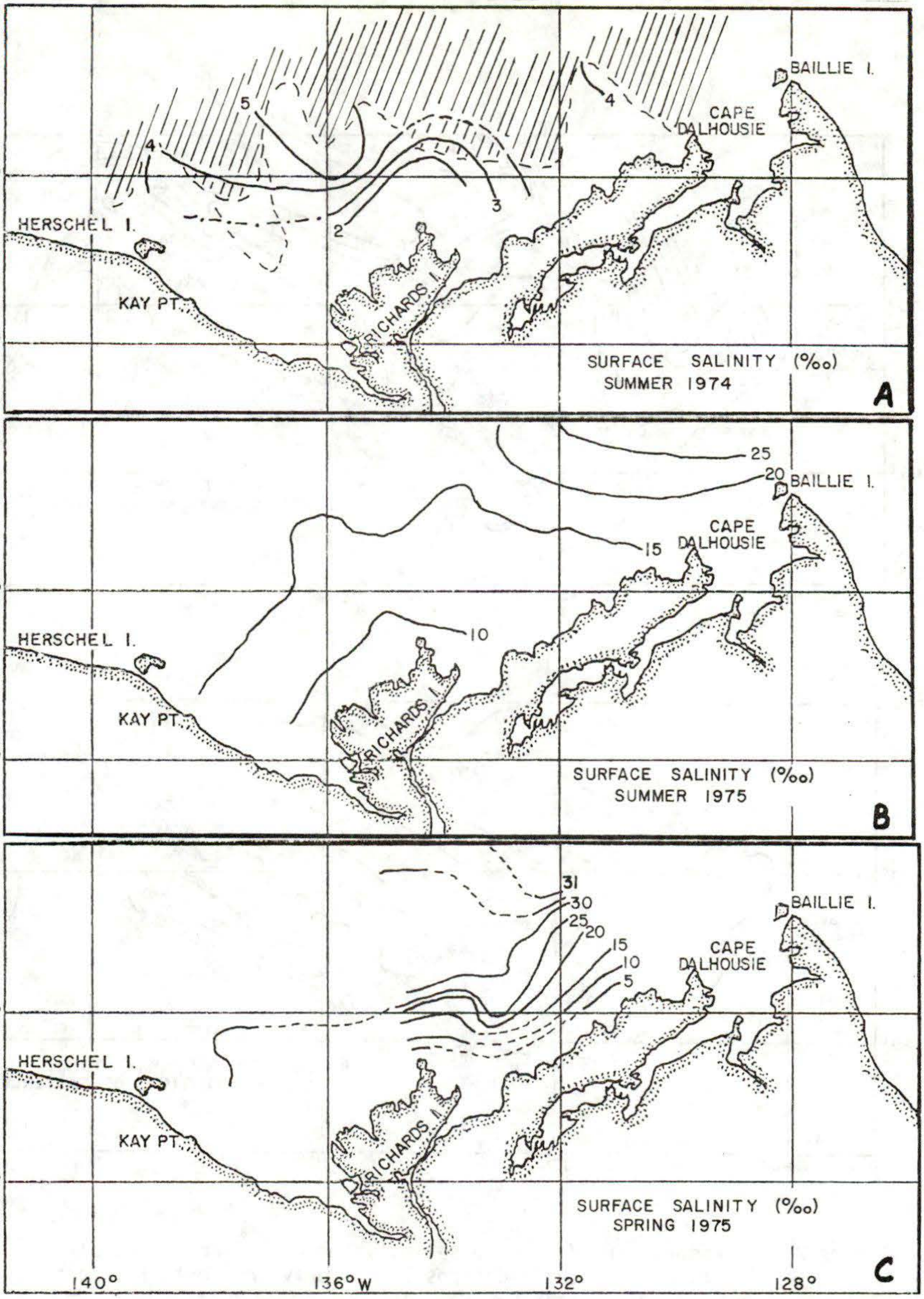


Figure 27. The distribution of surface salinity: (a) summer 1974 with pack ice shaded; (b) summer 1975 with open water; and (c) spring 1975 with mainly ice covered conditions.

the high-salinity zones, and can join long trailing fingers or tongues at the juncture of lower- or higher-salinity water. However, this effect does not always occur in the case of the deepest-draught ice. Some of these features are illustrated as satellite imagery which is discussed in a later section. Both Kugmallit and Mackenzie Bays often have high concentrations of broken ice in the form of fingers or tongues; these are assumed to be associated with the intruding high-salinity water. This high-salinity water in both areas is assumed to be partly related to the estuarine mechanism's demand for saline water to replace that mixed into the surface brackish water which escapes offshore and eastward. It is also probably due in some degree to periodic upwelling resulting from offshore winds which can persist for a time after the offshore winds have ceased or even changed to the onshore variety.

6.3 Data Comparisons: Water and Ice Motion

6.3.1 Surface Drift Measurements

The M.V. Theta was allowed to drift with the ice in the summer of 1974 during the silent hours and when the ship was in fog. Some examples of the drift records obtained are shown in Figures 28 and 29. Generally, winds accompanied surface drift; however, the stronger winds did not always accompany the faster drifts. For example, during August 12 the winds were light westerly (under 18 km/h), the recorded drift varied from 36 cm/sec to over 50 cm/sec. However, on August 29 and September 3 the winds were much stronger than those just noted, but the corresponding drift speed was appreciably slower. The discrepancies result from the fact that the surface drift can be a function of a number of variables such as wind, prevailing current, and ice conditions, whose effects are not easily separable. However, it does illustrate that the ship's surface motion was influenced to some degree by the wind.

During the spring of 1975 radio beacons were placed on the ice off Kugmallit Bay and their positions fixed by Decca. Five beacons were set out; two did not move, having definitely been placed on landfast ice. The other three moved to the west during most of the time they were tracked, as shown in Figure 30. Open leads were present about a half mile north of the beacon in landfast ice at the second position (which was also the location of Ice Camp B). Current measurements from the ice to the bottom were carried out at this location and will be discussed later. Also during the spring an ice camp was located off Sachs Harbour, Banks Island, on moving pack ice; movement of the ice on which it was located is shown in Figure 31.

6.3.2 Vertical Current Profiles in the Summer of 1974

Two profiles on current velocity were obtained with the Savonius Rotor current meter at Station 11 (Figure 11) before

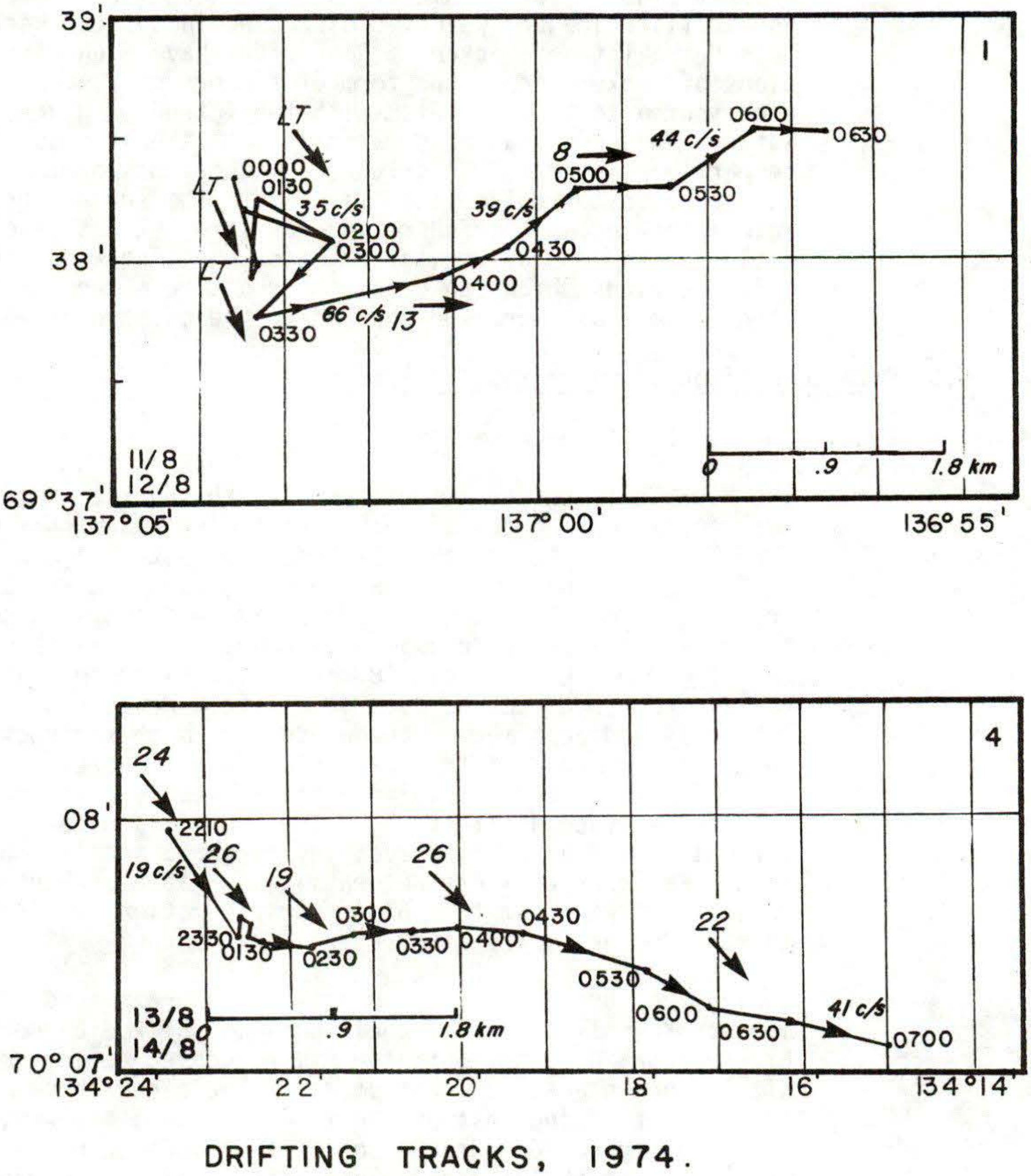


Figure 28. Examples of the recorded ship's drift in the ice during summer 1974 with arrows indicating the wind velocity in km/hr.

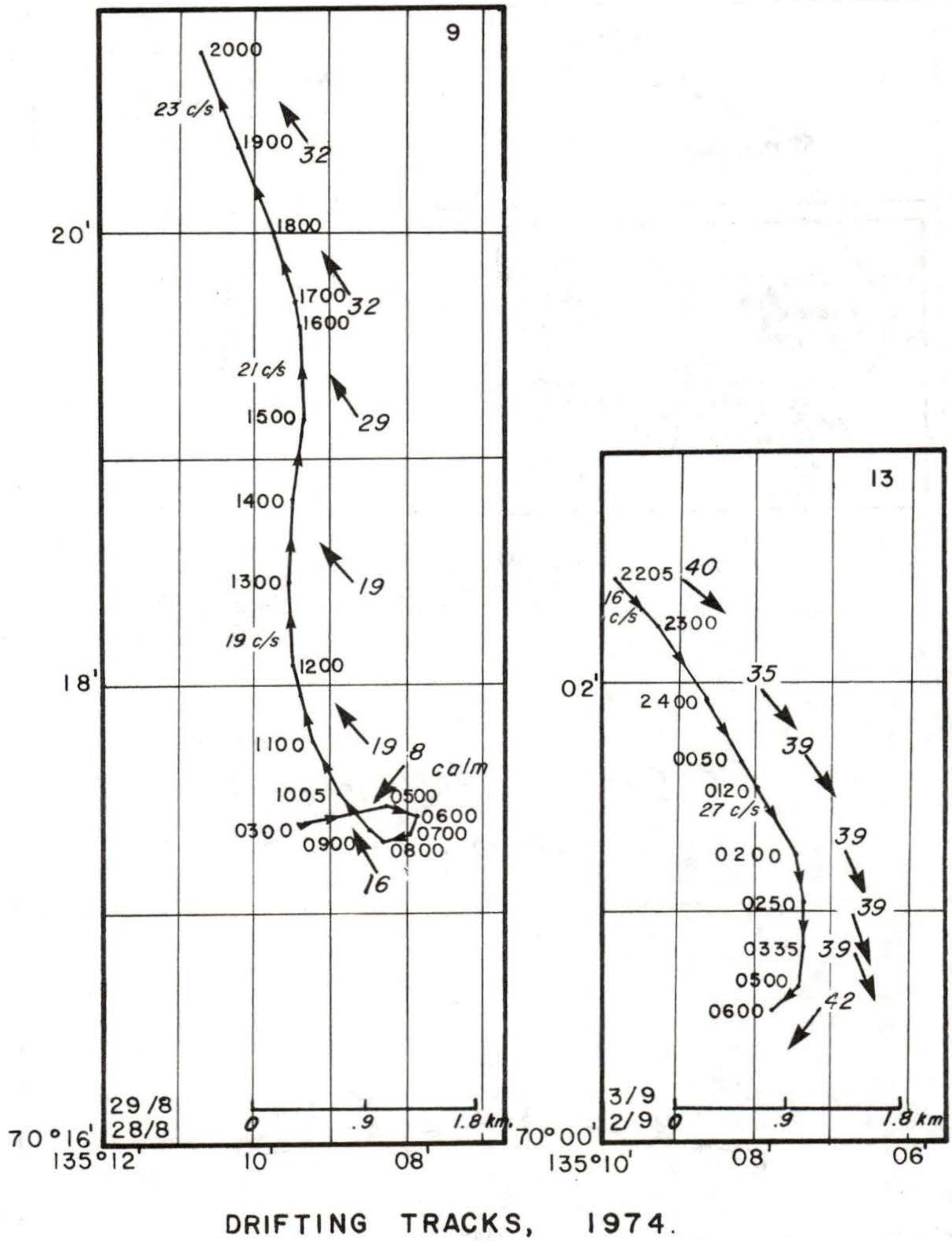


Figure 29. Examples of the recorded ship's drift in the ice during summer 1974 with arrows indicating wind velocity in km/hr.

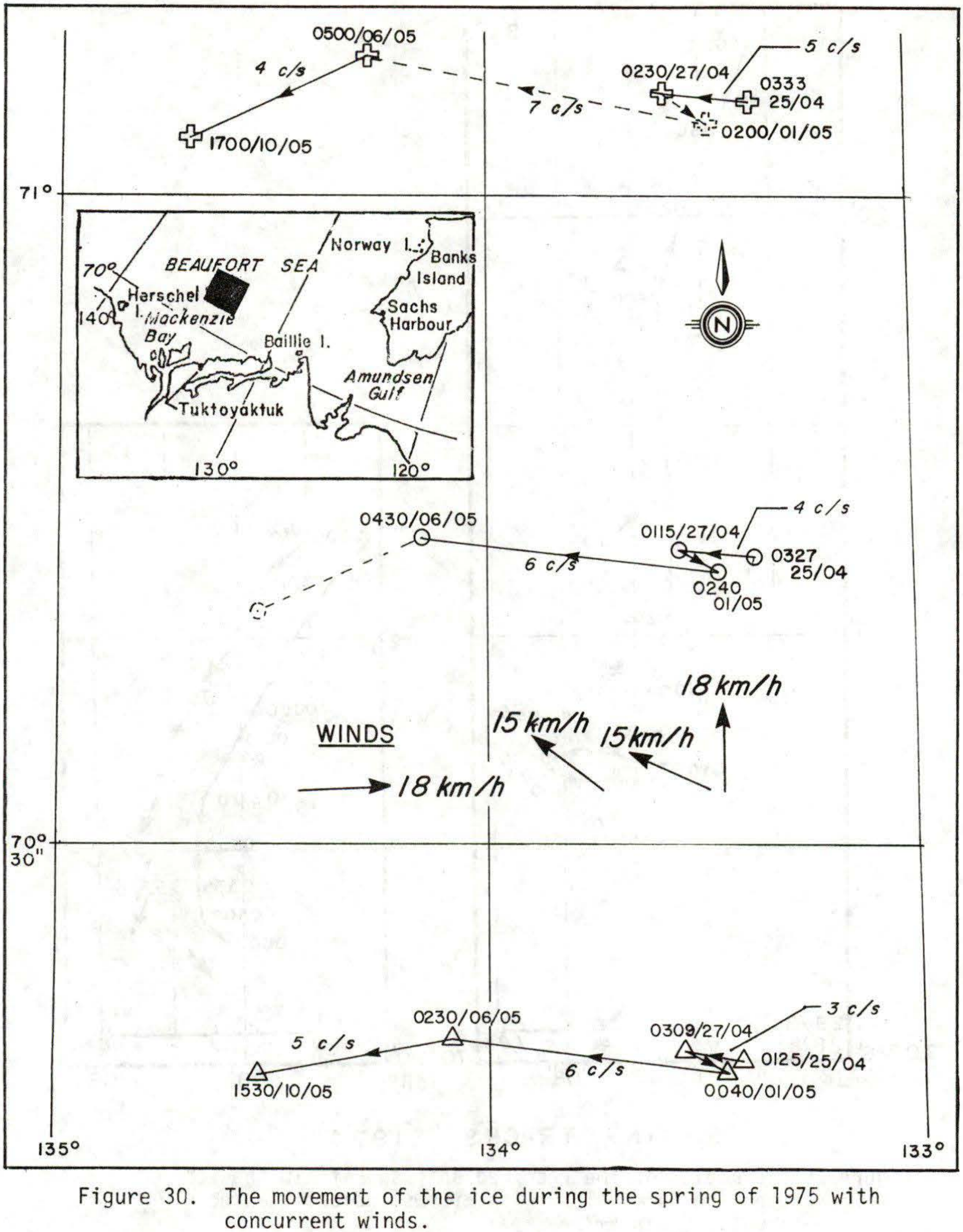


Figure 30. The movement of the ice during the spring of 1975 with concurrent winds.

