Open Water Surface Currents

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Beaufort Sea Project

OPEN WATER SURFACE CURRENTS IN THE SOUTHERN BEAUFORT SEA

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

1. SUMMARY

One of the investigations of the 1974-75 Beaufort Sea Project was an offshore, near-surface current study. A drifting surface drogue was developed that could be deployed and tracked using an aircraft, thus enabling examination of the surface currents over a large area of the Beaufort Sea.

In 1974, a field crew, using a Twin Otter aircraft, tracked a number of these drifting drogues from early August to mid-September. Due to severe ice conditions, the area of the drogue study was limited (see Fig. 2) to Mackenzie Bay, Kugmallit Bay and a ten mile range off the northern coast of the Tuktoyaktuk Peninsula as far east as Point Atkinson - although some ice floes with radio beacons placed on them were tracked further offshore (70°30'N). The limited observations seemed to indicate that the currents were chiefly wind-driven. This was especially evident in the cases of (1) steady northwest winds and (2) steady east winds, which dominated the summer in their strength and duration. It was observed that during a northwest wind, a northeasterly longshore current developed along the whole coast enhanced by the Coriolis force on the Mackenzie River discharge. During the strong eastern wind from September 11-15, the movement of water was to the northwest, often at speeds of up to 40 cm/sec in a wind with a speed of approximately 10 m/sec. Several persistent features observed were (1) a strong northwest current of 40 to 80 cm/sec flowing out of Mackenzie Bay to the east of Herschel Island and (2) an east flowing current along the Tuktoyaktuk Peninsula.

A similar field programme was conducted in 1975. Tracking was carried out again using the Twin Otter with the assistance of a Bell 206 Helicopter. The ice conditions in 1975 were entirely different from 1974 which no doubt had a significant effect on the surface currents and their response to weather systems. At the outset of the programme on July 21st, an ice reconnaisance showed the pack ice (Fig. 2) to be north of 71°10'N at 133°W out from Tuktoyaktuk and north of at least 70°N at 139°W out from Herschel Island. These ice limits, although they steadily moved shoreward as the programme progressed, provided a much larger open water working area than in 1974, so that most of the work in 1975 was carried out north of 70°N (vs south of 70°N in 1974).

The 1975 data again shows that the wind plays an important role in driving the currents, especially in the case of steady northwest winds and the aftermath of these winds; the other most important factor being the discharge from the Mackenzie River. Eddies of several different scale sizes and areas of divergence and convergence complicate the picture. In Mackenzie Bay, a persistent divergence is observed, and north of Richards Island a convergence is frequently observed. Considerable further study would be necessary to derive a more complete and coherent picture of the various time scales of surface water movement.

2. INTRODUCTION

The Beaufort Sea Environmental Project, jointly sponsored and financed by the oil industry and the federal government, was a group of investigations organized to study the impact of offshore oil drilling on the Beaufort Sea and its environs, and conversely the effect of the Arctic environment on the practicability of offshore drilling.

The most important aspect of the oceanography of the sea to affect drilling will probably be the movement of water and ice - critical to the prediction of oil movement in the case of a spill and also crucial to the determination of safe drilling methods. Consequently, it was essential to have a greater knowledge of the surface currents in the region of the Beaufort Sea likely to be affected by oil drilling. The chief objective of this study was to determine an overall picture of the offshore near-surface circulation in the Beaufort Sea south of the polar pack from Herschel Island to Cape Dalhousie using the direct observations of drifting drogues. This involved covering a very large geographical area in a limited length of time so that a technique for tracking drogues over a large area using aircraft was evolved.

The overall circulation picture is the result of many factors on several different time scales and it has been the intention of the study to achieve some understanding of the effect of wind, tides, fresh water discharge and pressure fields on the surface currents (1) in the long-term mean over the several months of the study; (2) in day to day variations; (3) in shorter time scale changes in the régime of hours. With the increased understanding of the near-surface currents, an attempt has been made to provide some predictions of the possible and probable movements of oil and ice, and to estimate some of the possible dangers involved in offshore drilling.

3. HISTORICAL REVIEW

There have been few direct observations of surface currents in the Beaufort Sea. Up to 1974, the chief source of direct current measurements has been from drifting ice islands such as T-3, NP-6, AR-1, NP-7, etc. in the Beaufort Sea north of 71°N. From the long-term paths of these drifting islands, the theory of the well-known Beaufort Gyre moving around the sea in a clockwise direction with an average peripheral speed of 4 cm/sec has been clearly defined and documented - for example by Coachman (1968) who concluded, referring to the gyre, that "over the long-term, the winds associated with the mean atmospheric pressure field drive the ice in a similar pattern". A theoretical treatise on "Winds and Currents in the Beaufort Sea" by H.P. Wilson (1974) constructed a meso-scale model of surface circulation based on the average wind patterns. He predicted a cyclonic circulation around the Beaufort Sea in winter with a centre northeast of Herschel Island. He also predicted an eastward flow of Mackenzie River water along the coast from the Mackenzie Delta to the Amundsen Gulf.

Current meter and drifting drogue measurements off these manned ice islands have provided other useful information about the surface layer such as the existence of the Ekman spiral in the wind-driven surface layer and movement of ice to the right of the wind as documented by Hunkins (1965). More recently, the development of high resolution satellite-based imaging systems (e.g. from ERTS and NOAA satellites) has allowed detailed study (Marko, 1976) of both pack ice drift and ice floe drift and their correlation with meteorological events.

There have been many years of scattered synoptic oceanographic cruises in the Beaufort Sea which have provided valuable insight into the surface component of the sea's circulation south of the polar pack. Cameron (1953), for example, from his 1952 data, plotted surface salinity distributions for periods of (1) northwest winds and (2) east winds which clearly illustrated the surface water movement in both cases. During northwest winds, there was a strong positive gradient of salinity from the coast towards the northwest with the low salinity Mackenzie River water hugging the coast as it moved northeast along the Tuktoyaktuk Peninsula. During east winds, the lower salinity water was driven offshore by the wind and salinity values were higher close to the coast as a result of the upwelling of deeper, more saline water. Today, again through satellite imagery, these characteristic circulation patterns can be seen more clearly in photographs of the Mackenzie River plume.

Another indirect clue to the dominant long-term average surface water movements is the sediment dispersal pattern on the ocean floor which indicates the Mackenzie River discharge of the past was generally towards the east (Pelletier, 1976). Geological evidence of littoral currents on the Beaufort Sea coast has been studied by Lewis (1976) by examining patterns of sediment erosion, transportation and deposition and defining sediment "sources" and "sinks".

The only recorded Lagrangian surface measurements ever taken in the southern Beaufort Sea were in the summer of 1970. A scientific party working off the *C.S.S. Richardson* (Healey, 1971) measured surface currents by tracking two types of free-floating current followers. The tracking sessions were limited to nine hours each in Kugmallit Bay, off Atkinson Point and off Pullen Island. Fourteen such tracking sessions were carried out.

From the above discussion, it is obvious that one of the biggest gaps in the somewhat sketchy knowledge of the surface circulation in the Beaufort Sea was exactly the area of greatest relevance to the subject of offshore-drilling - the summer open water area south of the polar pack. Hence, a systematic study of the overall surface circulation of the southern Beaufort Sea was an urgent requirement before any exploratory offshore drilling occurred.

4. STUDY AREA

The geographical area of the study reaches from Herschel Island at 140°W to Cape Dalhousie at 128°W in an east-west direction, and from the five fathom contour line off the Mackenzie Delta and Tuktoyaktuk Peninsula to as far north as the polar pack in a north-south direction. Fig. 2 shows the study area in 1974 and in 1975 where its northward extent was limited by the pack ice boundary in both years. In 1975, the polar pack was 180 km offshore north of the Tuktoyaktuk Peninsula whereas in 1974, the polar pack formed a huge dam around the whole delta region from Herschel to Cape Dalhousie, approximately 35 km from shore. The difference in the polar pack boundary between 1974 and 1975 is quite dramatic, and this difference would be expected to have a significant effect on the surface circulation.

The dominant topographical feature of the southern Beaufort Sea is the Mackenzie River Delta (see Fig. 1) through which the Mackenzie River drains into the sea. The main channels of the Mackenzie drain into Mackenzie Bay (west channel), through Richards Island (middle channel), and into Kugmallit Bay (east channel) - 30% of the discharge is into Kugmallit Bay, 10% into Mackenzie Bay, and 60% through Richards Island (Davies, 1976). A peak flow of approximately 800,000 cfs from the Mackenzie occurs from mid-May to the beginning of June which drops to 250,000 cfs in July and August. Other major rivers entering the area are the Babbage and Blow Rivers discharging into the western side of Mackenzie Bay. The entire coastline is indented with many smaller bays, and dotted with spits and islands. The main islands are Herschel Island in northwestern Mackenzie Bay, Pelly, Hooper, Gary and Pullen Islands off the Mackenzie Delta and Richards Island which forms the main part of the delta.