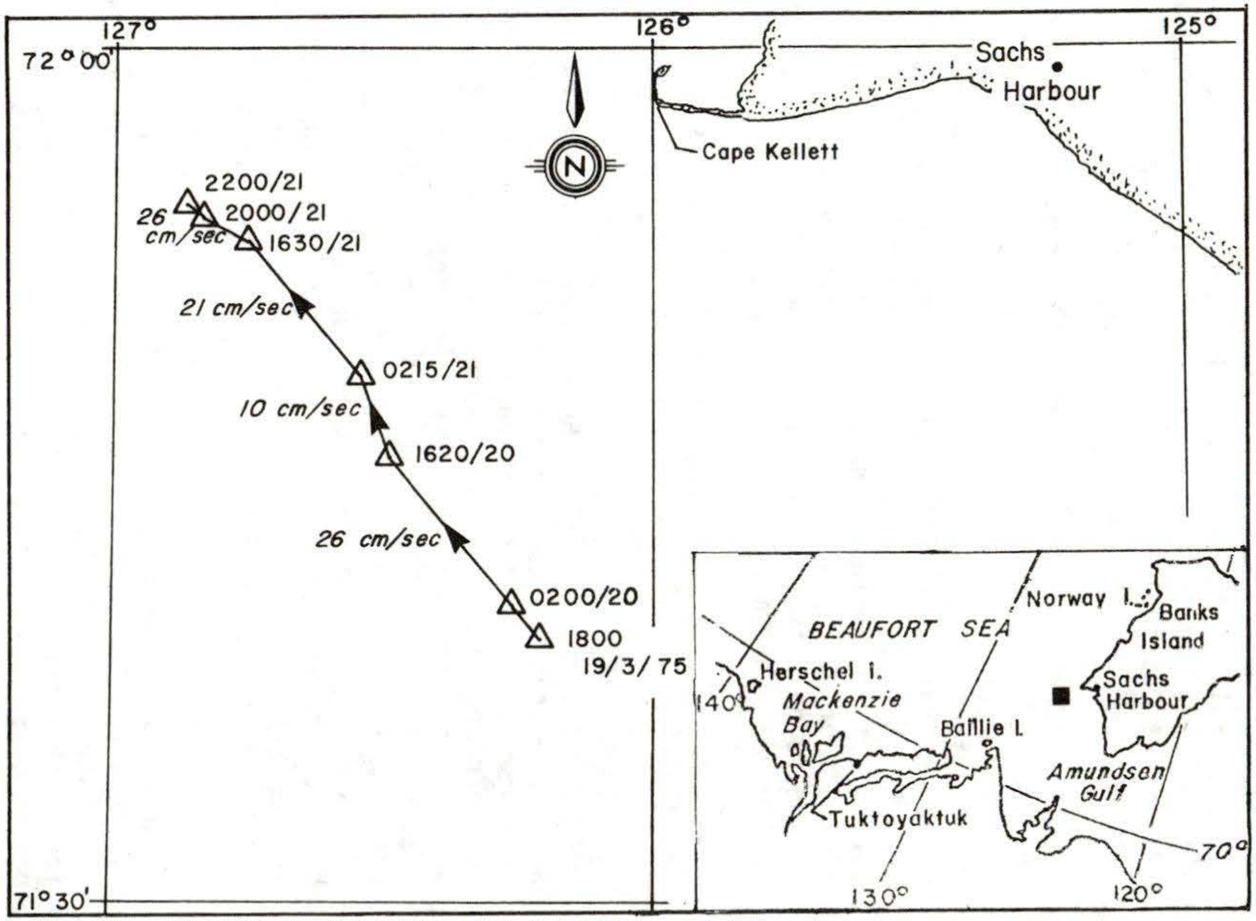


Figure 31. The movement of Ice Camp A during the spring of 1975.

meter malfunctioned. Figure 32 shows the variations in current direction and speed with depth. The first profile shows that the maximum currents of approximately 25 cm/sec were recorded at the surface, while the smallest of approximately 5 cm/sec were found at mid-depths (20 m); values increased to just over 10 cm/sec near the bottom (60 m). The general flow direction in the column was to the northwest. One hour later at the same position the surface current had decreased to 13 cm/sec, still to the northwest; however, the mid-depth current (below 15 m) had turned to the southeast, while below 40 m the motion was apparently to the east. This represents an anticlockwise change in direction with depth.

The third current profile of the 1974 season (Figure 32) was obtained at Station 54 and was recorded as the ship drifted with the ice field. The effect of the ship's motion was removed from the current data and the result plotted. There was a net motion just north of east for the whole water column. Surface currents averaged about 13 cm/sec with a minimum at 7 m depth (pycnocline depth). The maximum current recorded of 23 cm/sec occured at a depth of 40 m. It is interesting to note that a dominant easterly flow is also indicated by the near-bottom current measurements of Huggett (1975).

6.3.3 Time Series Taken in 1975 off Kugmallit Bay and in Herschel Canyon

Time series of current profiles were obtained during the spring and summer of 1975. Hourly observations of profiles were made from an ice camp off Kugmallit Bay and were resolved into WE and NS components. The summer data have not yet been analyzed, however, examples of the results obtained during the spring are shown as progressive current vector diagrams in Figures 33 to 35; and as hourly current vs depth profiles in Figure 36. The currents were strongest at mid-depths and decreased both towards the surface (ice) and the bottom. The mid-depth currents were rotary tidal with a maximum speed of about 13 cm/sec. A net movement to the north and east is indicated by the progressive vector plots.

In contrast, in the spring of 1975, time series east of Herschel Canyon in Mackenzie Bay (Figures 37 to 41) indicate little tidal influence. A net northerly offshore movement was observed at all depths; speeds were least just under the ice, with a secondary minimum at 10 m. Measurements could not be carried out to the bottom because of a short cable. It can be seen that there was a reversal of flow at mid-depths (20 m) before midnight of May 1 (Figure 39). This was reflected in a simultaneous reduction in the offshore movement at deeper levels. It is possible this effect may be the result of changes in air-pressure gradients since no obvious correlation with local winds was evident.

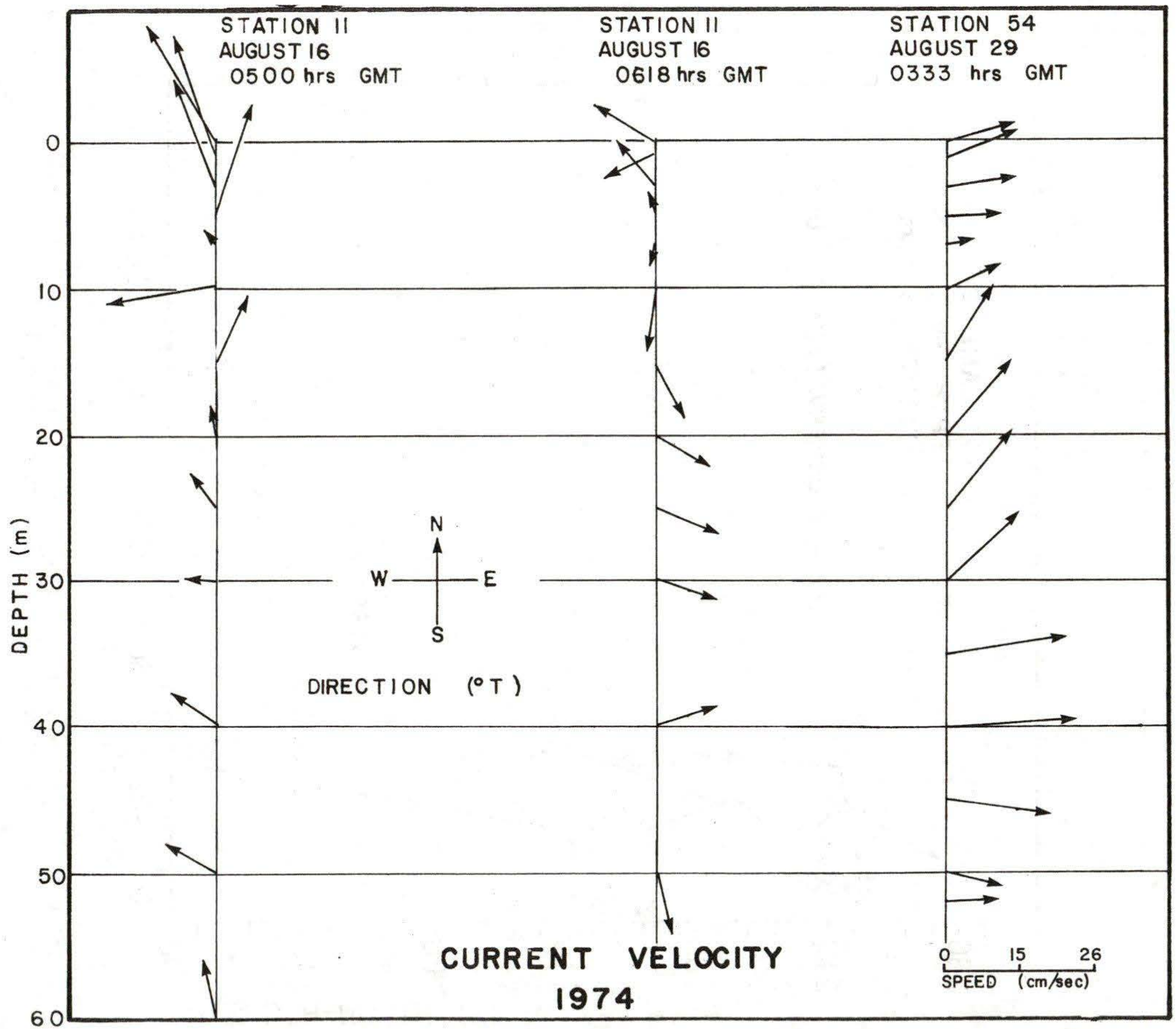


Figure 32. Three current profiles, obtained at Stations 11 and 54 during the summer of 1974.

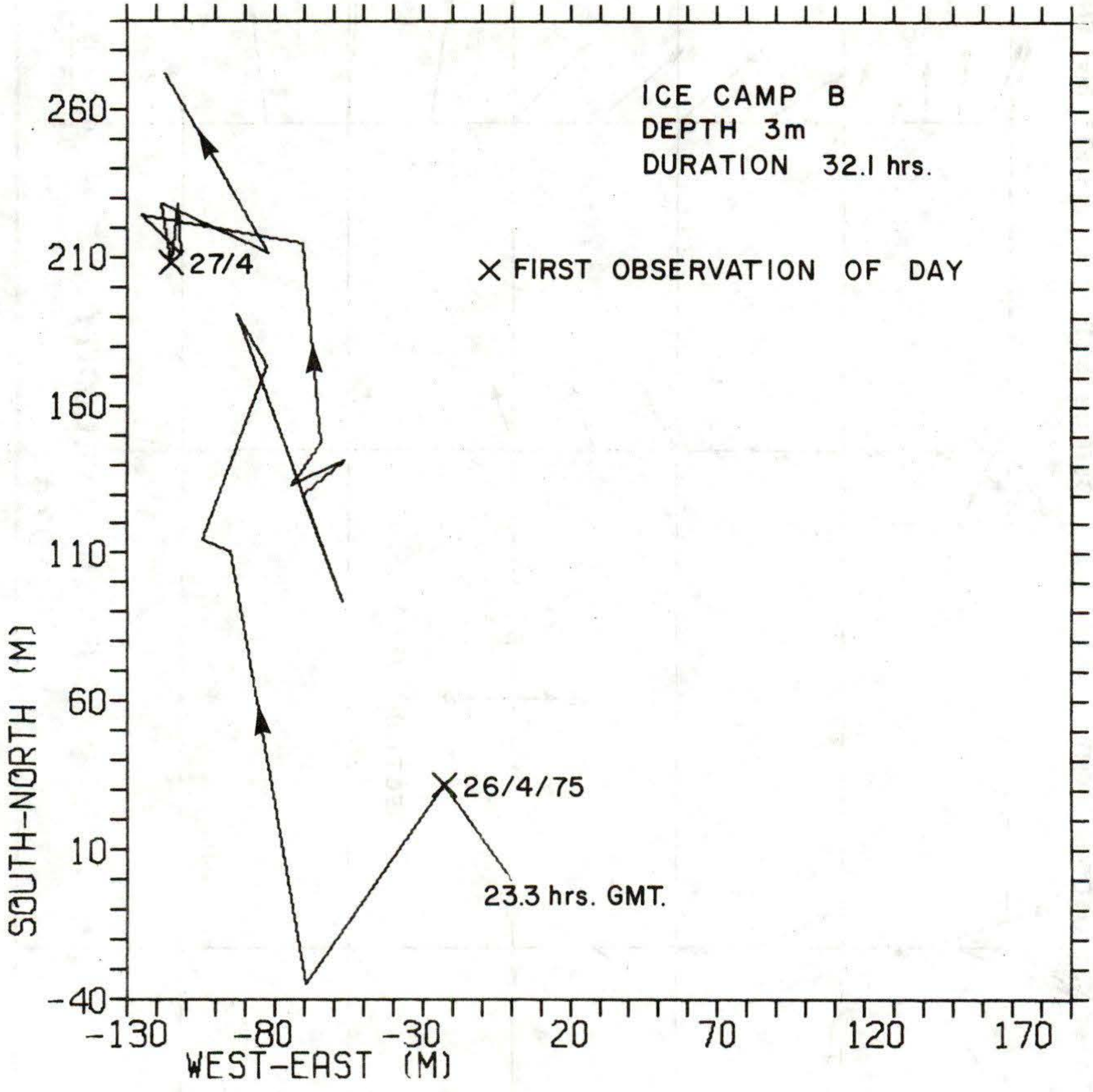


Figure 33. Progressive vector diagram of the current at 3 m depth in Kugmallit Bay during the spring of 1975

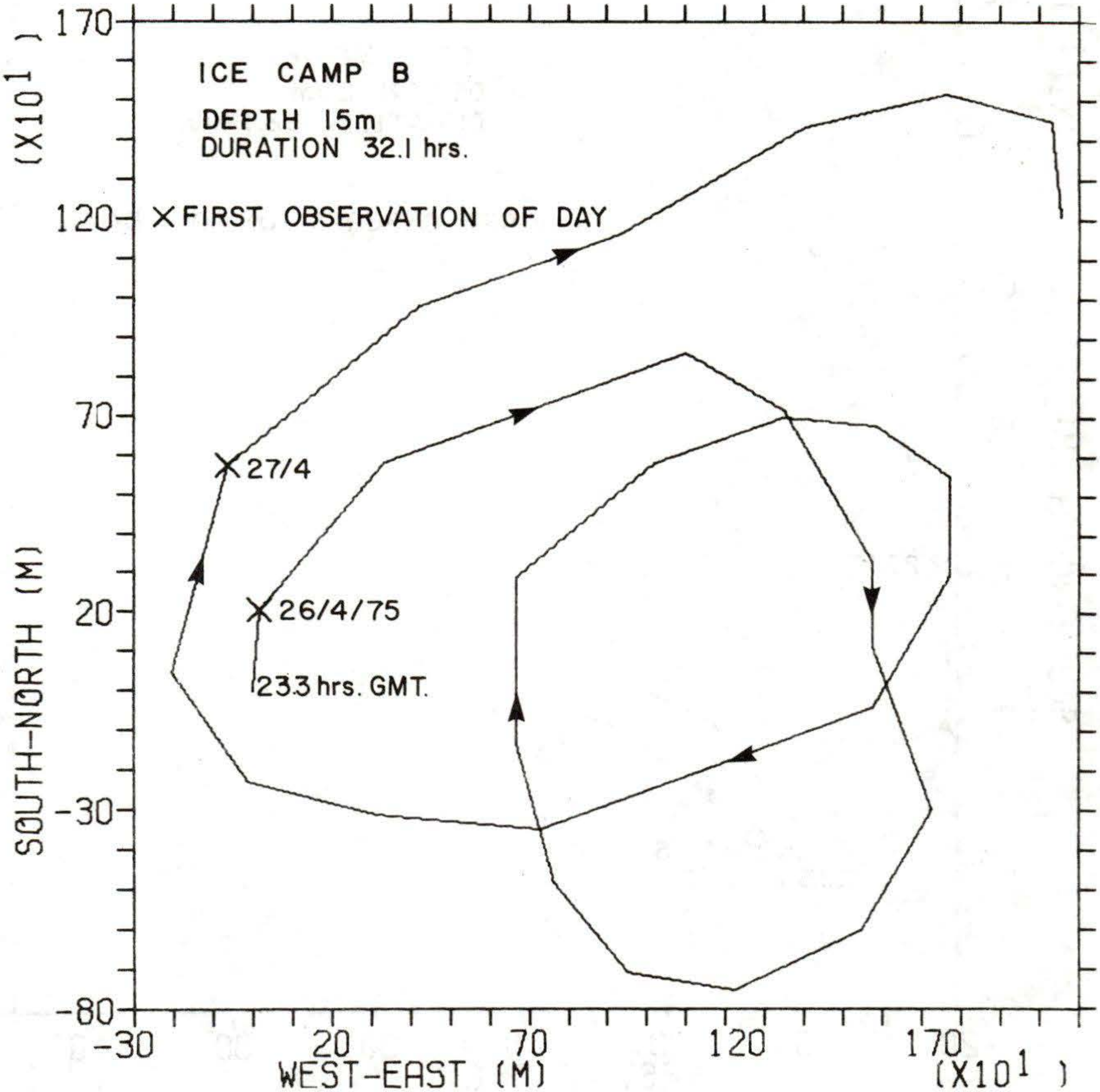


Figure 34. Progressive vector diagram of the current at 15 m depth in Kugmallit Bay during the spring of 1975.

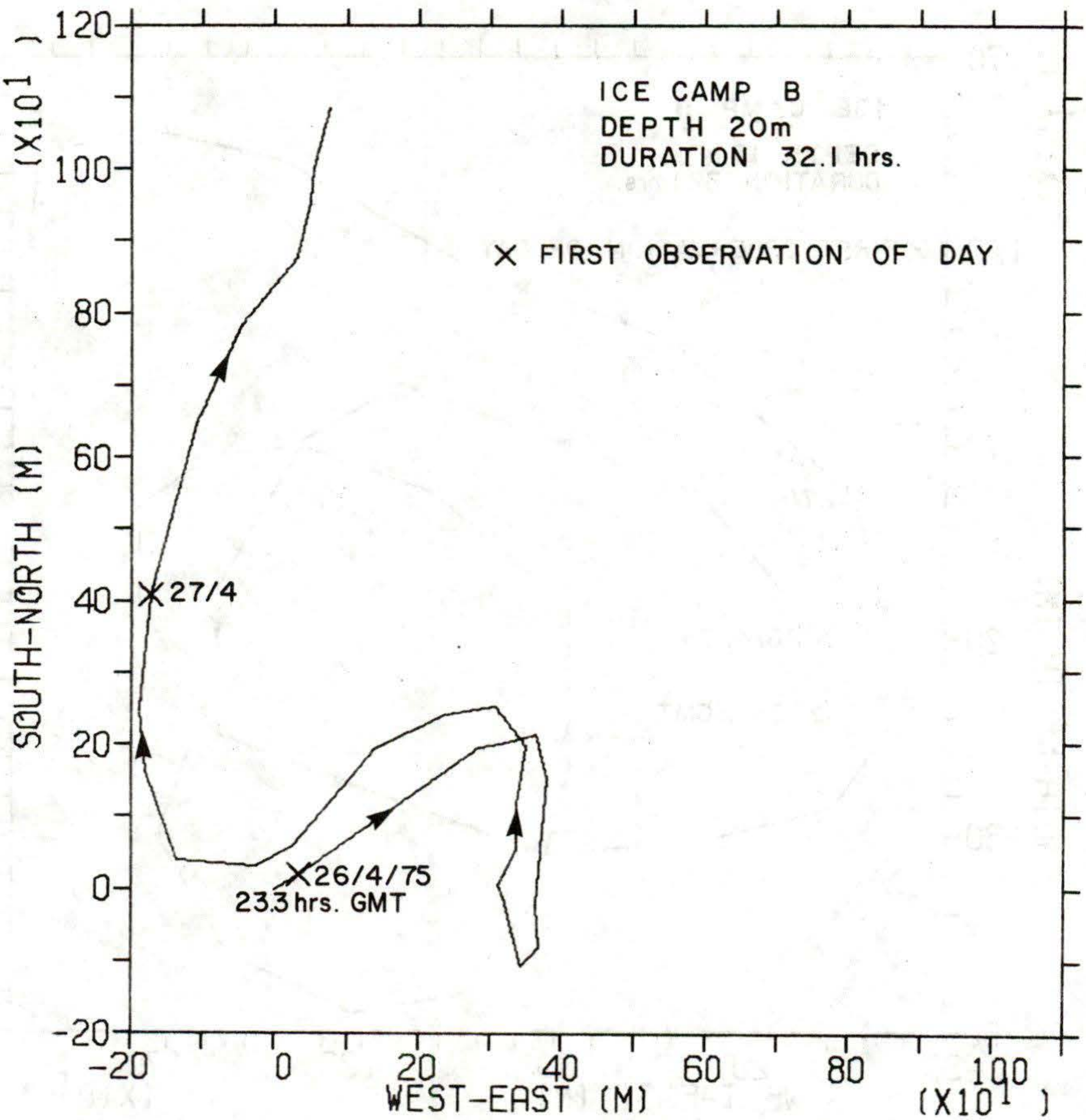


Figure 35. Progressive vector diagram of the current at 20 m depth in Kugmallit Bay during the spring of 1975.