Topographically, the region is uninteresting - the whole coast being very flat with the exception of the Richardson Mountains running in a north-south line on the Yukon-N.W.T. border to the southwest of Herschel Island.

The bathymetry is shown in Fig. 1. The main features are the extension of the delta as a continental shelf which stretches offshore 180 km to the 400 metre contour, and Herschel Canyon east of Herschel Island which extends from Mackenzie Bay deepening in a northwest direction offshore.

Summer weather in the Beaufort Sea can vary considerably from one year to the next. During the 1975 field season, 63% of the winds at Immerk Island near Pelly Island were from the west and 37% from the east. The summer was punctuated with four northwest storms of average wind speeds greater than 8 m/sec and only two northeast storms. Steady northwest winds appear to be a salient feature of the summer climate; they are usually caused by the passage of a low pressure system from west to east across the northern Beaufort Sea. They push the polar pack and ice floes towards the shore. Strong east winds are caused by the movement of a high pressure system from east to west and are instrumental in breaking up the polar pack and pushing it offshore. Between storm passages, periods of reasonably calm, fine weather can prevail for days or even several weeks.

The frequency and strength of northwest storms appears to be the determining factor controlling ice conditions and the average summer climate.

5. METHOD AND SOURCES OF DATA

5.1 The Drogue

5.1.1 1974

The idea behind the experiment was to drop and track drifting surface drogues using aircraft. The drogue itself (Fig. 3) consisted of a flat styrofoam float, 30 cm wide x 60 cm long x 1.2 cm thick. To one side of the float was attached a 7 m long plastic panel (later shortened to 3.5 m long), weighted at the end with an iron bar which hung into the water acting as a sail to be moved by the currents; to the other side of the float was attached a 21 m long floating plastic panel (later shortened to 14 m long), painted orange to make it visible from 7 km at 1600 m altitude, thus easily seen from an aircraft. A buoyant, 66 cm high, cylindrical radio beacon, constructed to withstand the impact of being dropped from a height of 35 m at a speed of 50 m/sec, was tied with string to the styrofoam; it transmitted a signal which was picked up (range - 48 km at 1600 m altitude) with the receiving equipment in the aircraft (see Appendix D). To make a package that could be dropped from the aircraft, the plastic panels were folded accordion-style and wrapped around the radio beacon; the package was then tied with string and fastened with water-soluble plastic. The cylindrical package was further held together by a square piece of nylon - 60 cm x 60 cm - wrapped around the bottom which was tied at the four corners with four lengths of string which were tied to a parachute of the same size - 60 cm x 60 cm. The parachute stabilized the fall of the drogue. Upon impact with the water, the water-soluble plastic tie dissolved, the parachute floated off and the drogue unfolded. The drogues were expendable, with the radio beacons designed to continue transmitting for two weeks before the batteries became too weak.

5.1.2 1975

Tests done on the drogues between the two summer field programmes resulted in several modifications to the drogue and drogue package. First, the parachute was eliminated from the dropping package as unnecessary (actually a hindrance to the unfolding of the drogue because the string tended to wrap itself around the drogue instead of floating off). Second, the beacons were sealed and taped to ensure against water leakage, and the strings replaced with plastic strapping. Third, it was eventually decided to eliminate the floating surface tail on the drogue for three reasons: (1) tests showed the wind drift of the surface panel to be a significant component of the total drogue drift; (2) the panel was subject to twisting, staying folded or completely ripping off in large waves or strong winds so the effect of the panel on drogue drift was not constant and determinable; (3) searches for visual sightings of the panel proved too exhaustive and time consuming from the Twin Otter except in good weather conditions. It was felt that a radio fix achieved a fine enough accuracy for the time scales being observed (order of one day). On several occasions, sightings of the drogue were made at the location of the beacon determined by the receiver operator. During the last three weeks of the field study 40% of the fixes were actually visually confirmed.

5.2 Tracking the Drogue

5.2.1 1974

The drogues were tracked daily using a Twin Otter aircraft outfitted with a VHF fm scanning monitor receiver with eight channels designed to pick up signals of ≃ 150 MHz transmitted from the radio beacons. Two antennae, mounted on either side of the aircraft, picked up the signal; the strength of signal from each antenna indicated the direction and distance of the drogue from the aircraft (Appendix C). The drogues were usually tracked daily, sometimes two or three times a day, weather and circumstances permitting. The positions of the drogues were fixed using a Decca Navigation system. A visual fix of the drogues was always attempted but low fog or strong waves frequently prevented this; in these cases, a radio fix of the drogue was recorded. A visual fix was more desirable as it permitted a check of the drogue condition and its position with respect to the ice. The accuracy of a visual fix was 100 m; the accuracy of a radio fix ranged from ± 250 m to ± 800 m. The factors contributing to the error were error of Decca fix, error involved in reading the Decometers in a moving aircraft and, in the case of a radio fix, the uncertainty of the location of the beacon with respect to the aircraft.

5.2.2 1975

The tracking equipment and procedure was similar to 1974 (see Appendix C) except that, as was mentioned in 5.1.2, exhaustive visual sightings were not attempted. For the short term experiment, a Bell 206 helicopter outfitted with floats was used for deploying and tracking the drifters so that very accurate visual fixes of the drogue positions were obtained.

Because of the high malfunction rate of the beacons in 1974, an attempt was made in 1975 to drop the beacons as low and as slow as the Twin Otter was capable of, which turned out to be 17 m at 25-40 m/sec, depending on the wind speed. Deployment from the Bell 206 helicopter could, of course, be done from a hover, usually at about 3 m above the surface. The extra care taken in deployment, combined with the extra sealant added to the beacons, increased their survival rate, although 25% of the first 40 dropped in 1975 still failed to live up to even 1/3 of the design lifetime of two weeks (see Table III), regardless of which aircraft they were dropped from. This suggests that the malfunctions of 1975 were not due to the impact of the drogue landing.

5.3 The Field Work

5.3.1 1974

The field work in 1974 lasted from the 7th of July to the 20th of September. In early July the ice was solid in against the Mackenzie Delta and Tuktoyaktuk Peninsula, preventing the deployment of drogues. The first week was spent checking the Decca navigation system and testing and calibrating the receiver and antenna system. On July 13, four radio beacons were put out on pack ice; two north of Mackenzie Bay at approximately 70°N and 70°30'N and two north of Toker Point at 70°15'N and 70°45'N. The ice and melt pools near the beacons were marked with rhodamine dye and orange paint for easier identification from the air. The movement of these four beacons was tracked daily and the daily positions plotted on a Decca Chart. On July 15, an open section of water 20 miles north of Toker Point allowed deployment of the first surface drifter. It was tracked daily along with the ice beacons. By early August, enough open water was available (Fig. 2) to carry out more extensive tracking of the drift drogues, although problems of ice interference were still encountered regularly. Following break-up, the ice beacons were placed on drift ice and these ice floes used as a measure of surface drift, chiefly because ice conditions prevented the deployment of drift drogues in deeper water.

5.3.2 1975

The 1975 field programme began on July 20th with an ice reconnaisance flight which defined the open water working area as extending from Herschel to Baillie Islands as far north as 71°10' (north of Tuktoyaktuk). Then an unfortunate series of circumstances put the aircraft out of commission for three consecutive weeks of the most favourable ice conditions of the summer for tracking. Some attempt was made to use the Bell 206 as a replacement aircraft but large waves and aircraft-sharing logistics severely hampered this attempt.

Tracking began in earnest on August 8th with the return of the Twin Otter. On the same day, a northwest wind began to blow which heralded the beginning of a minor storm surge lasting three or four days during which time drogues were tracked north of Richards Island and the Tuktoyaktuk Peninsula. A move to deploy drogues north of Mackenzie Bay immediately following the storm was severely restricted because of large quantities of drift ice in the vicinities of intended deployment (around 137°30'W and 70°N). From this day on, the ice stayed in the area northeast of Herschel in sufficient quantities to prevent safely deploying drogues. This explains the apparent gap in data in this area on the plots presented.

An attempt was made to initially space the drogues in a grid with about 25 km between drogues as far north as 70°45', and to cover as wide an area as was feasible with the aircraft range and time limitations. The extent of coverage soon became restricted in the western sea as ice moved in on Herschel Island with the northwest storm in early August. As in 1974, a few ice beacons were deployed in heavy ice areas. The initial spacing quickly became irregular as the drogues dispersed with the wind and current. The widening gaps between the drogues were filled as much as weather, ice conditions, aircraft time and logistics permitted.

From the 17th to the 24th of August, the fog was too low over the water to allow deployment of drogues from the Twin Otter, although on the 23rd and 24th the Bell 206 managed to sneak under the fog and drop six beacons off Hooper Island.

On August 16th and 17th, an attempt was made to conduct an experiment to investigate: (1) how well a single drogue represented the motion of the area of water it was in; (2) short-term variations, of the order of one hour, in the drogue movements to study tidal effects, local wind effects, short-scale time response to the wind and effects of large scale eddies; (3) any other information that might possibly be derived such as dispersion and upwelling. This is described further below.

The description of the field work points out most of the problems encountered which hindered efficient collection of data - the chief ones being:

1) aircraft malfunction
2) aircraft sharing
3) weather which cancelled flying, especially fog and large waves with Bell 206
4) tracking equipment malfunction such as antennae breaking in mid-air or antennae leads coming loose in flight which would cancel a flight
5) beacons malfunctioning - signal becoming weak and sporadic or transmission of signal ceasing after only a few days; interference from other sources especially on one frequency - one day we tracked down a radio tower!
6) ice progressing further south during northwest winds and blocking off whole areas to further study - i.e. Mackenzie Bay.

5.4 Drift Observations

The daily drift observations for 1974 and 1975 have been plotted (Appendices A and B) and the average speeds between positions calculated. The drogue drift velocities have not been corrected for wind drift. Once the floating panel was removed from the drogue, the buoyancy of the remaining assembly was such that the beacons and styrofoam panel were usually awash, especially in any kind of swell. The drift data may therefore be biased to the direction of the prevailing wind because part of the beacon and styrofoam panel were sometimes exposed to the wind, but this was thought to be less than 0.5% of the wind speed for the drogues with the surface panel, so that it should be less for these without.

The uncertainty in the calculated speeds may be determined assuming a standard deviation of σ_x and σ_y in the x and y coordinates of a particular drogue position.

The motion of the drogue between any two observations can then be described by velocity components -

$$U_{ij} = (X_i - X_j) / (t_i - t_j)$$

and $$V_{ij} = (Y_i - Y_j) / (t_i - t_j).$$

Assuming further that the standard deviations σ_x and σ_y are independent of time and position, we find

$$\sigma_u = \sqrt{2}\, \sigma_x / (t_i - t_j)$$

$$\sigma_v = \sqrt{2}\, \sigma_y / (t_i - t_j).$$

Also, if the speed is given by

$$S_{ij} = (U_{ij}^2 + V_{ij}^2)^{\frac{1}{2}}$$

$$\sigma_s = (\sigma_u^2 + \sigma_v^2)^{\frac{1}{2}} = \sqrt{2}\, (\sigma_x^2 + \sigma_y^2)^{\frac{1}{2}} / (t_i - t_j).$$

From these relations it is apparent that the uncertainty in the velocity as determined by a system with fixed location accuracy can be decreased by increasing the time interval between the observations used to compute the velocities.

With $\sigma_x = \sigma_p = 500$ m and a time interval of 24 hours, the speed uncertainty is $\pm$ 1 cm/sec.

Presentation of the drift tracks with a qualitative discussion of the apparent correlation between the daily drift of the drogues and the corresponding average day to day weather patterns appears in Appendix B.

5.5 Cluster Experiment

Because of the turbulent nature of the oceans, the track of any given marked particle will deviate from the average track of a cluster of marked particles or from the average track of single particles released from the same point at different times. In the surface current experiment, where there was an attempt to estimate the mean currents, it was of interest to have an estimate of the deviation of an individual marked particle from the mean path of the water starting from the same place and time. In order to estimate this average deviation, a cluster experiment was devised that would also serve to give some insight into the shorter term variations in the velocity of a single drogue caused by tides, local small scale turbulence, local winds, and larger scale eddies. Two clusters of three and four drogues were deployed by helicopter 25 miles northwest of Atkinson Point. The clusters were 25 miles apart and the drogues in each cluster were initially spaced about 100 metres apart. The idea was to track the two clusters as often as possible for a 24 hour period or slightly longer - to cover a full tidal cycle and the average time interval between the daily tracking of drogue positions. Closely spaced observations were of course limited by the necessity to refuel and restriction on the length of flying time in one day - unfortunately, these limitations were severely increased by fog, aircraft sharing, and helicopter malfunction which reduced the observation period to 10 hours on August 16th and six hours on August 17th. For these periods, the helicopter went back and forth from one cluster to another, taking the positions of all drogues in each cluster every 30-40 minutes. Every two hours, the helicopter refueled at Atkinson Point - the interval between positions was then two hours. The helicopter hovered above each drogue while a Decca fix was taken - so the fix was accurate to .01 of a lane; at each return to Atkinson Point, the Deccometers were checked for drift and re-referenced. The drift was virtually zero. The error in the calculated speeds was ± 1 cm/sec - the error in position was smaller than when using the Twin Otter but the time interval between positions was also smaller.

5.5.1 General motion

Figs. 4a,b,c and d show plots of the two drogue cluster movements for August 16th and 17th. For August 16th, the cluster of four is shown as a succession of squares and the cluster of three as a succession of triangles. Note the deformation, rotation and change in size of the formations; by the 17th, neither the square nor the triangular formation is still apparent. On the 16th, the mean paths of the two clusters were quite dissimilar. The "3" cluster drifted toward the northwest at a fairly constant rate of 25 cm/sec in a slightly curved path (anti-clockwise motion); the "4" cluster followed an elliptical clockwise path to the north-northwest with a speed ranging from 10 to 40 cm/sec. The wind recorded during the drift period on August 16th from the helicopter was calm until 1830 when it began to blow from 60°T at 2.5 to 5 m/sec. The Canmar Barge at 133°W and 70°10'N recorded east and northeast winds of 2.5 to 5 m/sec for the entire tracking period. At any rate, the mean drift on the 16th does not appear to be directly driven by the wind; nor is there any evidence of a reversal in current in response to the wind. The more westerly tracks of the 17th seem more wind related.

The elliptical path of the "4 drogue" group on the 16th may be tidal or a combination of tidal and inertial oscillation - the period is approximately tidal (see the tidal curve in Figs. 5a and b) but the inertial and tidal periods are very close at 70°N. The graphs of the x and y components of velocity in Fig. 5a correspond quite closely to the tidal curve from Atkinson Point. The motion of the "3 group" doesn't have the appearance of a tidal or inertial ellipse. Without records of drift covering several complete tidal cycles, it is impossible to obtain a reliable estimation of the tidal residuals.

Visual observations from the Twin Otter and Bell 206 helicopter of a fairly extensive system of eddies from 70°-70°45'N in the region of the experiment indicates that part of the observed motion may be caused by these eddies. Eddies of apparent convergence were identified by concentrations of drift wood at their vortexes. The estimated scale size of the observed eddies was 5-10 km; the elliptical motion of the "4 group" was 3 km in diameter. From the air, pairs of eddies appeared to be joined by stream lines. This or a very large eddy may account for the motion of the "3 group". Similar pairs of eddies have been observed in ERTS satellite photos (Figs. 7a and b). If the drogue motions are due to large diverging or converging eddies, this should show up in the eddy diffusivities of drogue pairs in the two clusters. The dispersion of the drogues due to turbulent diffusion should be enhanced in a region of divergence and suppressed in a region of convergence, especially near a singularity (Okubo, 1970). The magnitude of horizontal turbulence can be estimated from distance changes within drogue pairs using the method of Stommel, by the relationship

$$F(\ell) = \frac{(l_0 - l_1)^2}{2\Delta t}$$

where l_0 is the distance between two drogues at t_0 and l_1 is the distance between the same drogues at t_1 and Δt is the time interval between t_0 and t_1. In the "4 cluster", on August 16th, the three drogue pairs which included drogue #32 (see Fig. 4a) which was on the outer edge of the elliptical path of the group, had an average eddy diffusivity coefficient of 7.57 x 10^4 cm^2/sec for a mean mixing length of 380 m. This figure is a factor of three higher than calculated by Stevenson, Garvine and Wyatt for a similar mixing length off Newport, California in 1974, and a factor of 10 higher than the average eddy diffusivity of the drogue pairs which didn't include drogue #32. This may imply divergence due to a large eddy. Between the 16th and the 17th, the magnitudes of $F(\ell)$ for all drogue pairs except #27 and #29 reached values up to and greater than 10^6 which is extremely high.