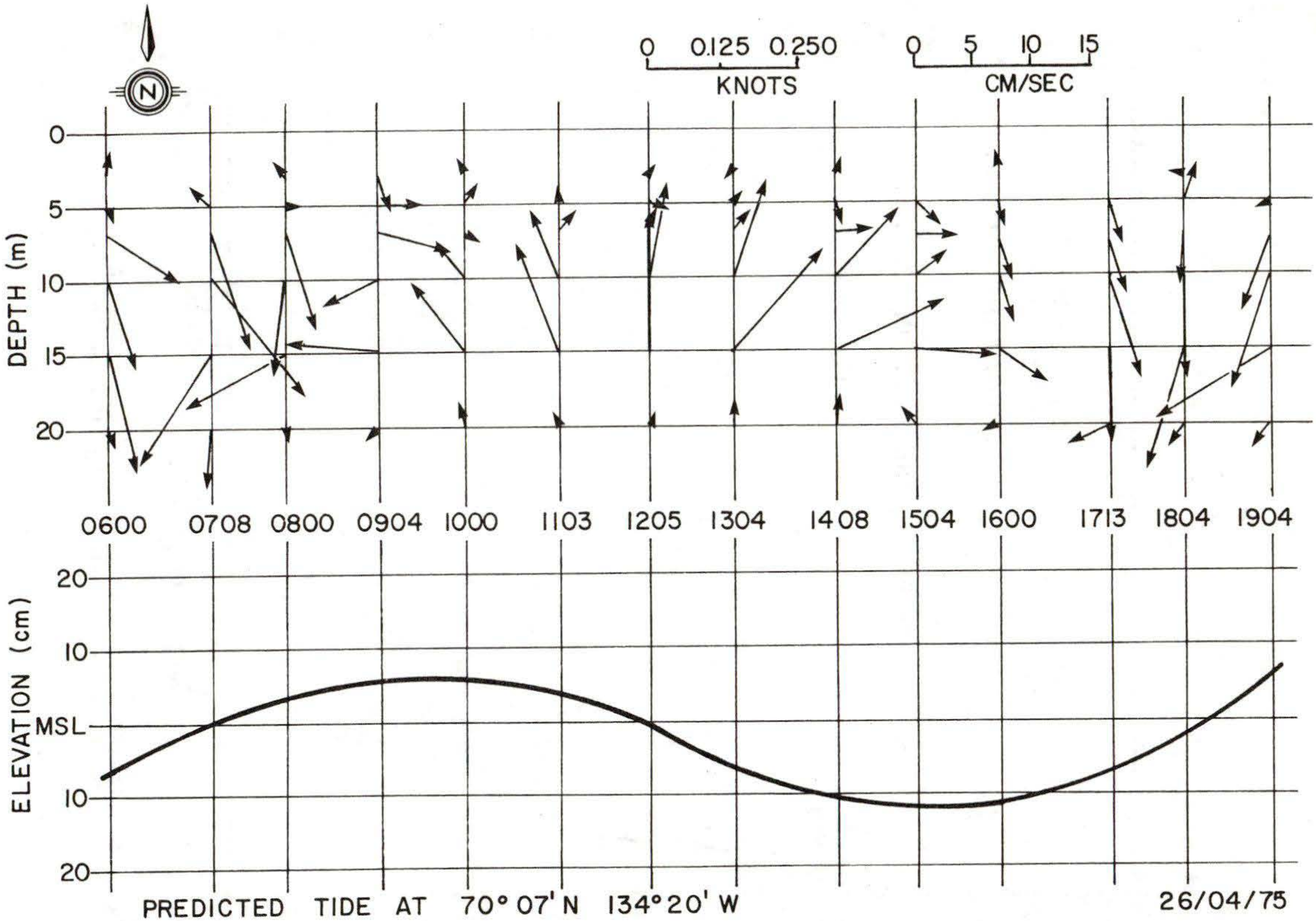


Figure 36. A portion of the time series of currents at Ice Camp B north of Kugmallit Bay, compared with the predicted tidal height.

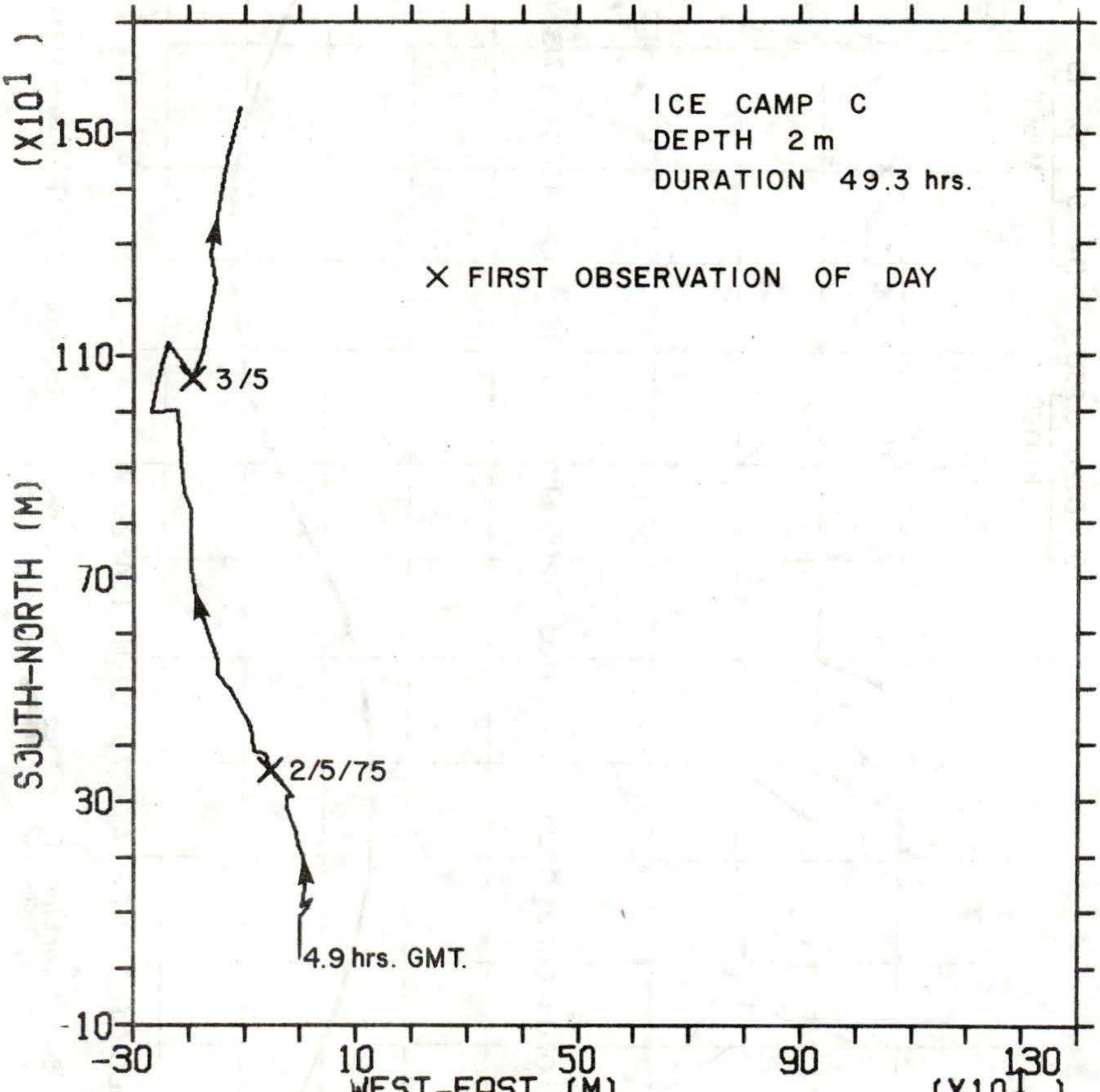


Figure 37. Progressive vector diagram of the current at 2 m depth in Mackenzie Bay during the spring of 1975.

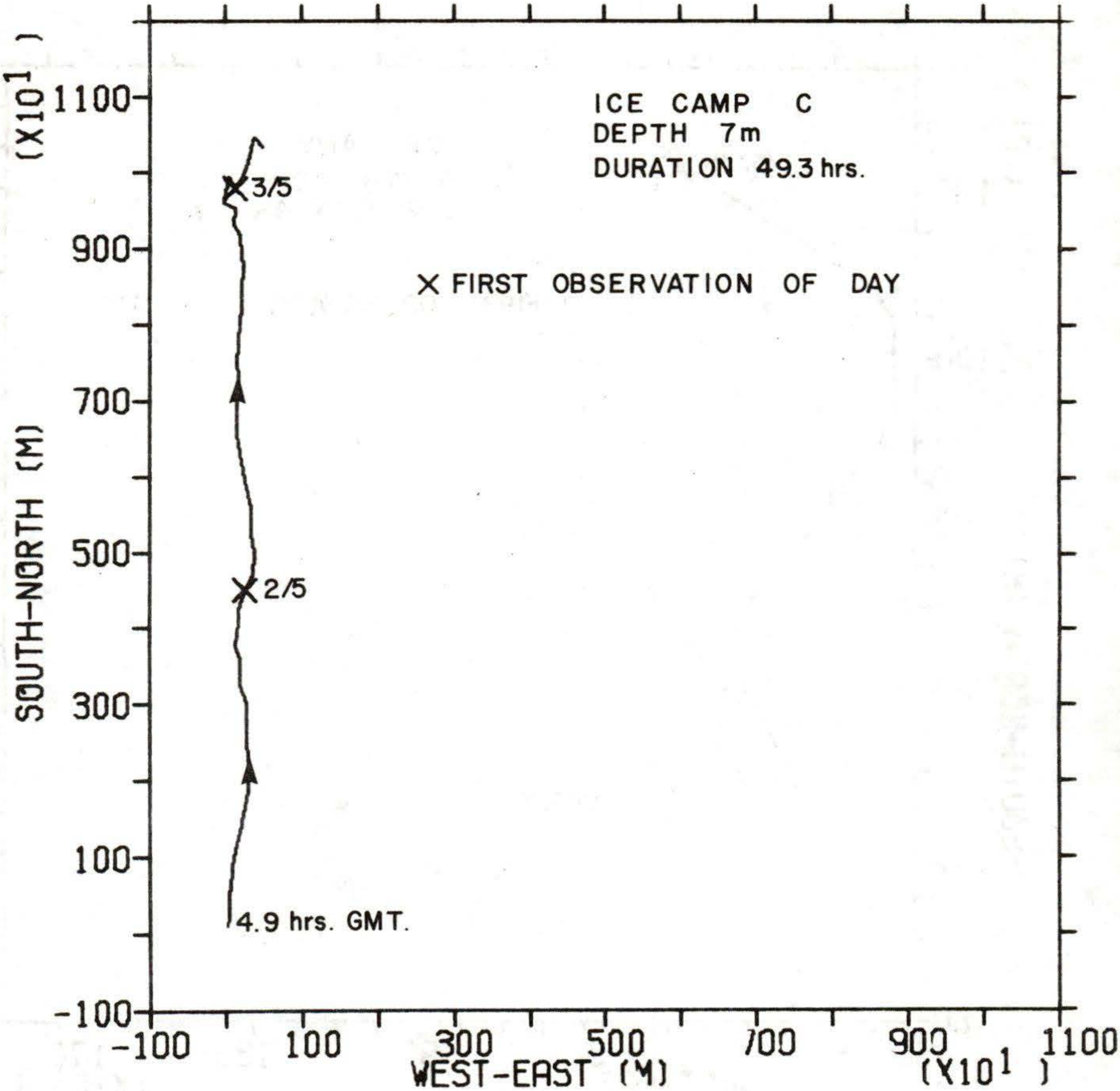


Figure 38. Progressive vector diagram of the current at 7 m depth in Mackenzie Bay during the spring of 1975.

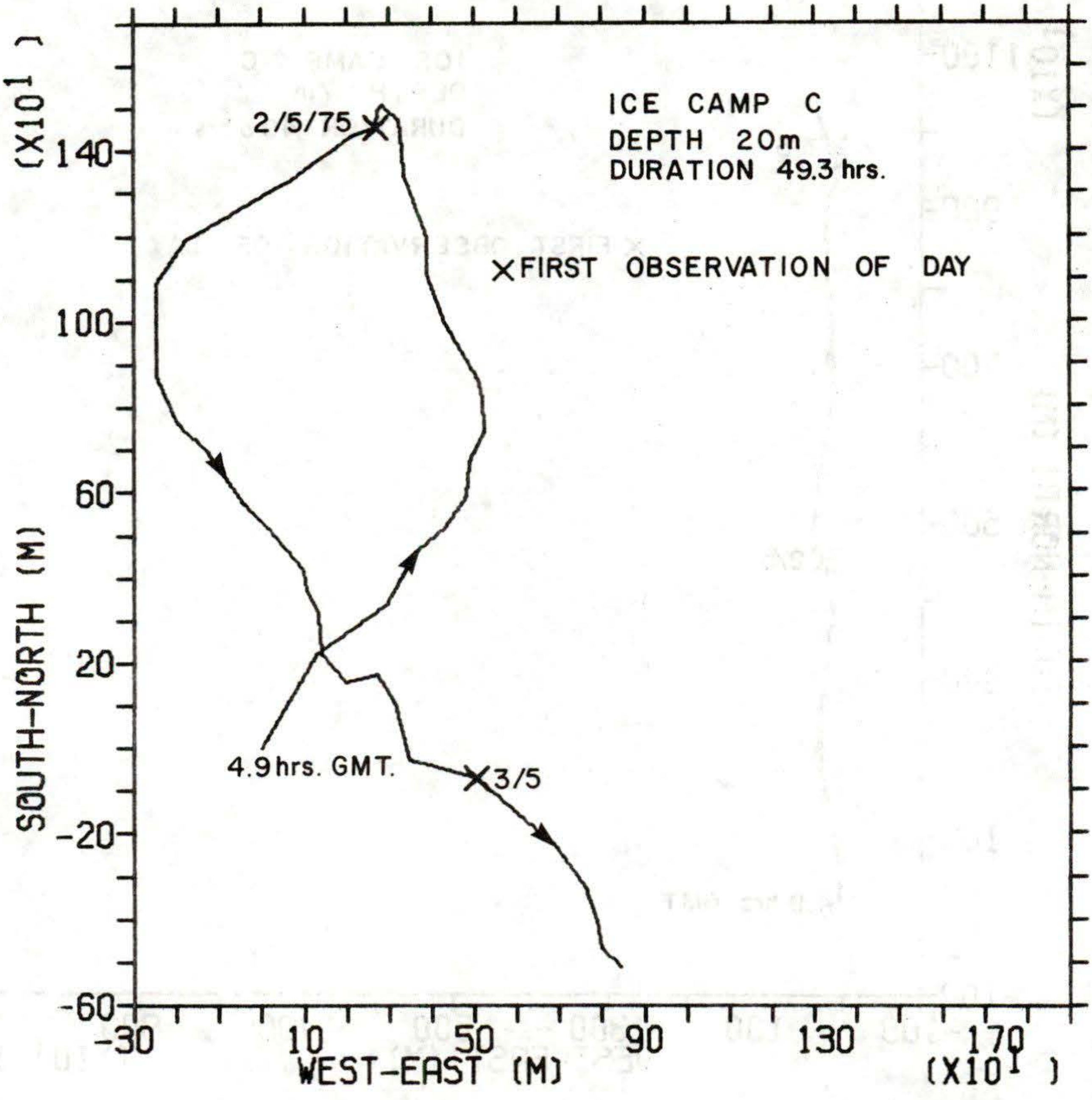


Figure 39. Progressive vector diagram of the current at 20 m depth in Mackenzie Bay during the spring of 1975.

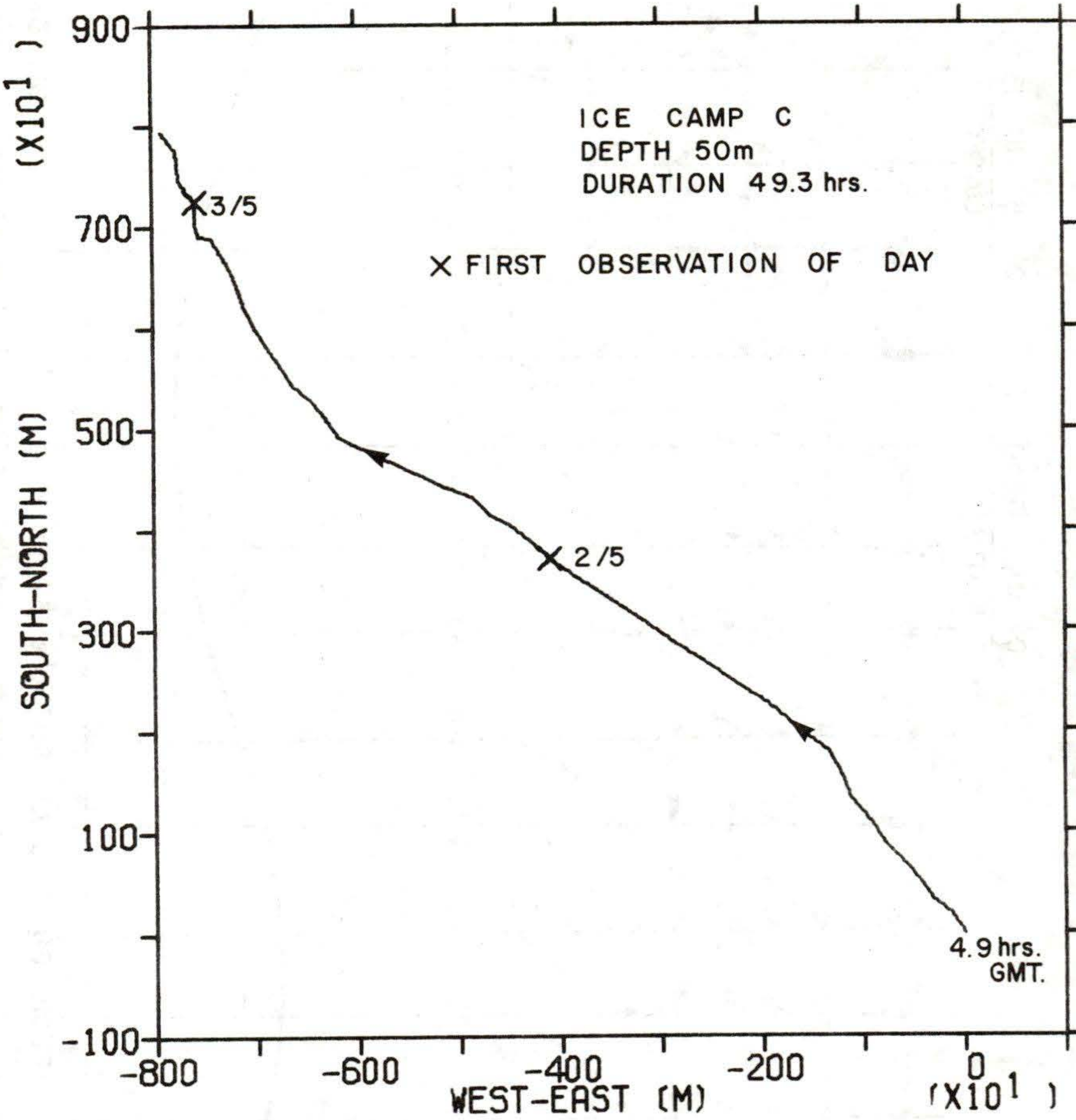


Figure 40. Progressive vector diagram of the current at 50 m depth in Mackenzie Bay during the spring of 1975.