In the "3 group", the eddy diffusivities on the 16th ranged from 3×10^3 cm^2/sec to 1.0×10^4 cm^2/sec. Drogue #30, also on the outer edge of their curved path, moved faster than the other two drogues - after 1600 the distance between drogue #30 and drogues #28 and #31 increased in a monotonic fashion - i.e. more than stochastic processes appeared to be involved. On the 17th, drogue #30 was even further apart from drogues #28 and #31 which were still only 182 m apart (initially separated by 122 m). Figs. 6a and b show plots of distance vs time for the drogue pairs.

5.5.2 Errors in mean velocity estimation due to dispersion

In order to determine how well any single drogue of the cluster represented the small water parcel the cluster occupied, the standard deviation σ_p of all drogue positions in the cluster from the centre of moment of the drogues in the cluster for each time were calculated. Then the velocity error was determined from $\sigma p/\Delta t$ where Δt is the length of time from t_0. In the "4 group" the calculated error in speed after 100 minutes was .3 cm/sec and after 26 hours was 5 cm/sec. In the "3 group", the calculated error in speed after 120 minutes was .4 cm/sec and after 27 hours was only .3 cm/sec.

5.6 Meteorological Observations

In 1974, the wind field was derived chiefly from six hourly pressure charts prepared at the Atmospheric Environment Service in Edmonton along with extropolation of the Tuktoyaktuk hourly wind data. The wind estimates were calculated from the spacing and orientation of the isobars using the equation:

$$V_{geo} = \frac{\alpha \Delta p}{f \Delta h}$$

(Petterssen, 1956), where p is the sea level atmospheric pressure, Δh is the distance between isobars, f is the Coriolis parameter and α is the specific volume of air.

The inaccuracy of inferring surface winds from geostrophic winds is evident upon examination of the two graphs in Fig. 8 which compare actual recorded surface winds from the *M.V. Theta* in the Beaufort Sea in 1974 to geostrophic winds calculated from six hourly pressure charts for the same times and locations. The *Theta* wind data was in no way used to draw the isobar lines so the two values are independent. Although there is evidently a direct relationship between the magnitudes of the geostrophic and surface wind values, the scatter is very large, especially below 9 m/sec. There is even less correlation between the directions of the two winds as Fig. 8 shows.

The surface wind is usually to the right of the geostrophic wind but the cross isobar angle varies from 0° to 180° with the greatest number of values between 0° and 72°; the angle does appear to decrease as the wind speed increases but here again, the band of scatter is extremely wide.

Some previous experimental work has been done on the relationship between geostrophic and surface wind such as that described by Hasse and Wagner (1971). Wind and pressure observations were taken in the German Bight from 15 light ships in an area 200 km x 200 km. A linear relationship was found between geostrophic and surface wind speeds for a given stability. For low wind speeds the magnitude of the surface wind was greater than the geostrophic wind and vice versa for higher wind speeds. The results of investigations into cross isobar angle showed considerable scatter. The average cross isobar angle was 17°, although the angle was higher (22°) for stable than for unstable conditions.

Because no satisfactory relationship could be found to convert geostrophic to surface wind from the weather charts, the method used to derive the wind fields for 1975 relied more on the hourly recorded winds from a much denser network of observing stations and less on the pressure field from the Arctic Central of the Atmospheric Environment Service in Edmonton. These stations were:

1) Tuktoyaktuk Airport - 69°25'N, 133°00'W
2) Komakuk Dew Line Station - 69°37'N, 140°00'W
3) Shingle Point Dew Line Station - 69°00'N, 137°30'W
4) Decca Red Station at Atkinson Point - 69°57'N, 131°25'W
5) Imperial Oil Barge 208 - 69°35'N, 135°30'W
6) Canmar Oil Barge - 70°10'N, 133°00'W
7) Nicholson Point Dew Line Station - 69°57'N, 129°00'W
8) *Pandora II* and *Theta* ships
9) Other ships in area (e.g. *Nahidik*)
10) Pullen Island Automatic Station - 69°45'N, 134°20'W.

Figure 9 presents wind data for the entire 1975 field programme for Immerk meteorological station near Pelly Island.

For comparison with the drift observations, vector sums of the observed wind data were computed for the period from noon to noon each day for those observations recorded in local time and from 1800 to 1800 for those kept in GMT. Those considered most relevant to the drift are shown on the plots in Appendix B. Vector sums were also computed on hourly winds from the Regional Update Model of the Atmospheric Environment Service for the periods for which these are available. The grid points used were 14 (69.83°N, 137.26°W), 15 (70.82°N, 135.30°W) and 21 (70.12°N, 132.43°W). These are also shown on the figures in Appendix B. All vector sums are listed in Table I.

6. ANALYSIS AND PRESENTATION OF DATA

In considering the near-surface currents in the southern Beaufort Sea, it is important to recognize that there are a number of processes at work, none of which is completely understood even in much simpler situations. The large scale variability of the surface currents is mainly determined by the action of the wind. However, the current pattern produced by the wind is affected by the presence of the Mackenzie River outflow, both indirectly by its effect on the density structure, which affects the dynamics of the mixed layer, and directly by the currents associated with it. Both of these patterns are affected on a smaller scale by eddies arising from baroclinic instabilities along the frontal zone between the Mackenzie River water or from interactions between the current patterns and the topography.

The component of the flow with the longest time scale is that associated with the river outflow. The dynamics of this in the case of a river flowing perpendicularly through a vertical straight coast into a deep ocean are described in Defant (1962). The forces involved are the Coriolis force, which tends to turn the river flow to the right along the coast and which is balanced initially by the centrifugal force associated with the curvature of the outflowing river as it turns under the Coriolis force, and finally by the pressure gradients due to the horizontal variation of the mean density of the water column because of the mixing of fresh and salt water. In the case of the Mackenzie River, this should lead to a slow broad flow eastwards parallel to the coast.

The distribution of the river water in the summer of 1975 is indicated in Fig. 10 by contours of dynamic height of the water surface relative to 10 decibars pressure, from oceanographic data reported by Herlinveaux et al. (1976). Since dynamic height is related to the height of the water column of the observed density required to give a given hydrostatic pressure, the larger values indicate lower density water. For geostrophic flow, the separation between the contours is directly proportional to the surface velocity between them which would be parallel to the contours, with the larger values on the right. However, in this case the upper layer is so thin that friction is probably important and the flow will have a significant cross isobar component.

In considering the outflow of the river it is important to recognize that it will be accompanied by an inflow in the salty ocean water beneath, to replace that carried away by mixing with the outflowing fresh water.

The component of the flow with the largest horizontal scale is probably the motion of the upper mixed layer due to the wind. On the other hand, the vertical scale of the significant part of this motion will be limited to the layer above the large density gradient as this will suppress the vertical component of turbulence and hence momentum transfers. According to modern ideas, there are two significant time scales. The longer one is represented by the scale of the variations in the wind, while the shorter is represented by the inertial period of 12 hours 46 minutes at 70°N. Changes in the wind give rise to velocities which rotate at the inertial period. In the open ocean the component of the transport, or vertical integral of the velocity parallel to the wind stress, oscillates about a mean value of zero while the component of transport directed at 90° to the right of the wind oscillates about a positive mean value. Both components have the same amplitude. One model pictures the transport as the sum of a fixed vector directed at 90° to the right of the wind stress plus a vector of the same length rotating at the inertial period. The actual net transport, i.e. the time integral of the transports, depends on the relationships of the vector wind changes to the rotating velocity vectors. For a steady wind the oscillations will eventually be damped out, but this probably takes several inertial periods or a few days so that few winds may actually be considered steady (Mellor and Durbin, 1975). In the case where a coast is found to the right of the wind, as with a west wind in the Beaufort Sea, a transport to the right of the wind moves water towards the shore, resulting in the build up of a pressure field which in turn redirects the flow until it is downwind parallel to the coast. In the case where the coast is found to the left of the wind, as with an east wind in the Beaufort Sea, the net transport is away from the coast, resulting in upwelling of deeper water near the shore to replace that transported away.

One of the problems with direct velocity measurements in the region of the Beaufort Sea is that it is difficult to separate the inertial oscillations with a period of 12 hours 46 minutes and random phase and amplitude from the semi-diurnal tidal signal with a period of 12 hours 25 minutes and a coherent phase and steady amplitude. Some of the current meter records recovered (Huggett, 1976) do show large fluctuations in amplitude at these frequencies, suggesting inertial oscillations.

The velocity of the drifters on the other hand corresponds to the transport above a certain depth, so that for a given wind field we expect the displacement of the drifter to be an increasing function of time. However, we should also expect a variability associated with the relationship of our sampling interval to the inertial period. In the open ocean a drifter which extended deep enough to capture the entire transport would trace out a cusped path. If this path were sampled at intervals equal to the inertial period the resulting positions would lie along a straight line. If it were sampled at any other period the direction of drift would appear to vary. All parts of the trajectory would, however, lie to the right of the wind.

In the real environment of the Beaufort Sea, the vertical structure of the water varies horizontally. The winds are not uniform, and the wind drift is not the only current. Our problem then is to try to determine what portion of the motion is reproducible and predictable, given information of the type likely to be available under practical circumstances.

The most obvious influence on the currents is the wind. Its effect on the surface salinity distribution was apparent to Cameron in 1953. A similar effect is also apparent in the drift measurements, as revealed by the contrast between Fig. 11, which shows all drifts during strong westerlies in 1974 and 1975, and Fig. 12, which shows all drifts during strong easterlies. It is thus tempting to hope that predictions of the surface drift might easily be made on the basis of the anticipated winds. However, this turns out not to be the case.

A quantitative relationship between the wind and drift was sought using various techniques. Fig. 13 shows the joint distribution of wind speed and observed drift for four combinations of variables. Fig. 13a plots the observed drift against the vector average of the nearest wind observation, for the whole area, while Fig. 13b plots the observed drift against the vector average of the wind at the nearest grid point of the Regional Update Model. In Figs. 13c and d the same comparisons are made, this time restricted to those drifts in "Zone D" as shown in Fig. 2, where they should not be influenced by the shore. In none of the cases is there a clear-cut relationship between the wind speed and drift speed.

Similar plots of the distribution of the angle between the drift and the nearest wind for various wind speeds are shown in Fig. 14. The drifts are widely distributed in relative direction, except for winds over 10 m/sec, where the small number of samples reduces confidence in the result. The sample with the highest proportion of drifts to the right of the wind direction is that from "Zone D". Here, 65% of the drifts are to the right of the observed wind. Examinations of the separate distributions of the wind directions and current directions for the observations from periods of strong northwest winds indicates that the drift directions are more variable than the winds.

From these analyses, it seems quite clear that no general predictive relationship between wind and current will be found for the whole area, or even for that portion of it away from the coast. However, looking at Figs. 11 and 12 it can be seen that the current directions for a given wind régime are much less variable within a small area. For example, eight drifts passed near 70°N, 133°W during northwest winds in 1975, with a standard deviation of only 17° around their mean of 110°. Similarly near 70°20'N, 131°W, 10 1975 northwest wind drifts have mean direction of 70° and a standard deviation of only 16°. Drifts during easterly winds seem more variable and there are fewer small areas with many drifts for comparable statistics. The one area with multiple coverage, near 70°20'N, 132°W, is in fact a good example of how variable the directions can be even under similar winds, thus warning against simplistic prediction schemes.

It is tempting to think in terms of a drift pattern varying on the scale of the wind field and the larger coastal features, but perturbed by some smaller scale random processes. It is not necessary to look any further than Figs. 7a and b for a suitable one. Eddies with a scale size of 10 to 50 km are commonly seen on satellite images and from aircraft. Because their scale size is somewhat smaller than a typical large drift they are not obvious in the drift tracks. However, there are many cases where drift paths cross, or where there are marked shears. It is difficult to be quantiative, but the perturbation velocities required would have to be on the order of 10 cm sec^{-1} to 20 cm sec^{-1}. The most likely sources of such eddies are baroclinic instabilities along the front between the Mackenzie River water or interactions of variability in the flow with topographic features. The state of the theory of either situation is such that it is difficult to apply.

The most that can be predicted is then a mean, generalized response to the stronger wind fields, which will in any particular case be perturbed by additional random velocities only slightly smaller than the wind drifts. The response has been estimated by averaging the drift observations over areas one degree of longitude by one half degree of latitude where sufficient observations were available and by extrapolation and hypothesis where they were not. The results are shown in Figs. 15, 16 and 17.

6.1 Northwest Winds

Fig. 15 indicates the expected surface water movement during steady northwest winds of 12 m/sec. Offshore, the water movement is southeast toward the coast 30° to the right of the wind at 35 cm/sec which is about .03 of the wind speed. The maximum drift speed recorded to the southeast during a northwest wind was almost 50 cm/sec. Within 10 kilometers of the coast, the current is parallel to the shore and moves to the northeast with a speed that ranges from 25 cm/sec north of Pelly Island to 50 cm/sec north of Atkinson Point and Cape Dalhousie. The maximum longshore drift actually observed was 75 cm/sec north of Cape Dalhousie.

Several drogues were washed ashore in Liverpool Bay and other small bays along the Tuktoyaktuk Peninsula. There is probably a clockwise circulation around Liverpool Bay. A very strong current flows around the northern tip of Baillie Island and down the eastern coast of the Bathurst Peninsula. There appears to be a counter-clockwise circulation into Kugmallit Bay with the river water from the east channel of the Mackenzie moving off to the east out of the bay and the river water discharging into Mackenzie Bay flowing around Richards Island and into Kugmallit Bay from the west. During northwest winds, the Mackenzie Plume can be seen from the air as a very well-defined silty strip, hugging the coast and indicating the direction of water movement.

Due to lack of data in Mackenzie Bay during northwest winds, the current field presented in this region in Fig. 15 is subject to some guesswork (it is based on only a few observations). According to Ekman's theory on boundary currents, a wind blowing parallel to the coast, as in the case of northwest winds blowing along the western shore of Mackenzie Bay, should cause a longshore current in the same direction as the wind which would cause a counter-clockwise type circulation in Mackenzie Bay with a southeasterly longshore current along the western shore. There is speculation based on some ships' drift measurements and visual observations from the air of ice accumulation and sediment-laden water that there is a small clockwise gyre set up in Mackenzie Bay during northwest winds causing a northwesterly longshore current along the western shore of Mackenzie Bay as in Fig. 15. There are not sufficient drogue drift observations available in western Mackenzie Bay during strong northwest winds to either confirm or refute this speculation, although some observations seem to support it with an observed current of less than 10 cm/sec. Drogue drift measurements record a definite northwestern current of 10 cm/sec off Stokes Point increasing to 25-30 cm/sec off Herschel following a northwest storm and during light south and east winds. Water movement in the southwest corner of the bay off Shingle Point appears to be quite random most of the time, probably due to Mackenzie River eddies and the geographical configuration of the bay.

The time-dependent aspect of the current field is not shown in the diagram. As a northwest wind begins to blow, an onshore current moving slightly to the right of the wind develops. The response of the current to the wind will depend somewhat on the initial velocity of the water but within six hours from the onset of the northwest wind, there will probably be a noticeable wind driven current flowing. Bottom currents at three locations in the Beaufort Sea (Huggett, 197) during the minor storm surge from August 8th to 12th, 1975 showed a six to eight hour lag behind the wind but the surface current response time is probably substantially shorter. The onshore current increases with an increase in wind speed. It builds water up against the coast causing a longshore current toward the northeast which would increase in speed to a steady state current within six to eight hours of the start of the wind, which is also the response time of the water height on the shore. The speed of the longshore current varies directly with wind speed and the lateral extent of the current offshore appears to increase with time to a maximum distance of 50 km offshore north of Atkinson Point and Cape Dalhousie. The heart of the current where the maximum long stream speed is observed is a line from 70°N, 133°W to just north of Baillie Island approximately 10 km offshore.

Some theoretical work has been done on the generation of longshore currents by wind stress perpendicular coast line. Bretschneider, for example, derived a relationship which shows the build up of a longshore current takes 3 to 8 hours, depending on the water depth and on a current speed dependent upon the wind speed of approximately 3% of the wind speed. The data seems to agree with the theory.

With strong west winds of several days duration, the winds often swing from southwest to west and then to the northwest. It is quite difficult to distinguish the effect of the three different winds using daily drogue positions when the wind may shift half way between observations. The response of the water to the west and southwest winds is undoubtedly similar to the response to the northwest wind shown in Fig. 15. If the wind is more southwest there is likely more of a longshore component to the drift and less of an onshore component as occurred on August 25th and 26th north of Gary and Hooper Islands. The circulation in Mackenzie Bay would then be anti-cyclonic with a longshore current flowing <u>southeast</u> along the western shore of the bay.

6.2 Following a Northwest Wind

Fig. 16 shows the characteristic drift pattern occurring upon relaxation of a strong northwest wind that has caused an increase in water height along the coast.