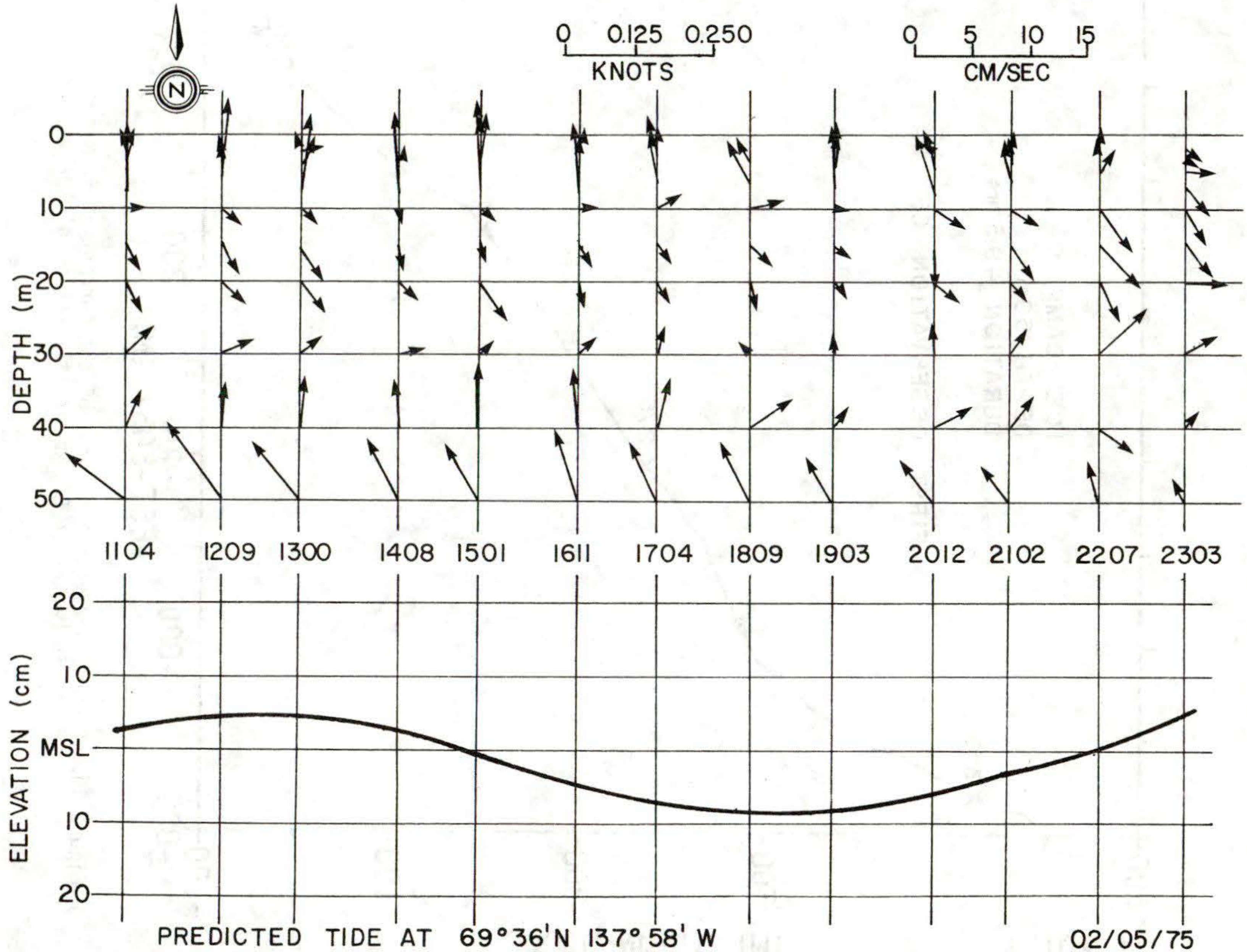


Figure 41. A portion of the time series of currents at Ice Camp C in Mackenzie Bay, compared with the predicted tidal height.

6.4 Surface Waves

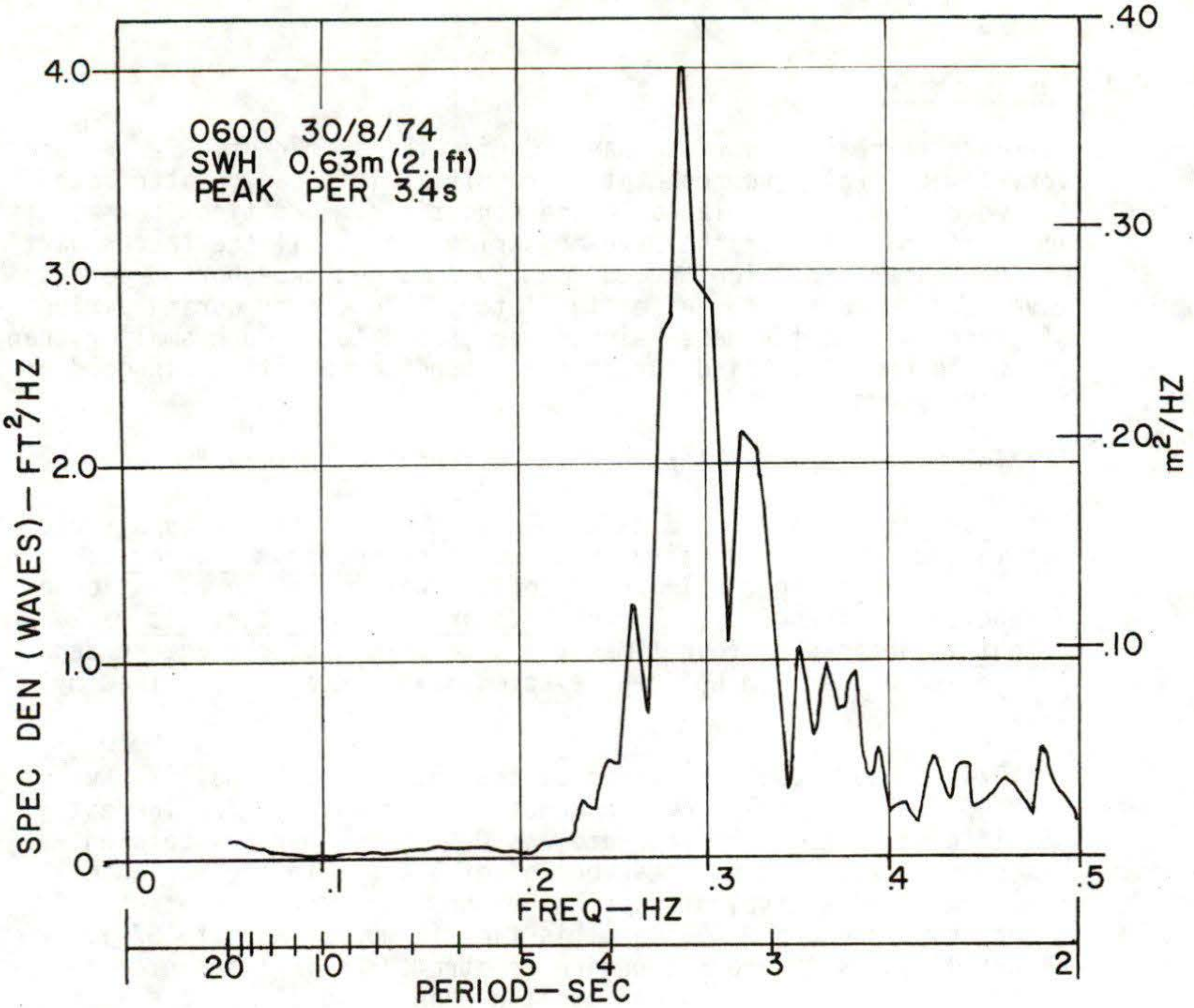
Attempts to measure surface waves during the summer of 1974 produced very few generally-representative results. This can be attributed to two causes, both related to ice conditions. Drifting ice made it impracticable to moor the wave-measuring buoy until the latter part of August, and this ice tended both to damp out the shorter-period waves and to reduce the effective fetch. Thus, even during periods of strong winds, the wave heights were found to be much smaller than one would expect to find during corresponding conditions in good or fair ice years.

The following terms will be used in discussing the waves observed.

The peak period is defined as the inverse of the frequency at which the maximum spectral density occurred. The spectrum diagram is a plot of variance spectral density of the water-surface elevation as a function of frequency. The significant or characteristic wave height is defined as four times the square root of the area under the variance spectrum between selected wave periods multiplied by $2\sqrt{2}$.

In 1974, a wave buoy was moored at the entrace to Kugmallit Bay (69° 46.6' N, 133° 21.0' W) in about 10 m of water. The largest significant wave height recorded was 0.63 m for periods between 2 sec and 20 sec, with a peak period of 3.4 sec in the variance spectrum. The equivalent wave height for wave periods between 3 sec and 4 sec was 0.35 m at this time (0600Z 30 August 1974). Figure 42 shows the corresponding spectrum. During the interval 29 to 30 August, the wind was greater than 5 m/sec from the south-east for more than half a day.

The lower part of Figure 42 shows a wave spectrum collected at location B in Figure 13 about 35 km northwest of Pelly Island (69° 53.8' N, 135° 57.2'W) where the water had a depth of 18 m. The data extends over the period 8 August to 6 September, although there are gaps because of poor or missing data. In this year the largest significant wave height was recorded on August 11 and was 2.4 m for periods between 2 sec and 20 sec, with a peak period of 5.9 sec in the variance spectrum. During 26 and 27 August, higher winds were observed but somewhat smaller waves of shorter periods were recorded on account of the ice front having moved closer to shore, reducing the fetch. The larger waves occurred with winds from the south-west or north-west. North-east winds also produced significant waves. It should be noted that since wave measurements are only taken for a 20 min interval every 3 hours, larger waves may have occurred which were not recorded. Assuming that ice was not present, the site was exposed to fetches greater than 100 km for wind directions of south-west through north-west and north-east to east. For example, with a 100 km fetch a wind of 14 m/sec blowing for more than 8 hours is required to generate waves 2.4 m high with periods just over 6 sec.



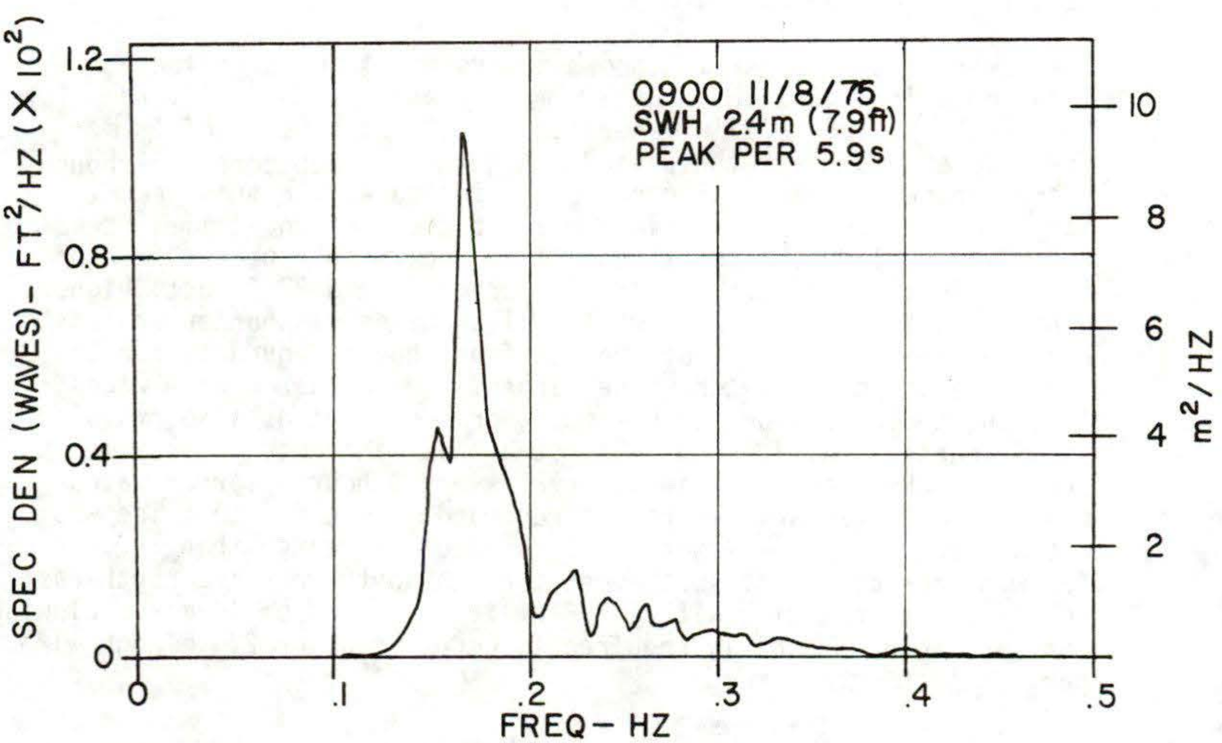


Figure 42. A comparison of the wave spectra for the records with the highest waves in 1974 and 1975.

Figure 43a is a scatter diagram from the recorded results of significant wave height as a function of peak period while Figure 43b is an exceedance diagram for wave heights greater than 0.3 m.

6.5 Ice Islands, Ice Island Fragments and Large Ice Floes

Ice islands (Figure 44A) as opposed to the pack ice, are composed of ice of terrestrial origin; they are formed when large pieces break loose from a parent shelf ice. In the Arctic, most of the ice islands are thought to originate from northern Ellesmere Island in the Canadian Archipelago (Hattersley-Smith, 1952).

Ice islands are characterized by larger area, greater thickness and greater structural strength than pack ice, as well as by their surfaces which have irregular rolling relief. Ice islands are generally of the order of 30 to 40 metres thick, although there are indications that thicker islands exist.

During the winter of 1961-62, five ice islands and numerous smaller fragments calved from the Ward Hunt Ice Shelf on the north coast of Ellesmere Island. The five ice islands varied in area from 68 km^2 to 133 km^2 (Hattersley-Smith, 1963). The movement of these islands generally followed the circulation of the Beaufort Gyre (Lindsay *et al* 1968) although one of the islands (WH-5) passed through Nares Strait which lies between Greenland and Ellesmere Island (Nutt, 1966).

The long-term drift of the ice islands in the Canadian Basin of the Arctic Ocean is represented by that associated with the Beaufort Gyre (Coachman, 1969). Koenig(1952) observed that the ice islands do not drift at the same velocity as the pack ice; the motion of the ice islands appears to be influenced less by the wind than by currents, probably because of appreciable draught of the islands.

The actual day-to-day drift path of the islands is generally erratic. Fluctuations in drift velocity can be attributed somewhat to variations in wind velocity and in ocean currents and to the frictional resistance of the pack ice. We cannot make any quantitative predictions regarding the motion except to say that the mean drift speed is generally between 2 cm/sec and 4 cm/sec with fluctuations as great as 20 cm/sec (Coachman, 1969).

Ice islands provide a large, stable platform for scientific measurements, however, it must be remembered that no control can be exercised over their drift. In the southeastern Beaufort Sea, they present a possible hazard to fixed offshore structures in their path. Although they move slowly, their large size gives them a large amount both of momentum and of kinetic energy. For example an ice island with an area of 5 km^2, a mean ice thickness of 40 m, a specific gravity of 0.92 and a speed of 17 cm/sec has a kinetic energy of 2.7×10^9 Joules. These values are representative of a relatively small ice island moving at a typical speed. For comparison, a vessel displacing 1.52×10^8 kg (150,000 tons) and moving at 750 cm/sec (14 knots) has a kinetic energy of 4.3×10^9 Joules. Ice islands are objects to be regarded with respect.

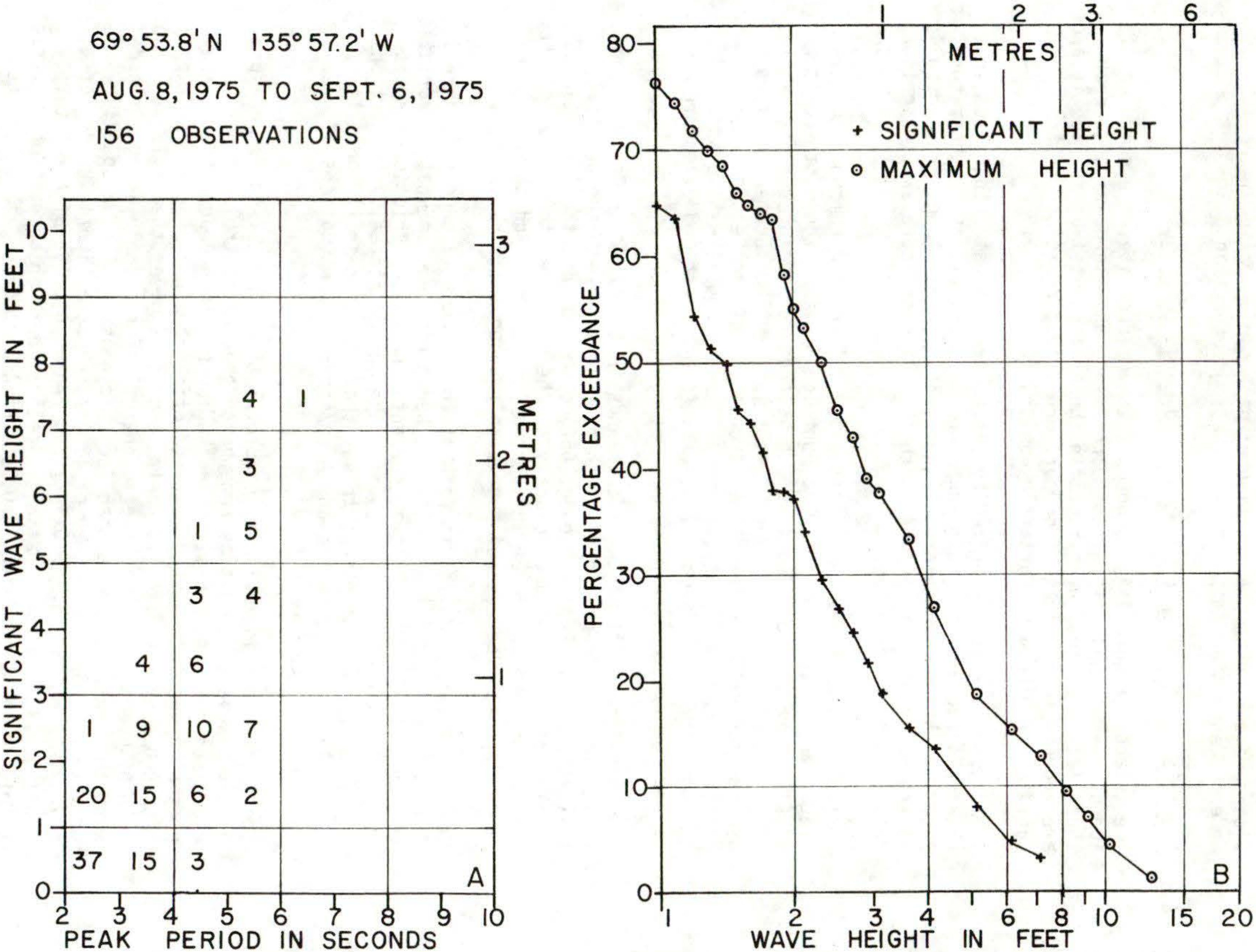


Figure 43. Some statistics for surface waves recorded in 18 m of water northwest of Pelly Island, summer 1975: (a) significant wave height as a function of peak period; (b) percent exceedance as a function of wave height.