After the wind has stopped the longshore current north of Tuktoyaktuk Peninsula continues to exist for at least two or three days before it decays due to frictional forces. In August, 1975 the longshore current north of the Tuktoyaktuk Peninsula was still 75% of the steady state value 48 hours after relaxation of the wind. But on the third and fourth days the current actually reversed direction north of Atkinson Point and at 70°30'N was reduced to 20% of its steady state speed during the surge. A very fast current of 75 cm/sec continued to flow southward along the eastern coast of Cape Bathurst.

Water also flows out of Kugmallit and Mackenzie Bays toward the northwest at 20 cm/sec and 40 cm/sec respectively, causing a westward current around Richards Island. This may have caused the reversal of current mentioned above. Notice: (1) the divergence in Mackenzie Bay and (2) the convergence north of Richards Island caused by this situation. Large eddies in Mackenzie River water observed north of Richards Island in satellite photographs (Fig. 7a) may be associated with the convergence. The divergence in Mackenzie Bay may be associated with Herschel Canyon and the V-shape of the isobaths in the bay. Just how much influence the wind has in determining the resultant current field is difficult to assess. As the relaxation effect decreases, the direct wind driven component of the current is more apparent.

6.3 Strong East Winds

Fig. 17 shows the current field anticipated during steady east winds of greater than 7 m/sec and 48 hours duration. This situation occurred only once in the 1974 summer in early September but the east winds persisted for at least 10 days so that a consistent current pattern was established. The field consists of an offshore, north westward movement of water at speeds up to 75 cm/sec and a westward longshore current of about 35 cm/sec set up by the changed density distribution. Observations indicate that a sudden relaxation of the wind causes a relaxation of the current within 24 hours. The strong northeast wind of September, 1975 produced a similar drift with a more southeasterly drift off Tuktoyaktuk Peninsula.

There are frequent periods of light east winds that last for periods of 24 hours or less. They appear to be instrumental in shifting the already existing current direction slightly or causing large scale eddies which distort the unidirectional current field but do not set up a uniform current pattern over the whole sea.

7. CONCLUSIONS AND RECOMMENDATIONS

The currents in the southern Beaufort Sea (south of 71°N) are a sum of many contributing factors, none of which alone explains the behaviour of the surface water movements. The two dominant influences on the mean daily drift are the major wind systems associated with the passage of large pressure centres and the Mackenzie River discharge. Their effect is strongly biased by the orientation of the coastal boundary features and moderated by local winds and small scale systems. The variability of all these features introduces a large unpredictable random component into the drift currents.

The wind system with the greatest effect on the currents is the northwest wind, especially during periods of storm when wind speeds are over 10 m/sec for extended periods. These winds are usually generated when a low pressure centre passes over the northern Beaufort Sea from west to east. As the low moves eastward across the sea, the winds tend to swing in direction from southwest to west to northwest, so that the wind direction during a "northwest" storm may actually vary through 90° - from 225° to 315°, although the effect on the water movements tends to be similar. The result of the strong, steady west wind is to impart a great deal of momentum into the water, producing strong southeast currents offshore and a northeasterly, long-shore current along the coast. A period of several days of calm or light winds often follows the storm and a fairly characteristic current pattern also seems to follow, although without the driving force of high wind. The effect of large scale eddies and variable local winds are more important, and a consistent current field is more difficult to identify. This is generally the case for intervals with winds less than 5 m/sec. In fact, satellite photographs and visual observations from aircraft testify to the numerous Mackenzie plume eddies visible during light winds and following the relaxation of a northwest storm. Fig. 7a, for example, is a satellite photograph showing an eddy north of Richards Island taken July 20, 1973 and Fig. 7b shows eddies off the Tuktoyaktuk Peninsula July 15, 1975.

The other strong winds that have been observed on the Beaufort Sea are easterlies and northeasterlies, accompanying the passage of a high pressure system. A period of drogue drift during strong, steady easterly winds was recorded in mid-September, 1975. In mid-September, 1974, easterly winds of greater than 8 m/sec were recorded for more than a week and produced substantial northwest drift of offshore drogues and ice floes east of 133°W and a longshore westerly current immediately next to the coast.

Looking at the entire period studied in 1975, the predominant current direction is to the northeast, probably chiefly as a result of (1) the periods of strong northwest winds and (2) the effect of the Coriolis force on the Mackenzie River discharge. The exception to this is off Herschel Island and Stokes Point where the dominant current direction is northwest. There appears to be a region of divergence in the middle of Mackenzie Bay which may be associated with Herschel Canyon and the change in direction of the isobaths.

7.1 Offshore Oil Drilling

With more specific reference to the problems of offshore oil drilling, a number of tentative conclusions can be reached.

(A) Possible Movement of Spilled Oil:

In a strong northwest wind, spilled oil could move onshore at speeds of up to 25 miles per day. As the shore is approached, the oil would move east along the coast at speeds of 25 miles per day or more, so that the shore could be contaminated for a considerable distance.

In east wind conditions, the oil would move more slowly and, generally speaking, it would move offshore into the polar pack. However, the western shores of Kugmallit and Mackenzie Bays could be susceptible to contamination, depending on the location of the origin of the spilled oil.

In all wind conditions, the motion would be quite unpredictable due to the presence of large scale eddies.

(B) Ice Hazard to Drilling Operations:

Again, in a northwest wind, downwind movement of ice floes and pack ice will be assisted by the surface currents so that fairly rapid movements can be expected. Under other wind conditions, the movements of ice would be more variable and less predictable.

8. NEED FOR FURTHER RESEARCH

This study has barely scratched the surface of understanding of surface currents in the Beaufort Sea. It was unfortunate that a denser spatial coverage of the entire Southern Sea could not be accomplished for each time period. The time spacing also leaves much to guesswork, especially under variable wind conditions and when studying time response to wind. Some particular areas of interest which still demand considerable further investigation are:

1) The large scale circulation in Mackenzie Bay
2) The area of convergence north of Richards Island
3) The apparent strong current flowing northwest off Herschel Island
4) Response time of the current to the wind, especially a northwest wind, and following relaxation of the wind
5) Dynamics of the numerous eddies.

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TABLE I

WIND VECTOR AVERAGES

Noon to Noon MDT or 1800 to 1800 GMT
Direction is direction towards which wind blows
Speed is in knots

DATE	KOMAKUK		SHINGLE		IMMERK OR GARRY N		TUKTOYAKTUK		NICHOLSON		ATKINSON	
July	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.
28-29					14	140	18	100	13	090		
29-30					8	070			7	050		
30-31					6	170			7	120		
31- 1									4	160		
Aug.												
1- 2							6	230	8	200		
2- 3							7	250	5	230		
8- 9					15	050					8	050
9-10					15	100					10	110
10-11					25	080					20	130
11-12					12	070					8	130
12-13					4	340					1	050
13-14	1	210			4	000					1	040
14-15	2	130	2	100	9	330	7	330			6	000
15-16	1	230	1	160	7	280	4	320			2	000
16-17	10	110	7	130	4	250	1	230				
17-18	6	120	13	110	10	140	9	100				
18-19	9	250	6	280	6	190	1	220				
									PULLEN			
19-20	4	230	1	320	2	290	0	-				
20-21	6	110	4	100	6	130			2	310		
21-22					7	140			13	120		
22-23					8	140			8	170	6	150
23-24					5	150			5	170	3	160
24-25					3	240			0	-		
25-26					16	010			19	010		
26-27					17	120	18	080			18	130
27-28					18	130	20	100			17	140
28-29					13	040	11	050			8	100
29-30					4	190	5	140	8	220	5	150
30-31					10	260			11	300	0	-
31- 1					12	170			13	180	8	180
Sept.												
1- 2	9	100			21	110			24	120	15	130
2- 3	1	210			1	260			3	120	4	140
3- 4	4	110			4	080			6	050	2	060
4- 5	2	300			6	150			9	140	4	150
5- 6	6	240			17	220			14	230	3	260
6- 7	5	180			22	240					18	270
7- 8	7	140			13	190					10	220
8- 9	2	290			2	330					1	185
9-10	1	040			5	060					2	100

TABLE I (Cont'd.)