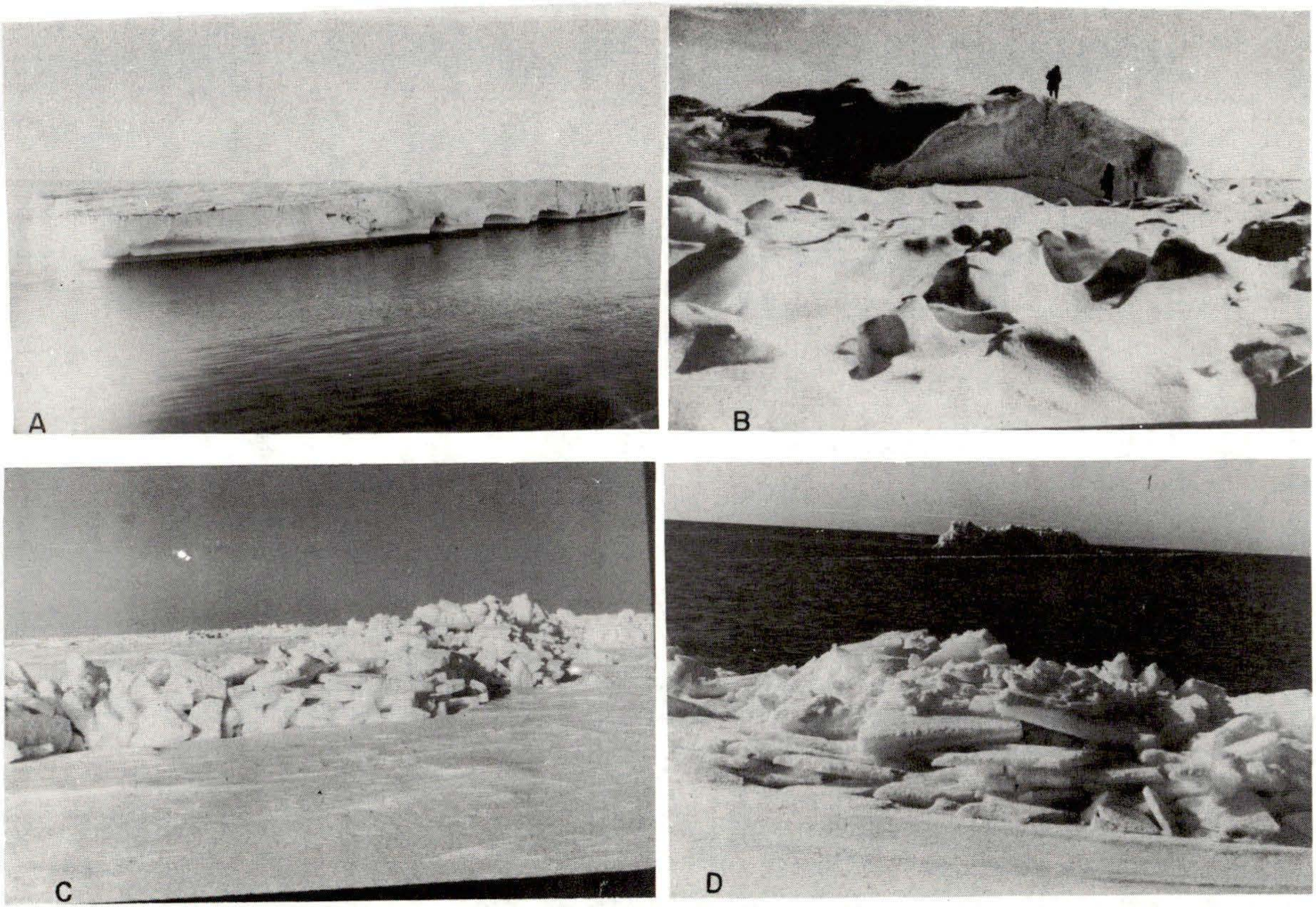


Figure 44. Some examples of ice types: (a) ice island fragment; (b) multi-year ice; (c) pressure ridge in new winter ice; (d) grounded fragment of a young pressure ridge.

The apparent lack of ice islands in the southeastern Beaufort Sea may be a function of the scarcity of data, rather than an absence of such islands. The island shown in Figure 44a was found off the east coast of Banks Island in Prince of Wales Strait in 1954.

Kusunoki (1962) has depicted the path which the Island T3 followed as it moved through the southeastern Beaufort Sea (Figure 45). The nearest it came to the Canadian Arctic coast was approximately 180 km north of Tuktoyaktuk; the shallowest depth it reached was within 500 to 600 metres (position taken obtained from Figure 45).

In areas of high lateral pressure, ice fields can be rafted into large thick masses resembling ice islands (Figure 44B), (Dunbar, 1952). These large floes, composed of sea ice, may be confused with ice islands. In our study area these floes, or pieces of them, are much more common than ice islands and are the more probable source of the scour marks found in shallow parts of the sea bottom. During 1974 a large amount of multi-year ice was evident in the southern Beaufort Sea. The moon-scape or stone quarry appearance of the area was dotted with floes similar to that shown in Figures 44B and 44C. The water depth where the piece of ice shown in 44D was located at 18 m and the height of the ice piece was estimated to be 6 m above the water surface. While the mass of a large floe, or of a fragment, is generally less than that of typical ice islands, they still attain sizes large enough to present a threat to man-made marine structures. Their motion is generally governed by the depth-integrated current as well as by the wind and the motion of surrounding ice. Limitations in the present state of knowledge make it difficult to provide quantitative predictions of the motions of these floes.

6.6 Some Results from Satellite Imagery

Satellite images provide instantaneous views of large areas of the earth from great heights. However, they suffer from the following drawbacks:

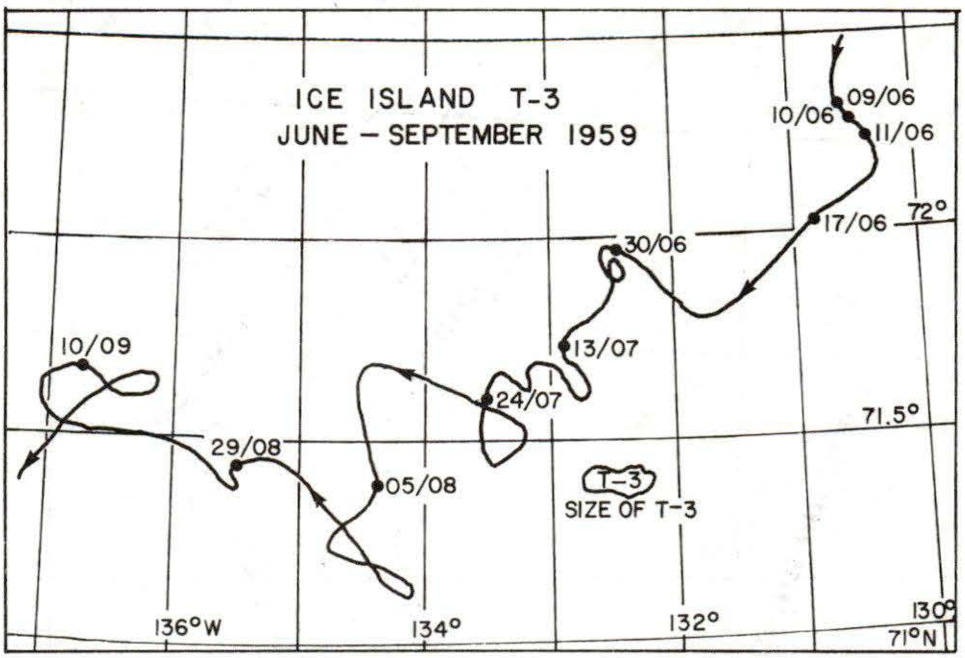
1) Clouds interfere with observations of the ground. This condition can result in a bias towards a "clear-weather" interpretation of events.

2) Observations are limited at present to daylight hours. In the Arctic, this precludes images during much or all of the winter.

3) Lack of repetition in coverage, due to the precision of the orbit of the ERTS satellite, makes daily coverage of the same area impossible.

In spite of these disadvantages, such images have been found useful in the present study.

The changes in ice conditions from year to year are quite apparent. In the study area, 1973 was a fair ice year, 1974 was a poor year and 1975 was a good year (Figure 46). The confinement of the Mackenzie River water between Mackenzie Bay and Cape Bathurst by



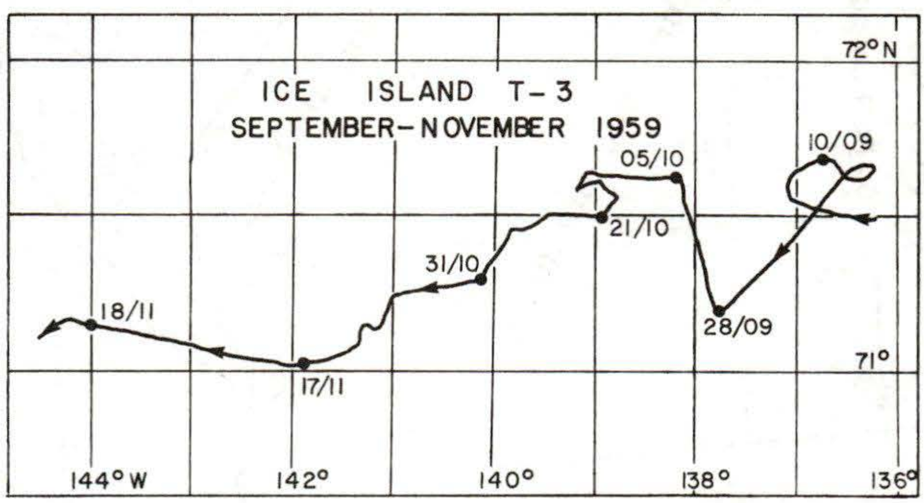


Figure 45. The drift track of ice island T-3 as it passed north of the Mackenzie River Delta (after Kusunoki, 1962).

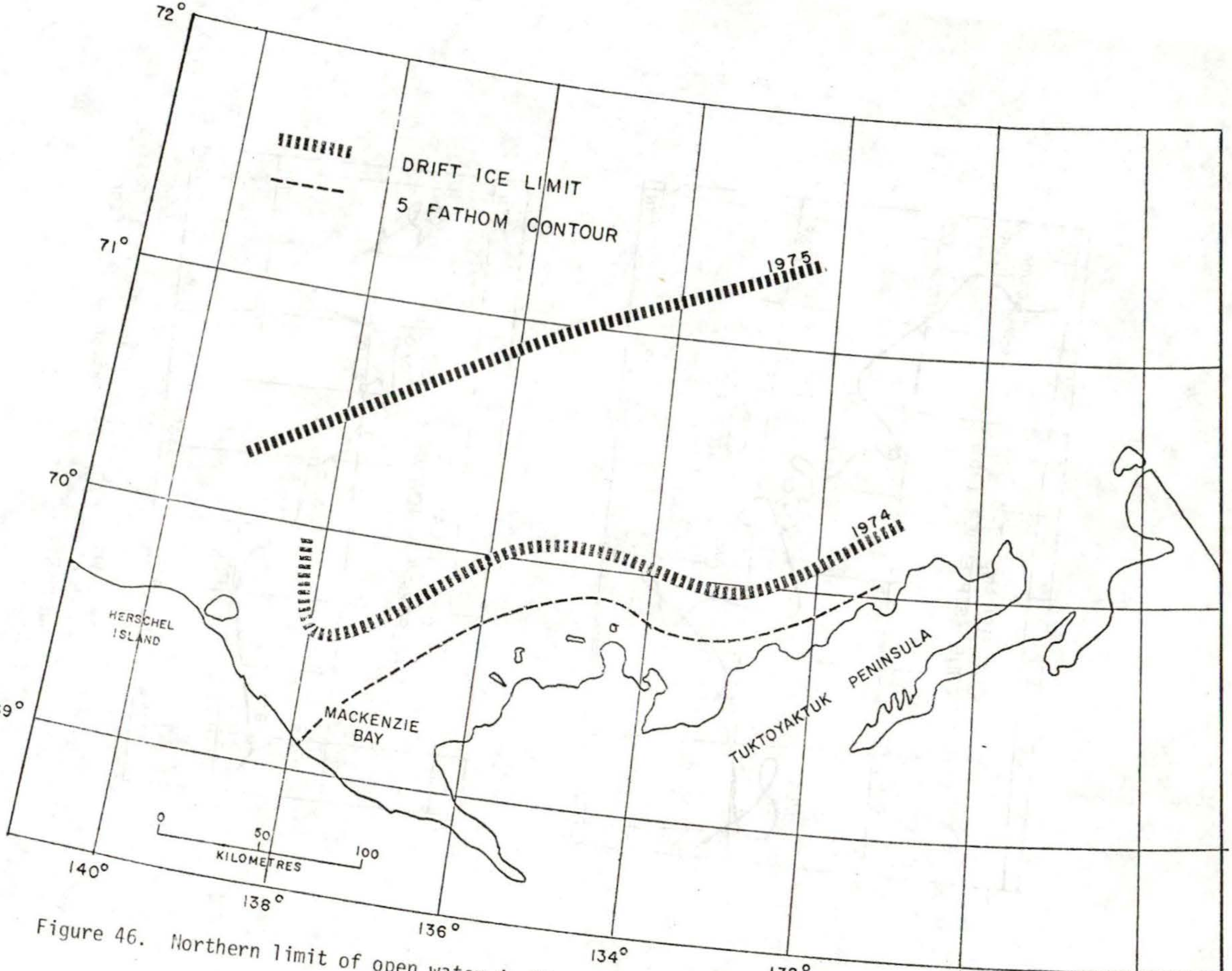


Figure 46. Northern limit of open water in 1974 and 1975.

ice is noticeable for the year 1974. Subsequent images in 1974 clearly show the opening of the ice and the movement of brackish water across the western end of Amundsen Gulf towards Sachs Harbour as well as around Cape Bathurst into Franklin Bay (Figure 47).

Also apparent are some of the primary features such as the general eastward movement of the Mackenzie River water along the Tuktoyaktuk Peninsula (Figure 48). Circulation patterns in Mackenzie and Kugmallit Bays are also revealed. A mechanism whereby the replacement of fresh water by more saline water can take place in Tuktoyaktuk Harbour is suggested by some of the images (Figure 49). Instead of the gradual process postulated by Barber (1968), i.e., that occurring because of the effect of westerly storms late in the summer; it appears that this replacement may occur intermittently during the open-water season, in the presence of strong north-through-east winds. North-easterly winds, it would appear, could cause an inflow of clearer, more saline water into Kugmallit Bay along the eastern shore. At the same time the divergent flow along the coast (upwelling) depresses the mean sea level, resulting in the flushing of the surface fresh water from Tuktoyaktuk Harbour. With the outflow from the east arm of the Mackenzie River confined to the west side of the bay, tidal exchange would serve to replace the fresh water with more saline water in the harbour.

Other circulation features that are revealed are the convergent northwesterly flow near Kay Point (Figure 50) during easterly winds (observed by both authors at various times) and the large eddies that can occur at the outer boundary of the silty Mackenzie River water (Figure 51). A pair of eddies north of Atkinson Point were observed and photographed from a helicopter in the summer of 1975. Their diameters are approximately 15 km (MacNeill, pers. Comm.).