WIND VECTOR AVERAGES

DATE	THETA		PANDORA		CANMAR		RUM 14 69.83,137.26		RUM 15 70.82,135.30		RUM 21 70.12,132.43	
July	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.
28-29							9	140	12	140	10	130
29-30							11	120	14	120	14	110
30-31							5	250	5	190	3	220
31- 1							8	280	5	250	8	270
Aug.												
1- 2												
2- 3												
8- 9	17	080										
9-10	25	090										
10-11	32	110										
11-12	13	080										
12-13	4	320										
13-14	3	300										
14-15	13	300	12	320			12	350	13	360	15	360
15-16	6	300	8	320			9	320	9	330	12	350
16-17	11	270	6	250	7	290	10	270	8	280	8	320
17-18	10	220	16	220	13	220	14	250	15	240	11	250
18-19	9	220	16	230	9	250	16	290	15	280	13	280
19-20	0	-	1	300	1	220	10	300	13	300	10	310
20-21	5	380	2	100	2	320	7	240	9	260	5	260
21-22	12	100	7	120	11	130						
22-23	10	120	8	140	10	120						
23-24	5	160	5	150	6	130	5	240	7	210	8	200
24-25	6	300	2	340	2	030	4	050	6	060	5	050
25-26	18	010	15	350	15	340						
26-27	26	100	23	110								
27-28	16	110										
28-29	5	060					18	100	18	090	19	090
29-30	4	260	4	190			6	190	9	180	8	160
30-31	10	270	7	260			5	340	4	010	5	010
31- 1	10	140	7	170			9	210	11	200	9	200
Sept.												
1- 2	18	110	17	110			14	180	18	170	16	170
2- 3	3	300	0	-			3	060	2	070	2	080
3- 4	7	130					2	000	7	350	8	000
4- 5	5	140					2	170	4	190	4	150
5- 6	10	200					13	270	13	260	10	260
6- 7	23	230					28	270	25	270	25	280
7- 8	15	200	20	210			21	250	21	240	19	250
8- 9			4	- 0			2	250	2	190	3	240
9-10			8	070			10	110	12	110	11	110

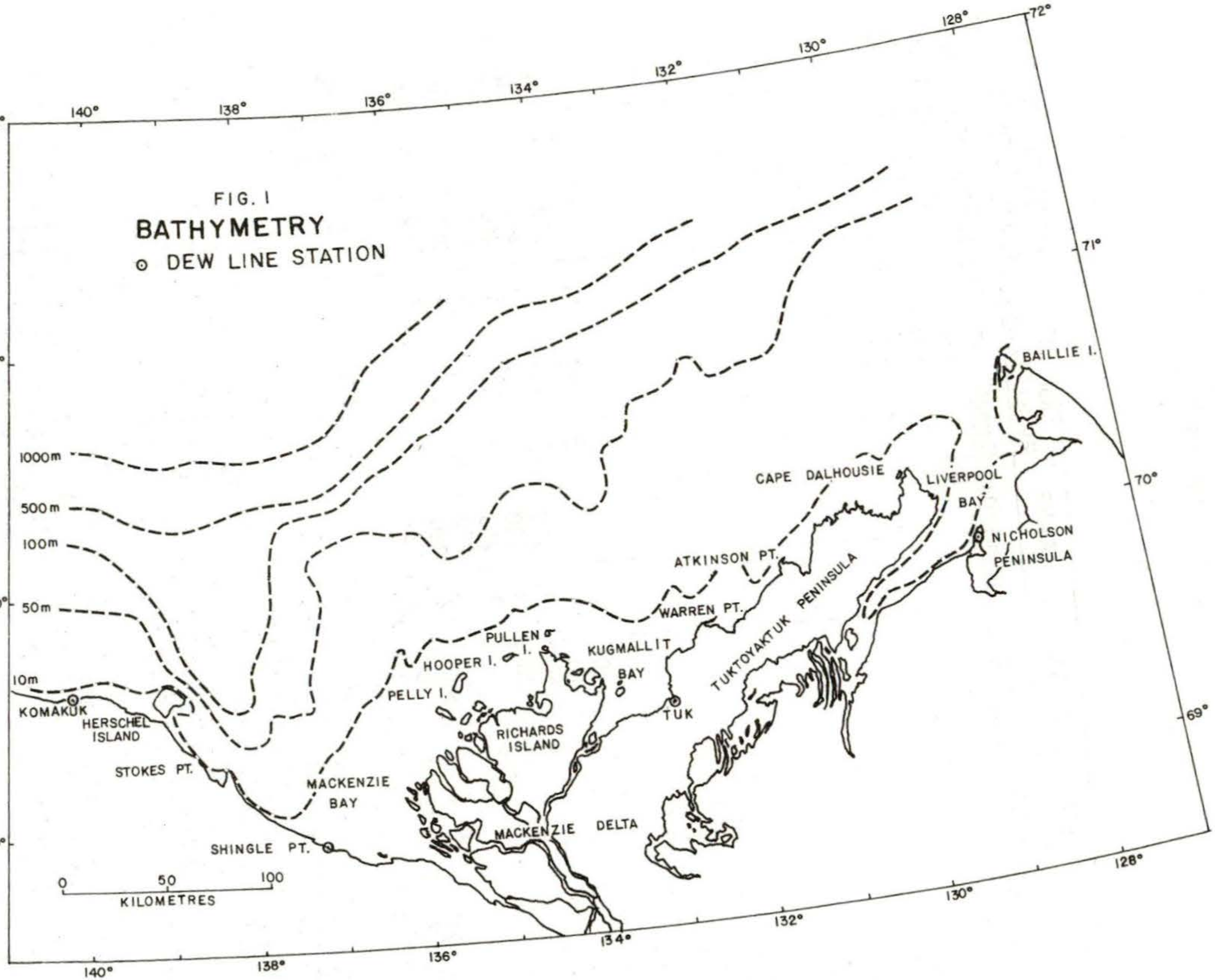


FIG. 1
BATHYMETRY

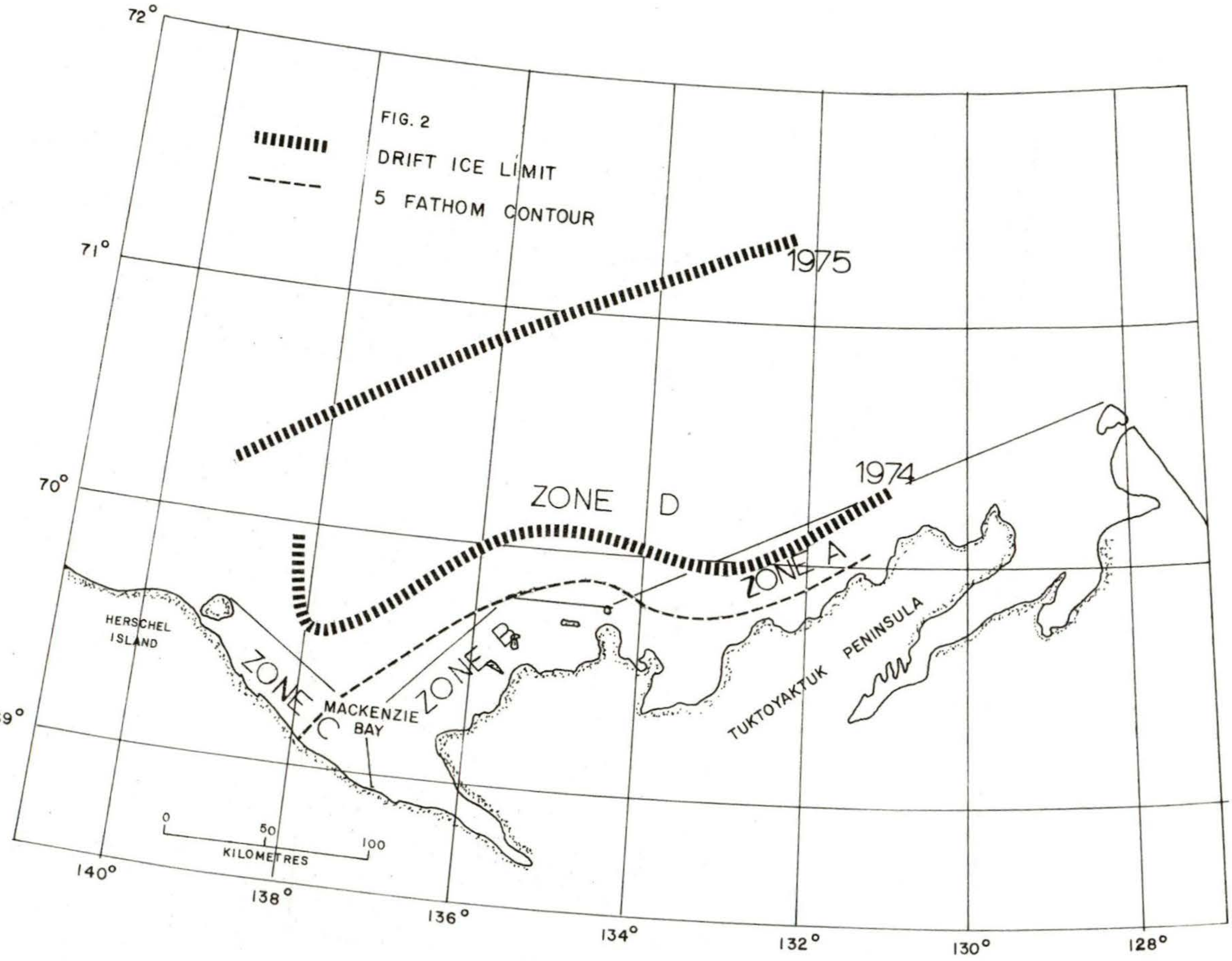


FIG. 2
DRIFT ICE LIMIT
5 FATHOM CONTOUR
1975
1974
ZONE D
ZONE A
ZONE B
ZONE C
HERSCHEL ISLAND
MACKENZIE BAY
TUKTOYAKTUK PENINSULA
KILOMETRES
0
50
100
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°