7. SUMMARY AND CONCLUSIONS

7.1 Water Properties

7.1.1 Non-Periodic Variations

The distribution of water properties in the southeastern Beaufort Sea is influenced both by periodic and by non-periodic phenomena. River discharge, silt load associated with that discharge, and insolation all are characterized by seasonal variation. This fact leads to yearly variations in the turbidity, temperature and salinity of the surface water as well as the extent of the ice cover. Non-periodic phenomena include wind and the variable year-to-year extent of the summer ice cover. Easterly winds are associated with divergent flow in the surface layer, leading to upwelling conditions with lower temperatures and higher salinities inshore; the ice tends to move offshore under these conditions. Conversely, westerly winds lead to convergent flow and to a retention of the low-salinity, warmer river water inshore, and tend to move the ice onshore. If the ice

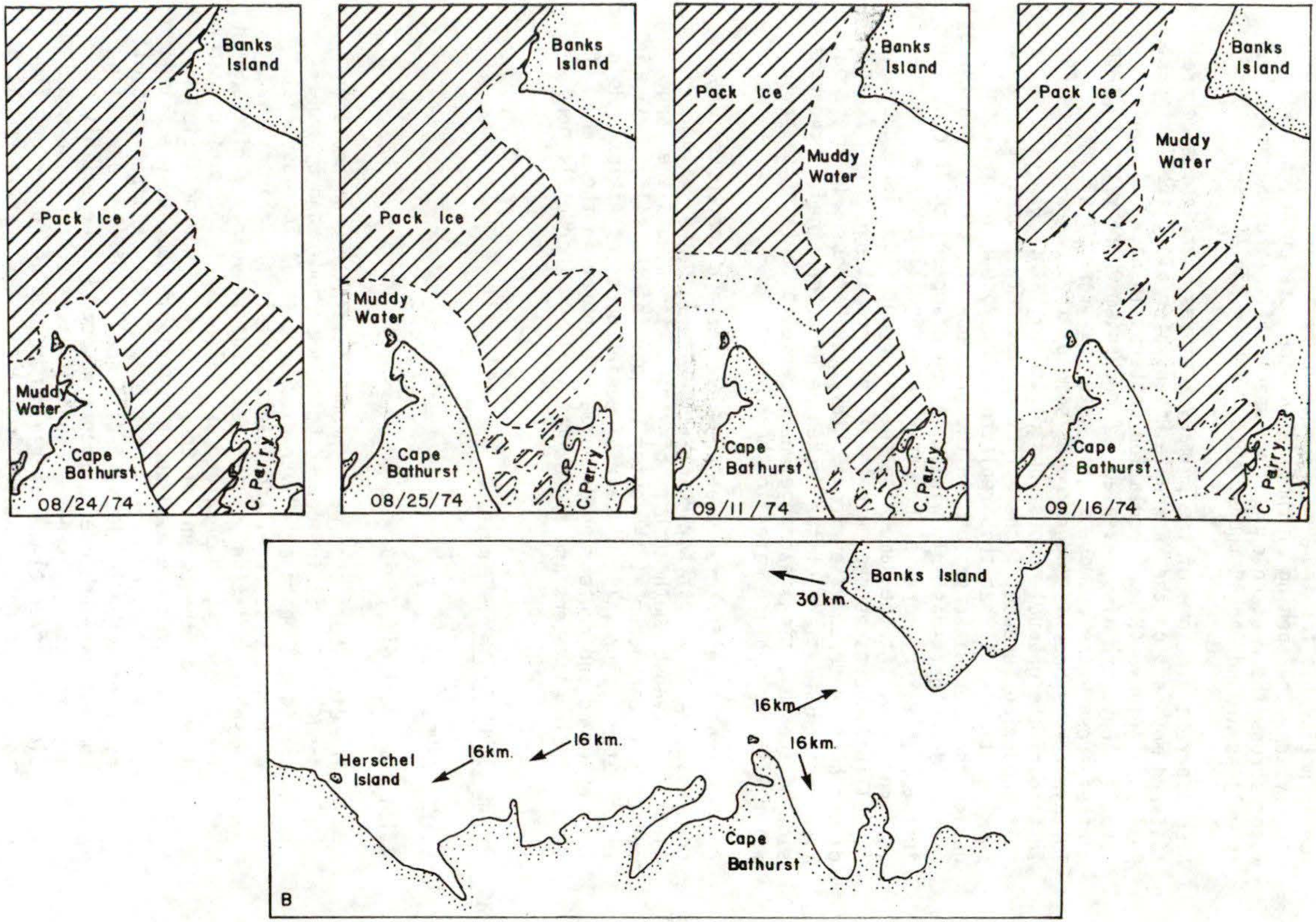


Figure 47. Depicts movement of muddy Mackenzie River water out past Cape Bathurst towards Sachs Harbour and down towards Cape Parry. Summer 1974.
B - Surface ice movements August 24 - August 25, 1974.

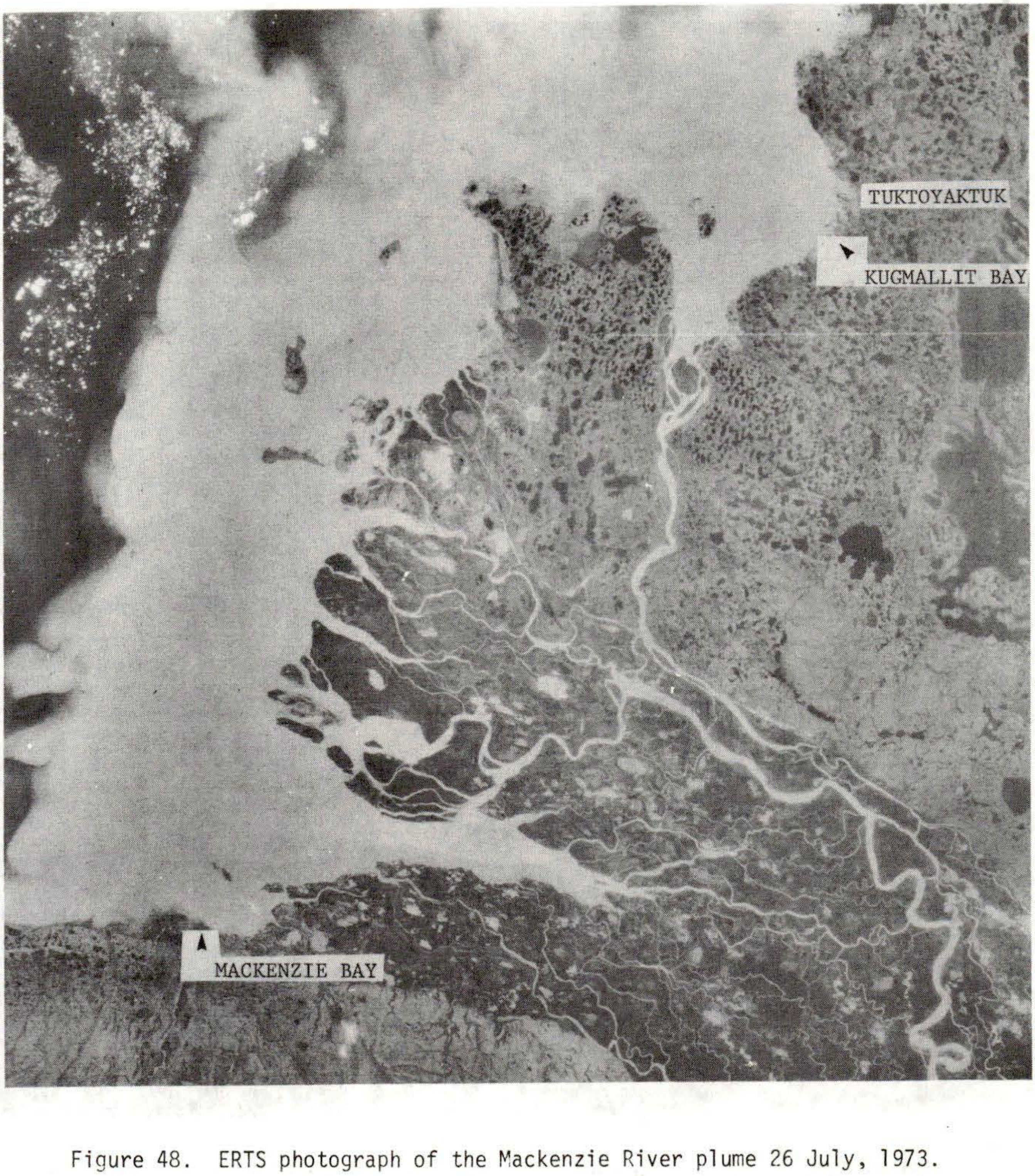


Figure 48. ERTS photograph of the Mackenzie River plume 26 July, 1973.

Figure 49. ERTS photograph of the Mackenzie River plume 8 September, 1973.

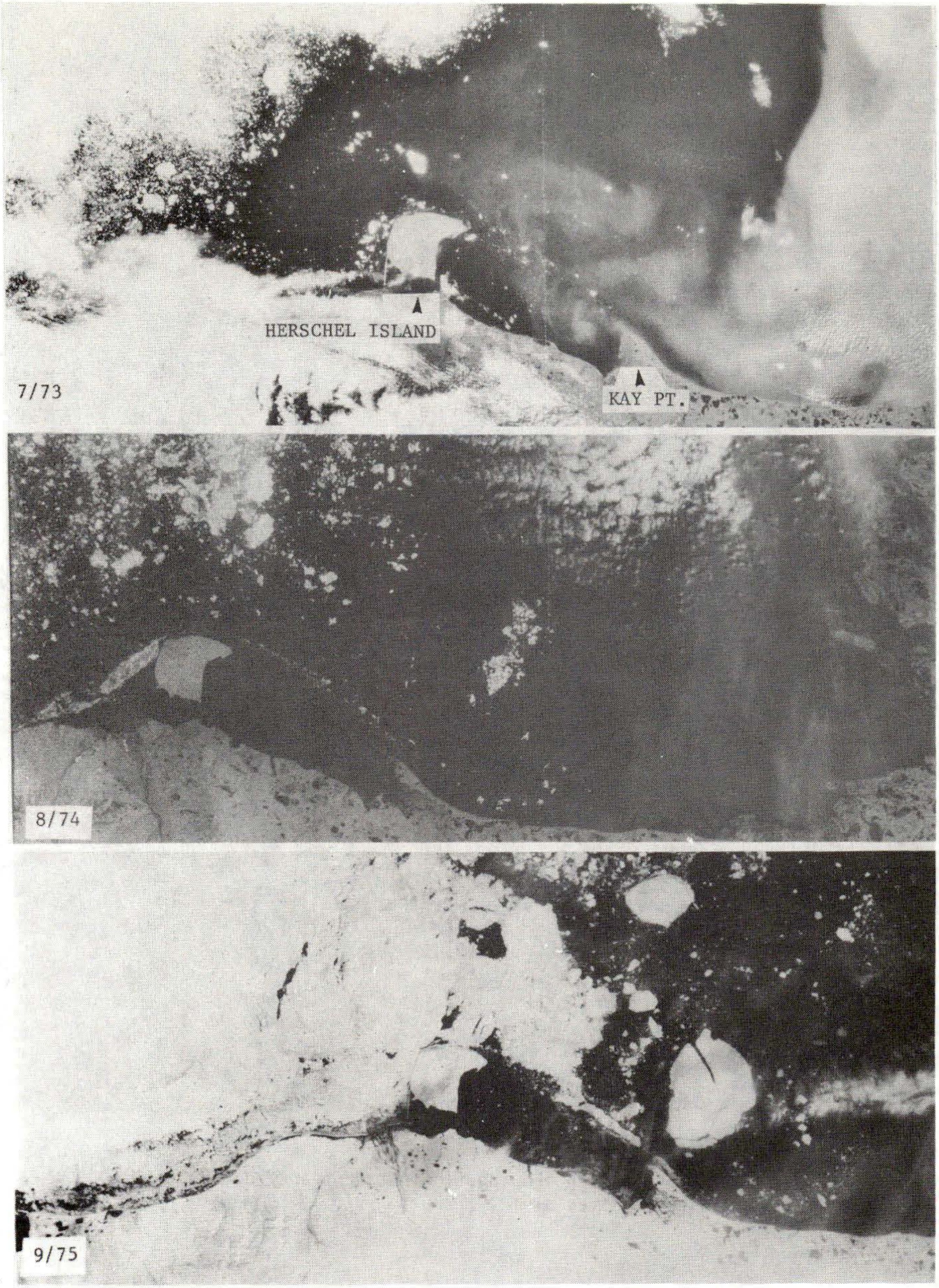


Figure 50. ERTS photograph showing the covergent flow pattern between Kay Point and Herschel Island observed in 1973, 1974 and 1975.

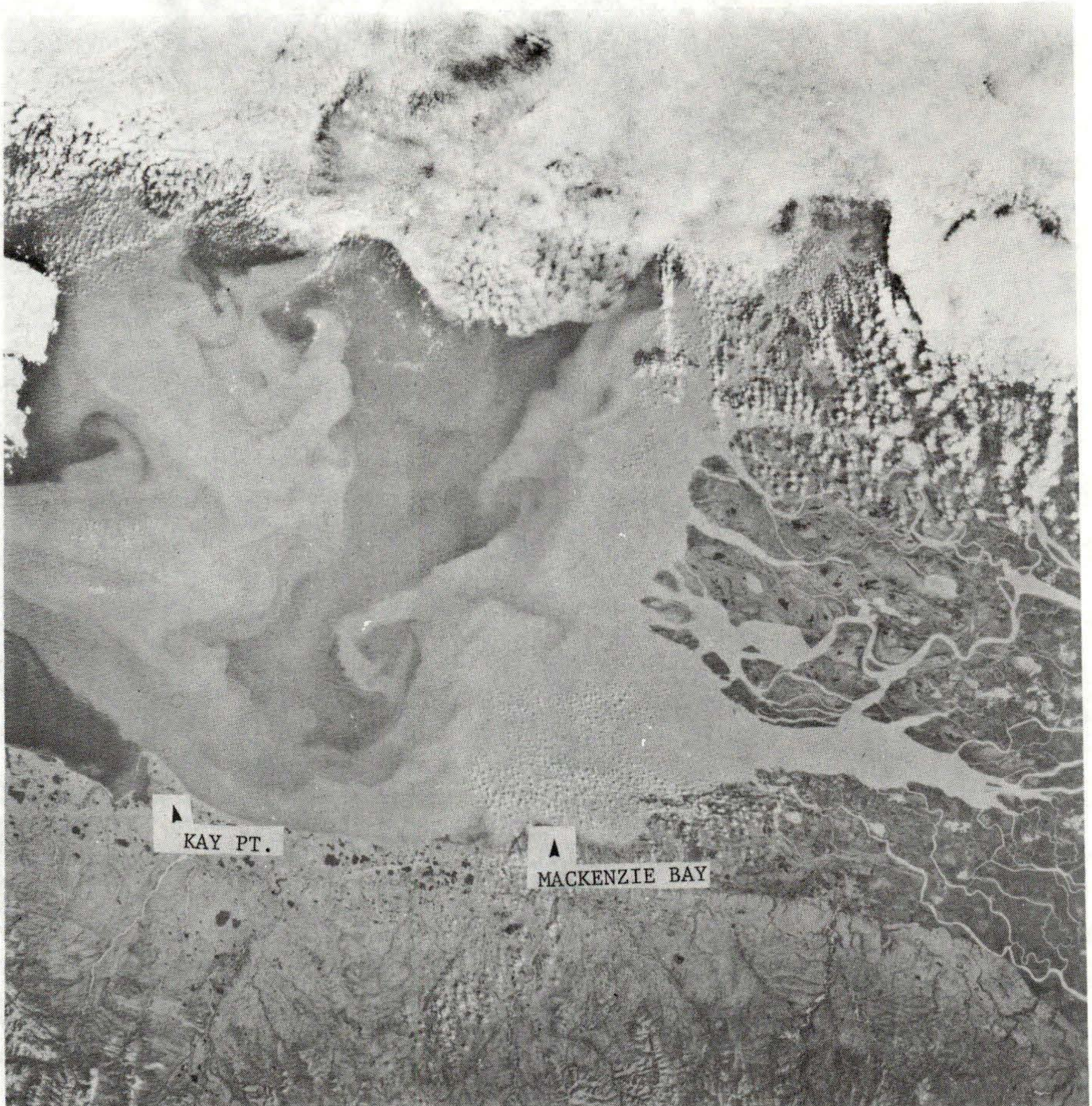


Figure 51. ERTS photograph showing flow patterns and eddy in the Mackenzie River plume, 17 July, 1975.

remains close inshore during the summer, the river water entering at the time is confined near the coast, resulting in a uniform, low-salinity (e.g., <5°/₀₀ in 1974) surface layer. With the ice well offshore, the river water can spread over a larger area, and be more subject to the actions of wind, waves and currents. The presence of ice also lowers the temperature of the water as well as that of the air; as a result, fog is quite common in summer.

The wind and the ice cover, which is strongly influenced by the wind, are also subject to short-period motions of the order of days or weeks. For example in 1974, a poor ice year, the winds were predominantly northwesterly during the early summer, resulting in ice encroachment toward shore; however, by early September the winds were mainly easterly, and the ice moved offshore for a short time.

7.1.2 Seasonal Variations

In winter the decreased river flow results in a less fresh water input and little silt is transported to the Beaufort Sea. At the same time the decreased biological productivity leads to an increase in the water transparency. As winter progresses more ice forms, increasing the salinity and lowering the freezing point of the water. The freezing process also results in convective mixing within and thickening of, the water surface layer. As the ice becomes thicker, its growth rate decreases due to decreased heat flow through it. The result is a water layer immediately under the ice extending in depth to as much as 40 or 50 metres, which is isothermal and isohaline, and has a negative thermocline and a positive halocline at the lower boundary. The water below this layer is generally only slightly influenced by seasonal changes; both its temperature and salinity increase with depth. In the entrance of Amundsen Gulf, a temperature of -1.71°C and a salinity of 31.12°/₀₀ were recorded for the upper layer in winter. Expected temperatures for this layer in winter in the Beaufort Sea range between -1.65°C and -1.85°C and for salinity the expected values range between 30.0°/₀₀ and 33.5°/₀₀. The rather small temperature and salinity vertical gradients during the winter result in a water column that has low stability, allowing wind in open water or current-generated mixing under-ice to take place easily and to a relatively great depth.

In contrast, the water column in summer is quite stable. The input to fresh water from melting ice and from increased river flow, as well as the increase in temperature due to insolation all act to produce a low-salinity, relatively fresh, surface layer and strong stable stratification results. Mixing processes, whether wind- or current-induced, are thus confined to this surface layer. At the same time, the increased silt load in the rivers and the increased biological productivity elsewhere lead to a decrease in water transparency within the upper layer. The actual temperature and salinity ranges possible throughout the summer in the surface water are quite large and depend upon wind conditions, ice cover and location. The higher temperatures and lower salinities are generally found inshore, with low salinities also occurring near melting ice. Hence salinities can range from $0°/_{oo}$ to $31°/_{oo}$ and temperatures from 0°C to 13°C in the surface layer. While water transparencies in winter are generally greater than 70% of the value in air, minimum values of virtually 0% can be attained in summer at some locations. Near the bottom a turbid layer having transparency values less than 10% has been found in summer.

7.2 Water and Ice Motions

Wind can produce not only surface currents but also waves, both short wind-waves and long-period waves, e.g., storm surges. Horizontal pressure gradients in the water, whether due to horizontal differences in atmospheric pressure, in water density or in the slope of the sea surface, can also generate currents. Among the most-easily recognized currents result from changes in surface elevation and those generated by tidal forces. The generated motions can be modified by bottom topography, Coriolis effect, friction and density stratification, or any combination of these.

In discussing the mean circulation pattern in the area it must be recalled that the currents at any one time may bear no resemblance to the mean. The largest persistent feature of the circulation is the Beaufort Gyre whose southern boundary lies at the northern edge of the study area during summer. This eddy is huge, extending as far as the North Pole, and is associated with a clockwise circulation. Mean speeds in the southern Beaufort Sea are of the order of 4 cm/sec, but a large variability exists.

The Gyre generally does not extend much further south than the edge of the continental shelf, to a depth of about 200 m. Closer inshore the surface water in summer moves to the east at about 50 cm/sec, fed largely by the Mackenzie River discharge. In Mackenzie Bay, most of the water from the river swings east along the northern side of Richards Island; however, near Kay Point there appears to be a current setting northwest, particularly during easterly winds. Inshore and close to the bottom there appears to be a general current set to the northeast, following the bottom contours. This flow probably extends throughout the water column below the surface layer and has a speed of about 5 cm/sec.

The actual flow at any given time may be different from the general movements discussed above. Wind has a strong influence on the flow in the surface layer. Under west or northwesterly winds there is a marked flow to the east throughout the region, with the wind aiding the general easterly flow of the river water. Speeds of more than 60 m/sec have been recorded. These winds lead to an onshore convergence in the surface layer because of the Coriolis effect.

Easterly winds lead to a westerly flow. Offshore velocities of over 50 cm/sec can occur under strong winds (> 10 m/sec). Closer inshore along the Mackenzie Delta and for a short distance along the Tuktoyaktuk Peninsula area there is still an easterly flow of the river water. The easterly flow soon reverses and leads to divergent flow (upwelling) along the coast. There is some evidence that the deeper water has a shoreward component.

When the wind is calm or changing the flow becomes more complicated in some areas. Eddies (some larger than 15 km in diameter) can be found, complicating the current structure and are revealed as anomalies in the surface salinity and temperature distribution.

Except for an area north of Richards Island, near the entrance of Kugmallit Bay, there is very little obvious tidal motion. Generally, the tidal currents are masked by the mean flow. Only in the Richards Island area do the currents clearly show a tidal component superimposed on a small mean flow; the reason for this anomaly is not yet clear.

Waves can be a problem during the open-water season. As well as interfering with shipping and threatening man-made structures, they provide the major erosional force. Acting together, short-period waves and a long-period storm surge can seriously erode coastlines, man-made islands and inundate large areas of the relatively flat coastal land. The most likely conditions for such events occur in the presence of northwesterly gales during a good ice year. The long fetch allows large waves to be generated and provides the condition for a positive storm surge. Most of the annual coastal erosion occurs during such conditions. Negative storm surges which are observed as a decrease in sea level at the shore are less of a problem, affecting mainly shipping in shallow areas. Not much is known about the currents associated with storm surges although the shorter-period waves generate littoral transport, moving finer sediments along the shore and thus contributing perhaps in some degree to the turbid layer near the bottom.

Ice motion is determined by winds, currents and its concentration. Most of the first-year ice is less than 2 m thick except at pressure ridges; it tends to move with the wind, as does the surface water. Multi-year ice, rafted ice and ice islands have a greater draught than does first-year ice, and would thus be affected more by depth-integrated currents than by the wind. Ice of shallow draft generally moves with the greatest speed when the wind is 10 m/sec or greater and when ice concentrations are low. As the ice concentration increases, internal ice stresses become significant and then the ice field as a whole moves more slowly than do the individual floes.

8. RECOMMENDATIONS

8.1 Distant Surface Water Movements

The destiny of buoyant surface materials released in the coastal areas of southern Beaufort Sea would be similar to the destiny of the muddy discharge water of the Mackenzie River. Thus the motions attributed to this surface water can be considered applicable to oil spills. Ice can have a significant effect on the distribution of the river water such as occurred during the summer of 1974 when the polar-pack ice virtually dammed up the Mackenzie River outflow, causing a shallow lake of fresh water to form between the ice and the shore. Near the end of August, satellite pictures showed that the dam had broken to the northeast of Cape Bathurst. The resulting surface outflow around Cape Bathurst moved toward Banks Island and took about 20 days to reach Sachs Harbour. Amundsen Gulf was ice-covered at the time. In contrast, in 1975 Amundsen Gulf was free of ice and at times the Mackenzie River water moved east around Cape Bathurst and along the mainland coast, while at other times, it moved offshore and to the west. These surface waters flowed rapidly, at times in excess of 50 cm/sec in response to the wind. It is evident that a concerted study of the more distant muddy surface water movements relative to the wind fields and ice boundaries would aid in oil spill contingency planning.

8.2 River Water Movements Under Landfast Ice

Observations of currents under the landfast ice during the spring showed slow, low-salinity water movements offshore toward a lead at the edge of the landfast ice. The Mackenzie River discharge appeared to have a major northward moving component in addition to the easterly one normally expected due to the Coriolis effect. This northward flow could have been the result of a 2 m hydraulic head difference between the bottom of the ice and the lead's surface water. This implies that leads in ice fields could induce pressure gradients which could cause a less dense water layer under ice and buoyant pollutants to emerge in leads. Further field observations could be made to explore the possible role that leads play in channeling the water of the Mackenzie River.

8.3 Convergent Regions

The clustering of ice floes observed in satellite photographs points to the existence of areas of convergent water flow. Also, some areas of coastline show greater concentrations of driftwood than others. These convergent regions would likely concentrate floating oil and other floating materials and could simplify cleanup by concentrating floating oil. More study should be directed to locating such areas, exploring in more detail the reasons they exist and their variability with time of year.

8.4 Upstream Observations of Sea Ice

If the historic track of ice island T3 is indicative of the route that polar pack ice follows through the Beaufort Sea from Banks Island to the southwest then the multi-year ice north of the Tuktoyaktuk Peninsula in the summer would exist about three months earlier somewhere off Banks Island, on the edge of the main polar pack. Hence, observation of the ice characteristics off Banks Island in the spring would provide an indication of type of ice to be expected offshore in the southern Beaufort Sea during the summer. Similarly, the type and concentration of ice floes as well as the winds prior to freeze up in regions upstream in the Beaufort gyre will be an important factor in determining ice conditions during the winter, particularly near the seaward boundary of the landfast ice. The track of T3 north of Tuktoyaktuk during 1953, near 71°N 134°W provides evidence of onshore and offshore movements of the southern edge of the Beaufort Sea Gyre in the summer which may provide additional clues to the frequency of pack ice excursions into shelf waters. A study should be initiated to verify these conjectures and their relationship to "good" or "bad" ice years.

8.5 Waves

Wave action is one of the main factors determining how effectively marine oil-drilling work can be carried out. Wave action could affect such aspects as anchoring, abandonment and reconnecting procedures and resupply. Oil countermeasures are also affected by waves in that they limit efficient deployment of equipment and personnel. It is clear that a combination of strong easterly winds and open water conditions in Amundsen Gulf and seaward of the Mackenzie Delta area could combine to produce larger waves than have been recorded so far. Unfortunately, no wave records were obtained during major easterly storms in either 1974 or 1975. An offshore wave measuring program should be initiated to verify empirical predictive techniques for the southern Beaufort Sea.

8.6 Bottom Currents

Current measurements indicate the existence of a persistent easterly bottom current on the continental shelf. It is not clear that this is a permanent feature and if it is related to the easterly flow reported off the north coast of Alaska. Further study is required to determine the persistence of this current and its source.

8.7 Water Transparency

More information on the seasonal variation of water transparency should be obtained. The likelihood of increased diver and submersible activity during offshore drilling operations makes this of particular importance.

8.8 Inshore Oceanography

This study on physical oceanography has dealt mainly with the movement of major water masses in the offshore regions of the southern Beaufort Sea and has largely neglected the smaller-scale oceanography inshore. Fisheries studies have revealed the importance of inshore bays, lagoons and estuaries as important juvenile fish feeding areas. In summer, these inshore areas are warmer and more productive while in winter they serve as overwintering areas for some fish species. Also, in summer these inshore areas serve as life support systems for many feeding and flightless moulting birds. Consequently, studies on water circulation and nutrient transport should be initiated in the relatively shallow inshore areas. These studies would also aid in defining the more biologically productive inshore waters and water movements of importance to oil spill countermeasures.

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A.1 SOME OCEANOGRAPHIC TERMS

Baroclinic Current - Also called the *relative current*, is the horizontal current due to the internal density distribution in the water. Density gradients in the water cause horizontal pressure gradients which in turn produce a flow. Since the density (mass distribution) varies with depth, baroclinic currents generally also vary with depth.

Barotropic Current - Another name for this current is the *slope current* since it is due to the pressure gradient caused by the slope of the water surface. Barotropic currents are independent of depth.

It should be noted that, by convention, the directions of the currents are always defined as that *to* which the current is flowing while the direction of winds are defined as the direction *from* which the wind is blowing.

Convergence - A convergence exists if there is a net inflow of fluid into a volume. In meteorology and oceanography the term may refer to two dimensional motion, usually horizontal. Since water can be considered to be incompressible for most purposes, horizontal convergence implies that there must be a vertical flow out of the volume to maintain mass balance. The vertical motion may include a change in elevation of the water surface.

Divergence - Divergence is the opposite of convergence, i.e. it refers to a net outflow of fluid from a volume. Again the term is often used when referring to horizontal motion.

The Core-Layer Method - Also referred to as the *core method*, it is a way of studying the spreading out and mixing of water types. The *core* is the region of a water layer where temperature or salinity (or both) reach extreme values, whether high or low. By plotting temperature versus salinity for the water in the layer (called a T-S diagram) at various geographic positions, a series of T-S curves are obtained. Using the T-S curve of the source region as a reference, one can determine the percentage of the original water type that is found in any locality. The method only works where the water properties of the core are significantly different from the surrounding water.

Estuary - An estuary can be defined as a partly enclosed body of water in which sea-water is diluted by fresh water run-off and with a connection to the open sea. Estuaries may be classified by either the bottom geometry or the water stratification. The inflow of fresh water, usually from rivers picks up some salt by mixing with the more saline water of the estuary. This water flows out to the open sea in the upper layer with an inflow of sea-water below it. The inflowing saline water replaces the salt removed from the estuary by the outflowing brackish water. Large areas of coastal seas may exhibit similar characteristics; for example, the northeast Pacific or parts of the Arctic Ocean.

Coriolis Force (Effect) - This effect arises from the fact that our usual coordinate systems are rotating with the earth. For horizontal motion this introduces an apparent force to the right for motion in the northern hemisphere and to the left in the southern hemisphere.

Geostrophic - The term geostrophic when applied to water currents or winds refers to flows which result from a balance between Coriolis force and the horizontal pressure gradient. It is assumed that any effect due to acceleration or the friction is small enough to be ignored in calculation of these currents. Both barotropic and baroclinic components can be calculated for a steady current by the geostrophic method if the pressure gradients can be determined. Usually only the baroclinic component can be determined. Usually only the baroclinic component can be directly calculated since the slope of the sea surface is difficult to measure.

Gyre - A gyre is a large-scale feature similar to a large eddy, and featured by circular horizontal motion. In the Arctic Ocean there is a gyre over the Canada Basin, characterized by a clockwise circulation of water (and ice) with average velocities ranging from 1 to 5 cm/sec and centred south of the north pole.

Halocline - A depth interval in the sea which is featured by a maximum in the salinity gradient as a function of depth. The water column may exhibit more than one halocline simultaneously; for example, the Arctic Ocean there is a main halocline between depths of 50 to 250 m as well as a seasonal halocline near the surface due to ice melt and run-off.

The terms *thermocline* and *pycnocline* are defined in a similar manner for temperature and density respectively. For low temperature water (as such occurs in the Arctic), the density is generally a weak function of temperature. Hence the density profiles are similar to the salinity profiles in appearance and the pycnocline coincides with the halocline.

Inertial Period - A body in horizontal motion will experience an apparent deflecting force at right angles to its path; to the right in the northern hemisphere due to the Coriolis effect. If the motion is in a closed circle relative to the earth's surface such that the inward-acting Coriolis force is balanced only by an outward-acting centrifugal force it is referred to as inertail motion. The circle formed is the *circle of inertia* and its radius, R, is proportional to the body's velocity, V. The time required to complete one circle is termed the *inertial period* and is proportional to $\frac{R}{V}$. The inertial period varies inversely with latitude.

Upwelling - In general terms, upwelling refers to the process whereby subsurface water is brought to the surface as a result of divergent motion in the surface layer. For example, if a wind blows parallel to a coastline with the land to the left of the direction to which the wind is blowing in the northern hemisphere, then there will be a net transport of water away from the shore in the surface layer (i.e., a divergence) due to the Coriolis effect. Deeper water, from depths less than 200 m, will then flow shoreward and come to the surface to replace the surface water transported away.

DATA COLLECTION AND REDUCTION

B.1 Observation Platform

During the summer of 1974 observations were made from the M.V. Theta, an ice-strengthened charter vessel resembling a North Sea trawler (Figure 1A). Her length, breadth and draft are 50 m, 8.5 m and 4 m respectively. An 800 h.p. diesel and a directly driven variable pitch screw give her a cruising speed of just over 9 knots.

Following standard practice, observations were made from the starboard side. Bottle casts and turbidity measurements were made from an A-frame gallows located on the main deck just aft of the break in the forecastle, while STD casts and current profiles were taken from a small gallows (Figures 1B, 1C) located on the main deck near the forward corner of the deckhouse. A small portable laboratory located on the main deck between the helicopter platform and the deckhouse contained the electronic equipment.

During the spring of 1975, various synoptic observations were made from the ice using a Bell 205 helicopter. C.T.D. casts were carried out by having the recorder, winch and generator in the helicopter. The helicopter normally landed beside a lead, or a hole was drilled in the ice through which the equipment could be lowered (Figure 2BO.

The time series were made at an ice camp from inside a portable shelter (Figure 3A). Four men occupied these ice camps taking hourly observations for 2 to 4 days. The first ice camp (Camp A - Inset Figure 12) was on a drifting ice floe about 1 m thick while the other camps, B and C were on shorefast ice of thickness 1½ to 2 metres.

In the summer of 1975 observations were taken from both the M.V. Pandora II and an anchored barge. The M.V. Pandora II was an ice-strengthened charter vessel originally designed as a drill-rig supply vessel; however, it was redesigned as a mothership for the PISCES submersible. This has not made her an ideal oceanographic vessel.

The chains, A-frame gallows and oceanographic winches were located midship on the starboard side about 6 m above the water. A small portable laboratory near the CTD winch contained the CTD electronics. At times the ship's waste water was pumped overboard during stations, making surface data of dubious value.

Observations were also taken from one of the barges at the Canmar site (70°10.6'N, 132°58.9'W), north of Tuktoyaktuk. These barges were moored by a four-point anchor system. Observations were made from the upstream side of the barges. Mud from the caisson hole was pumped overboard, possibly leading to non-typical water transparency measurements in the water column.

Surface wave observations were made using wave-rider buoys (Figure 4A) supplied by the Wave Climate Study, Marine Environmental Data Service (M.E.D.S.), Department of the Environment, Ottawa. The buoys contained an accelerometer and a VHF transmitter which operated continuously.

The acceleration signal is integrated twice before transmission. At the base receiving station, a timer and controller activate the receiver and tape recorder every three hours to make a twenty minute recording of the waves. The buoys respond to wave frequencies between 0.05 to 0.5 Hz (20 to 2 sec. periods).

B.2 Salinity and Temperature Measurements

B.2.1 Bottle Casts

Bottle casts were carried out primarily for the collection of water for chemical analysis but also for the calibration of the STD (described later) and as a backup in case of poor STD data. Reversing thermometers were used on the bottles. A third of the salinity samples were analyzed aboard ship with an Autolab laboratory salinometer, the remainder were analyzed in Victoria. The reversing thermometers gave considerable trouble and the failure rate approached 50% at times during spring and summer operations.

The accuracy of the salinity determinations carried out in the above manner was estimated as ± 0.005°/₀₀, however at low salinities, particularly below 10°/₀₀, the uncertainty is much greater. Only a minority of the samples (i.e. near surface) had low salinities, most values being greater than 30°/₀₀.

For the reversing thermometers an accuracy of ± 0.02°C can be expected for a single thermometer measurement while for the average of two thermometers at the same depth the uncertainty was estimated to be ± 0.01°C.

Normal bottle cast procedures were followed using standard depths of 0, 1, 3, 5, 7, 10, 15, 20, 25, 30, 40, 50, 75, 100, 125, 150, 175 and 200 metres. Modifications were made as conditions required. "Soaking times" of 5 to 10 minutes were used.

B.2.2 STD and CTD Measurements

A Guildline 8202 Arctic probe with a 8101 deck unit was used to obtain vertical profiles of salinity and temperature. A small winch, equipped with electrical slip rigs, was used to hold a seven conductor cabe (Figure 3B). Salinity and temperature profiles were recorded on paper charts. A 0 to 300 decibar pressure transducer was used, giving a depth range to 300 metres. During the spring and summer of 1975 a similar CTD was used. The unit worked well except for a period when temperatures outside the helicopter ranged between -35°C to -40°C. As soon as the helicopter's side door was opened the ink in the recorded pens would freeze. The underwater probe also had to be kept above 0°C for its "chopper" motor to operate properly when turned on. The overall accuracy of the unit was estimated to be ± 0.05°/₀₀ for salinity and ± 0.01°C for temperature.

B.2.3 C/T Probe Measurements

In the spring of 1975 a Hydrolab model TC-2 conductivity and temperature probe was used to obtain profiles. Two problems were discovered during use: the deck read-out unit was temperature sensitive and the long time constant of the temperature probe. The conductivity appeared to less influenced by the temperature of the deck unit than the temperature. Thus some difficulty was encountered when attempting rapid profiling in low air temperatures (-35°C). The probe also showed a tendency to ice up when exposed to low air temperatures too long before entering the water. Accuracies of ± 0.15°/₀₀ and ± 0.05°C apply to these data.

Salinity and temperature data were obtained from the Canmar barge in the summer of 1975 using a Beckman model *in situ* salinometer. Instrument accuracies were similar to the Hydrolab unit. However, large wire angles reduced the reliability of recorded profiles.

B.3 Turbidity Measurements

Two different types of instrument were used for light transmission observations. During the summer a Hydrowerkstatten #382 instrument with a 75 m calbe was utilized. The underwater unit consisted of an incandescent lamp in one watertight housing and a photocell in another watertight housing. The two units were mounted on a piece of aluminum channel separated by 1 metre. Included in the photocell housing were two optical filters (RG1 and BG12), the filter to be used being selected by the polarity of an applied voltage.

At first, difficulties in instrument operation resulted from the low water temperatures. This problem was solved by inserting a small package of silica gel dessicant in each underwater unit. The readout unit was located on deck, and the measurements were in terms of photocell current where the reading in air was used as a reference (100% transmission). The profiles are considered to be qualitative rather than quantitative, particularly those associated with use of the BG12 filter, which resulted in greater than 100% transmission in a number of cases. It is possible that this may have been a temperature effect. The general shape of the profiles appeared reasonable, the "turbidicline" coinciding with, or being located just below, the depths of the halocline and thermocline.

The procedure in making a cast is as follows: After a careful cleaning of the lenses on the underwater unit, the "in-air" readings were made sequentially using both filters, taking care not to expose the photocell to the direct sun. Readings were then made at standard depths, to a maximum depth of 65 m, using one optical filter on the way down and the other on the way up.

During the spring and summer of 1975 a Hydroproducts 612S turbidity meter was used; this instrument possessed no filters, and only a white light source. The optical path length was also one metre. It was used in a similar manner to the other unit. The readings of this unit were relative to a transmittance of 92% in air; hence these results were converted to values with a 100% reading in air to facilitate comparison with the 1974 data. Figure 5 shows a comparison of measurements from the two instruments under identical conditions.

B.4 Current Measurements

The main current meter used in summer and spring was a Hydroproducts Model 460 speed sensor and model 465A direction sensor. The direction sensor had been modified for use in the Arctic. In the summer of 1974 only a few profiles were obtained, since both leakage of the underwater termination and breakage of the electrical conductors occurred, however, in the spring of 1975 the meter worked very well. Accuracies were ± 5° for direction and ± 3% of the reading for speed with a low speed threshold of 2.5 cm/sec (0.05 knots).

During the spring of 1975 a Cushing electromagnetic current meter was used, but the cold temperatures (-35 to -40°C) appeared to damage the unit, even though it was exposed to these temperatures for only short periods of time. The unit was repaired and used during the summer of 1975 with good results.

B.5 Ship Drift and Meteorological Observations

Whenever the ship was stopped for any length of time the officer-of-the-watch was requested to record, at regular intervals, the ship's position as well as the ship's head, wind direction and speed. The ice-cover was influenced not only by the wind and currents, but also by the ice, and at times by the ship's engine since it was not possible to maintain a zero propellor pitch setting. Errors due to misreading of the Decca receiver may also have occurred. Despite such possible errors, the drift obervations are considered useful.

Meteorological observations were made by trained technicians as well as by others in the scientific complement during 1974 and 1975 from both vessels. In the spring, weather observations were taken at the ice camps by the oceanographic personnel. Air pressure, temperature and wind were recorded.

B.6 Ice Drift During Spring

Radiobeacon buoys (Figure 4B) were set out on the ice north of Kugmallit Bay to a distance of 90 miles from Tuktoyaktuk. The buoys were located by using a directional antenna and receiver installed in a Bell 206 helicopter to home on the beacon, then the position of the helicopter was fixed by Decca. Fog limited the number of observations which could be made. The buoys are described by MacNeill and Garrett (1974).

The ice-camp drift off Sachs Harbour was determined by Decca fixes from a helicopter which positioned the ice camp at least once daily.

B.7 Data Reduction

B.7.1 Summer 1974 Data

Turbidity measurements were plots of light transmission as a percentage of the transmission in air, as a function of depth for red and green light. Cross-sections of water transparency were drawn up as well.

When the Savonius current meter was used, the manufacturer's calibration was used for the speed sensor while directions were checked using the ship's gyro for a true north reference. Vertical profiles of current velocity were plotted for each cast. Three useable casts were obtained.

From a total of 60 oceanographic stations, 137 STD casts were chosen for digitization with 58 of these casts originating from the time series at Station 11. The computer processing of the data was done in steps. In the "pass one" program the digitized values were converted from digitizer inches into uncorrected values of depth, salinity and temperature. Another program was used to compare these results with bottle cast data. A linear correction equation was chosen:

$$\Delta y = a + by$$

where Δy was the correction to be applied to variable y, i.e. salinity or temperature as measured by the STD, and "a" and "b" are constants determined by a least-squares fit. The corrections were applied to the salinities and temperatures by the "pass-two" program.

The calibration data tended to form two clusters; low salinity (high temperature) from samples above the halocline (thermocline) and high salinity (low temperature) below. Hence it was considered that fitting a curve rather than a straight line was not warranted.

Then in the "pass-three" program the corrected results were used to calculate actual depths, sigma -t's, specific volume anomalies, dynamic heights, potential energies and sound velocities at standard pressure intervals. The output from "pass-three" was then subjected to a plotting program which produced vertical profiles of temperature and salinity versus depth for each cast.

The wave data, on magnetic tape, were sent to the Wave Climate Study, Marine Environmental Data Service (M.E.D.S.), Ottawa for processing. A description of the available processing is given in a manuscript report available from M.E.D.S.

B.7.2 Spring and Summer 1975 Data

The turbidity profiles and current profiles were plotted in a similar manner to the 1974 data. In addition, the north-south and east-west components of the currents were calculated and plotted. Progressive vector plots were also constructed for the currents at each depth. Wave data were again processed by M.E.D.S.

Including those obtained during the time series, there were 119 CTD casts obtained in the spring, plus 76 from the summer of 1975. The CTD profiles were treated in the same manner as the 1974 STD data, except that salinity values were calculated from the conductivity and temperature observations.

B.8 Other Sources of Data

For purposes of comparison, data from previous years was plotted. As well as the data from previously mentioned publications such as Cameron (1952, 1953) and Healey (1971), data from various ice breaker cruises was used (Marine Surveys Division 1963a, 1963b, 1964).

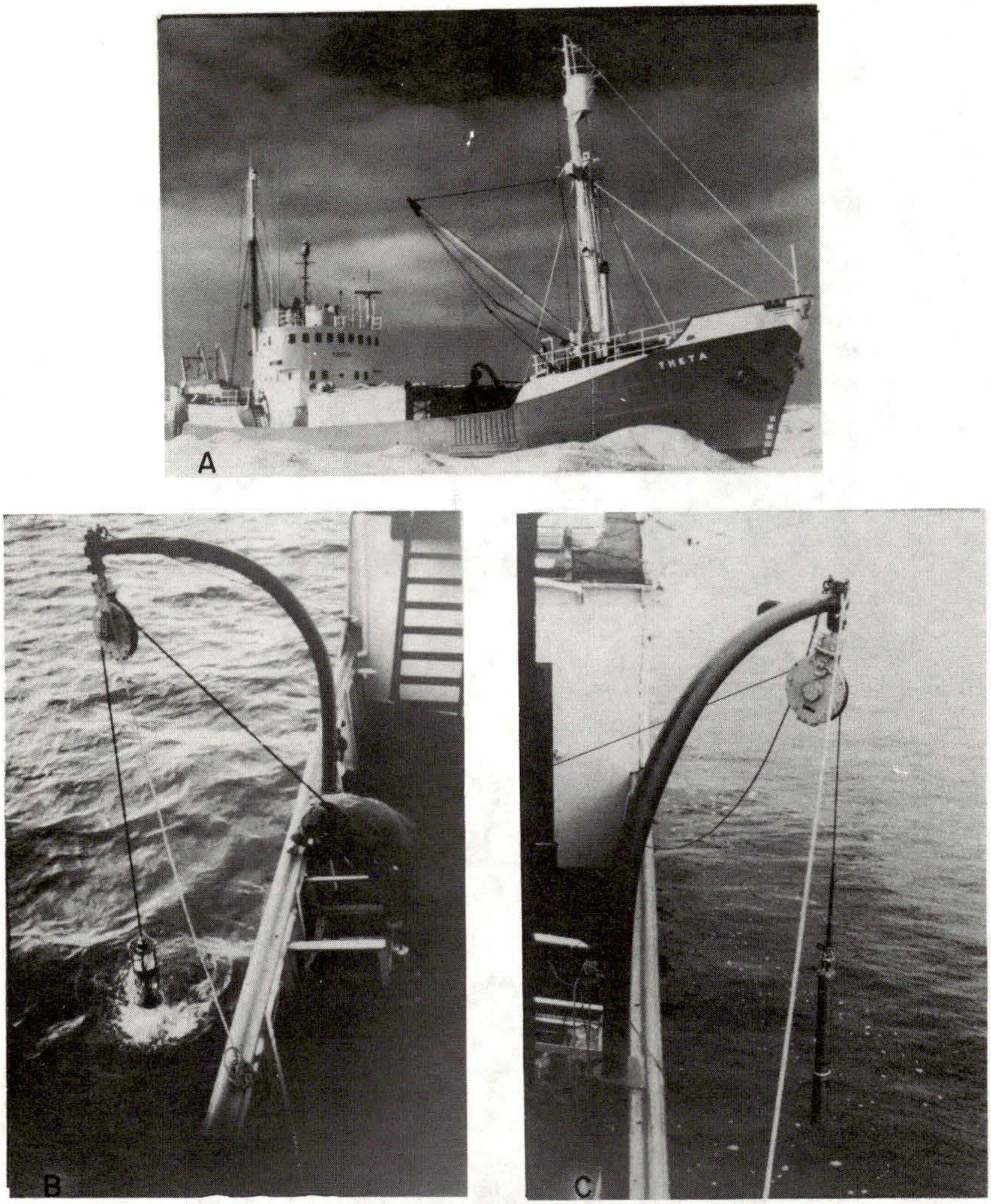

Figure 52. A: shows the M.V. Theta in multi-year ice during the summer of 1974. B: a current meter. C: an S.T.D. being lowered.

Figure 53. Oceanographic observation from a 205 helicopter. A: S.T.D. probe through lead. B: C.T.D. probe through drilled ice hole.

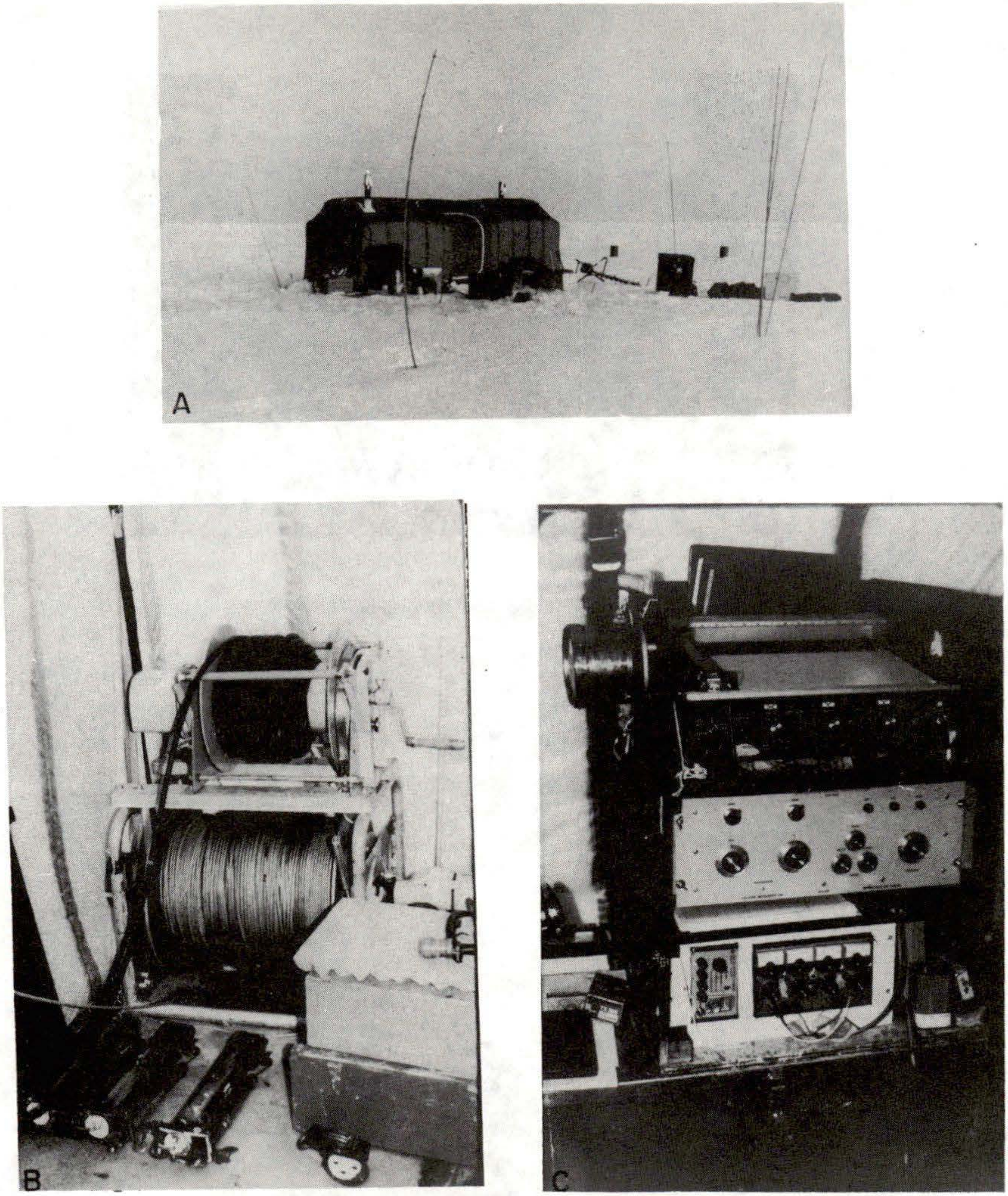

Figure 54. A: Spring 1975 ice camp shelter with, B: current meter, CTD winch and Fjarlie bottle, and C: CTD x-y recorder and deck unit.

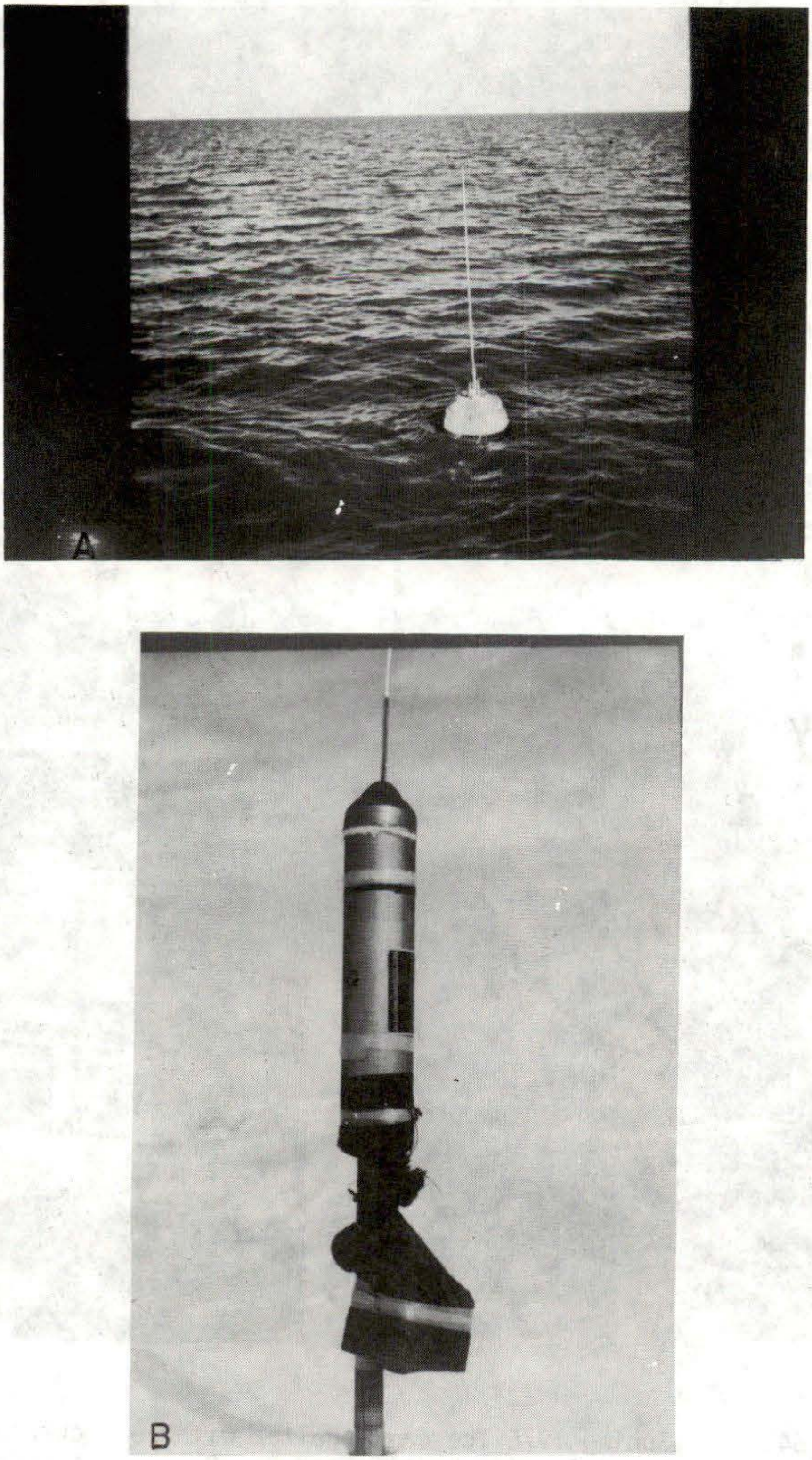

Figure 55. A: Wave Rider buoy used in Beaufort Sea Study. B: Radio beacon used in ice drift measurements.

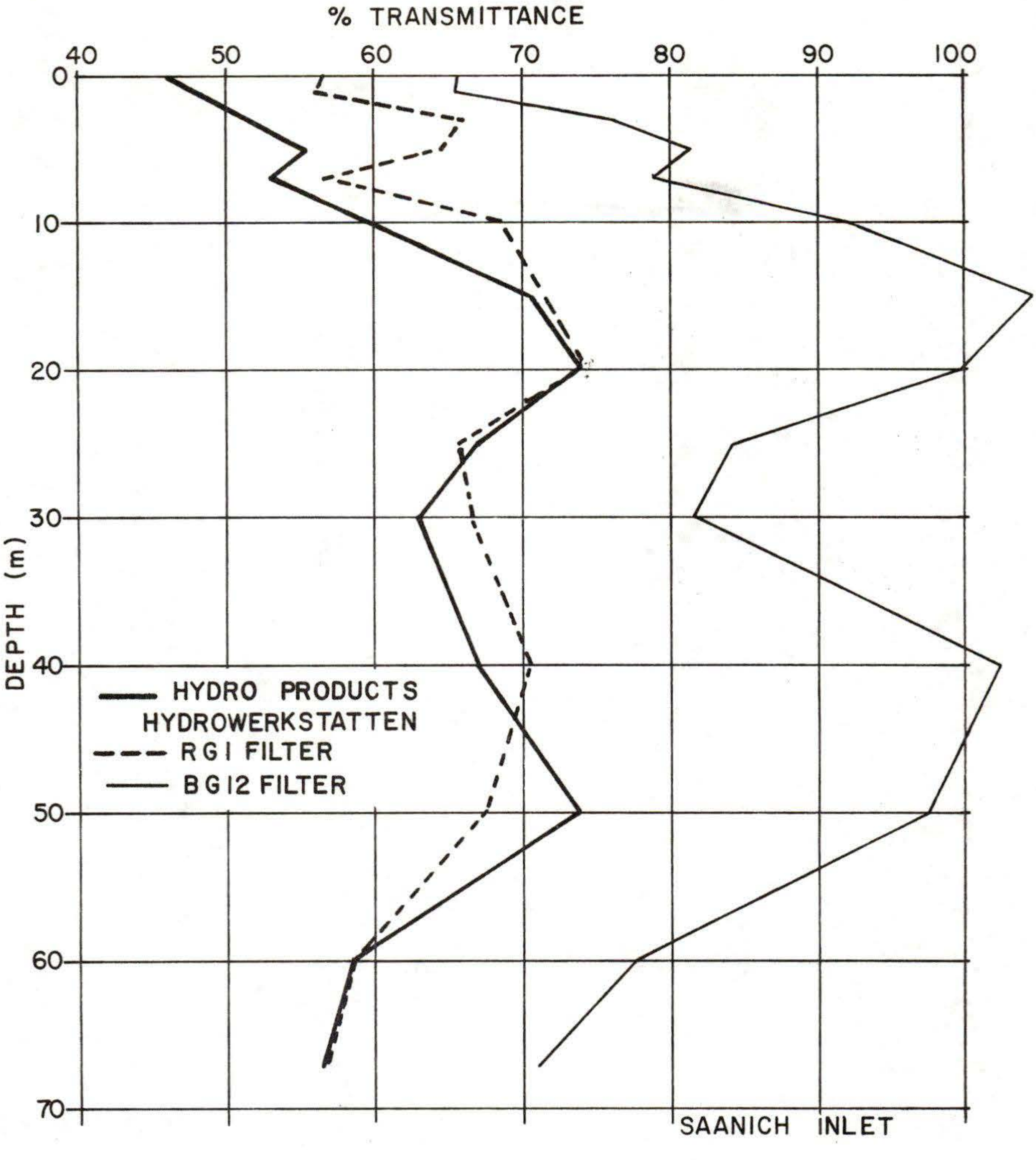

Figure 56. Comparison measurements using two turbidity measurements.