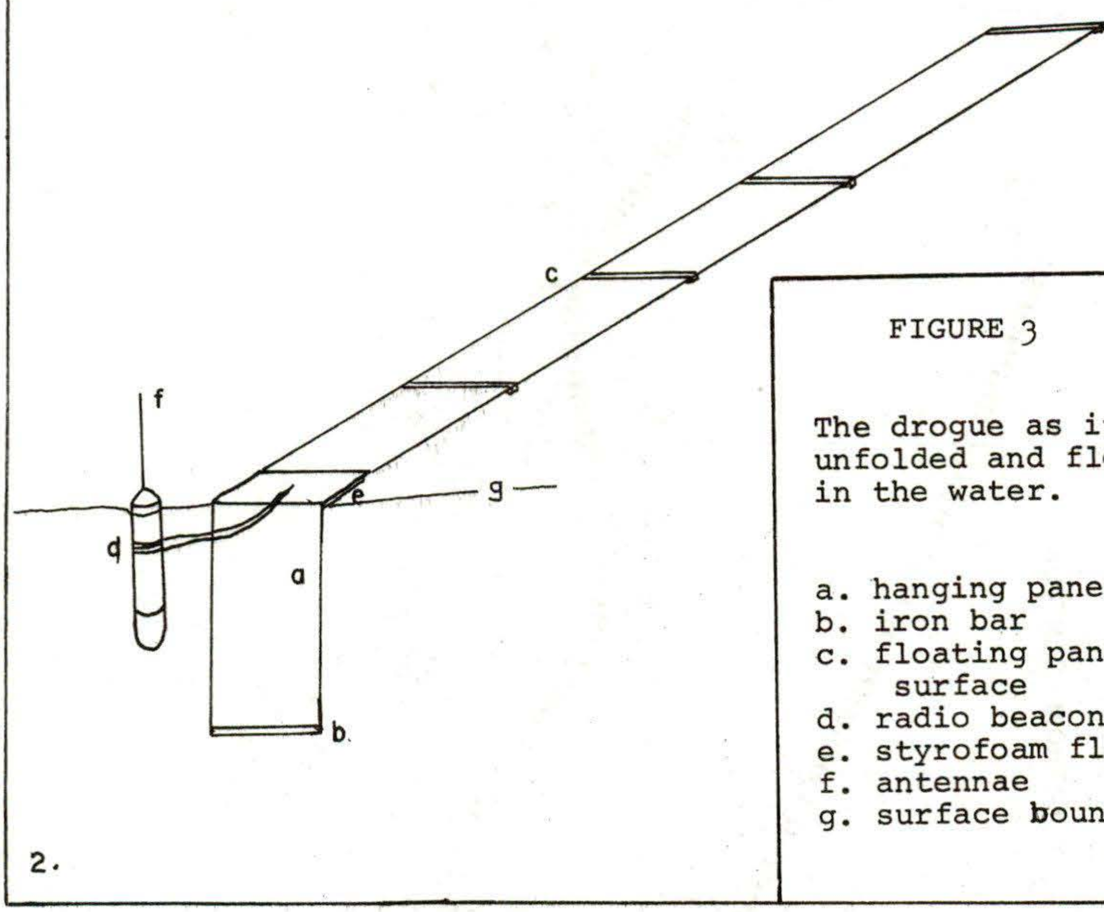


FIGURE 3

The drogue as it looked unfolded and floating in the water.

a. hanging panel
b. iron bar
c. floating panel on surface
d. radio beacon
e. styrofoam float
f. antennae
g. surface boundary

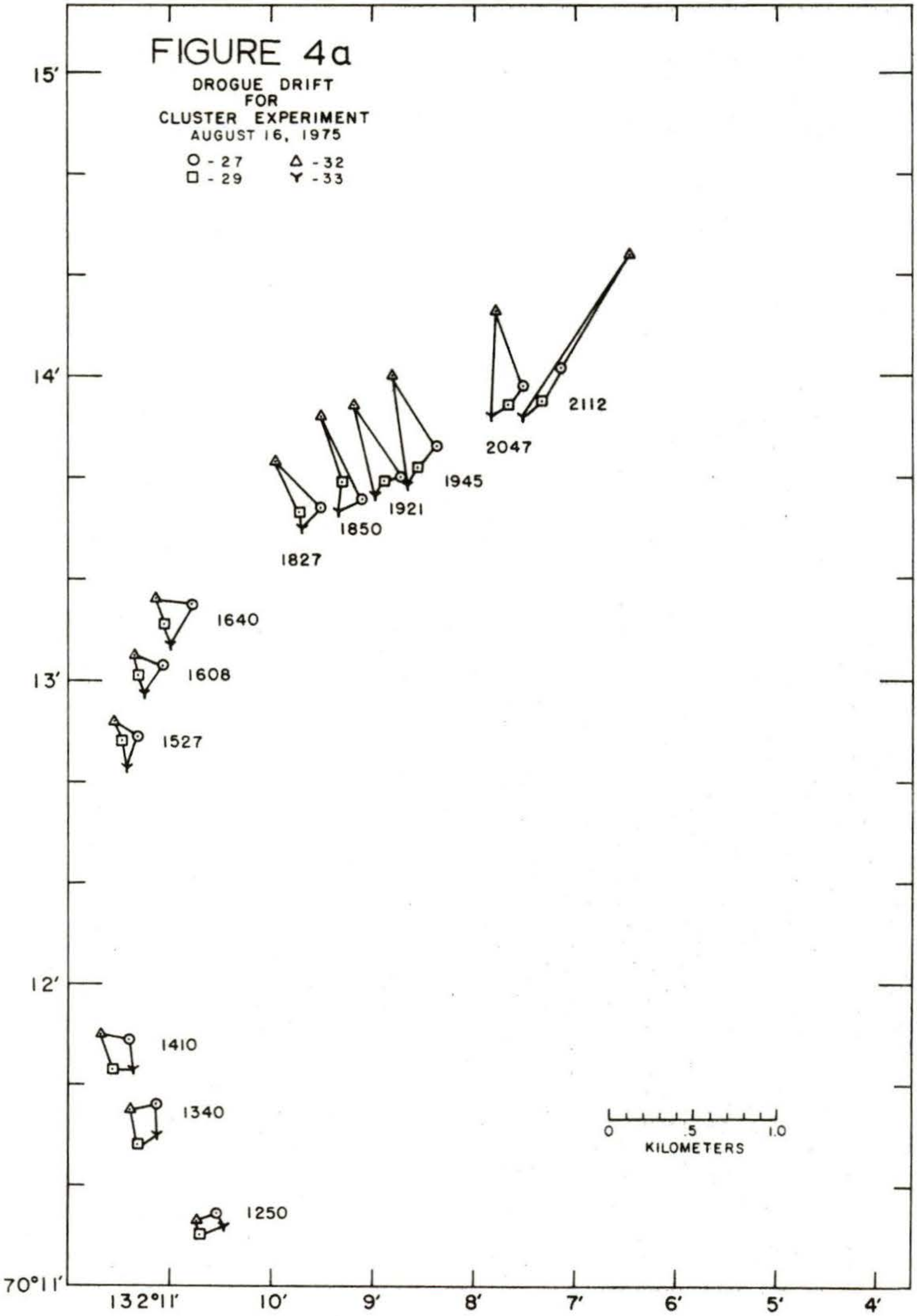


FIGURE 4a
DROGUE DRIFT
FOR
CLUSTER EXPERIMENT
AUGUST 16, 1975
○ - 27
△ - 32
□ - 29
Y - 33
15'
14'
13'
12'
70°11'
132°11'
10'
9'
8'
7'
6'
5'
4'
2112
2047
1945
1921
1850
1827
1640
1608
1527
1410
1340
1250
0
.5
1.0
KILOMETERS

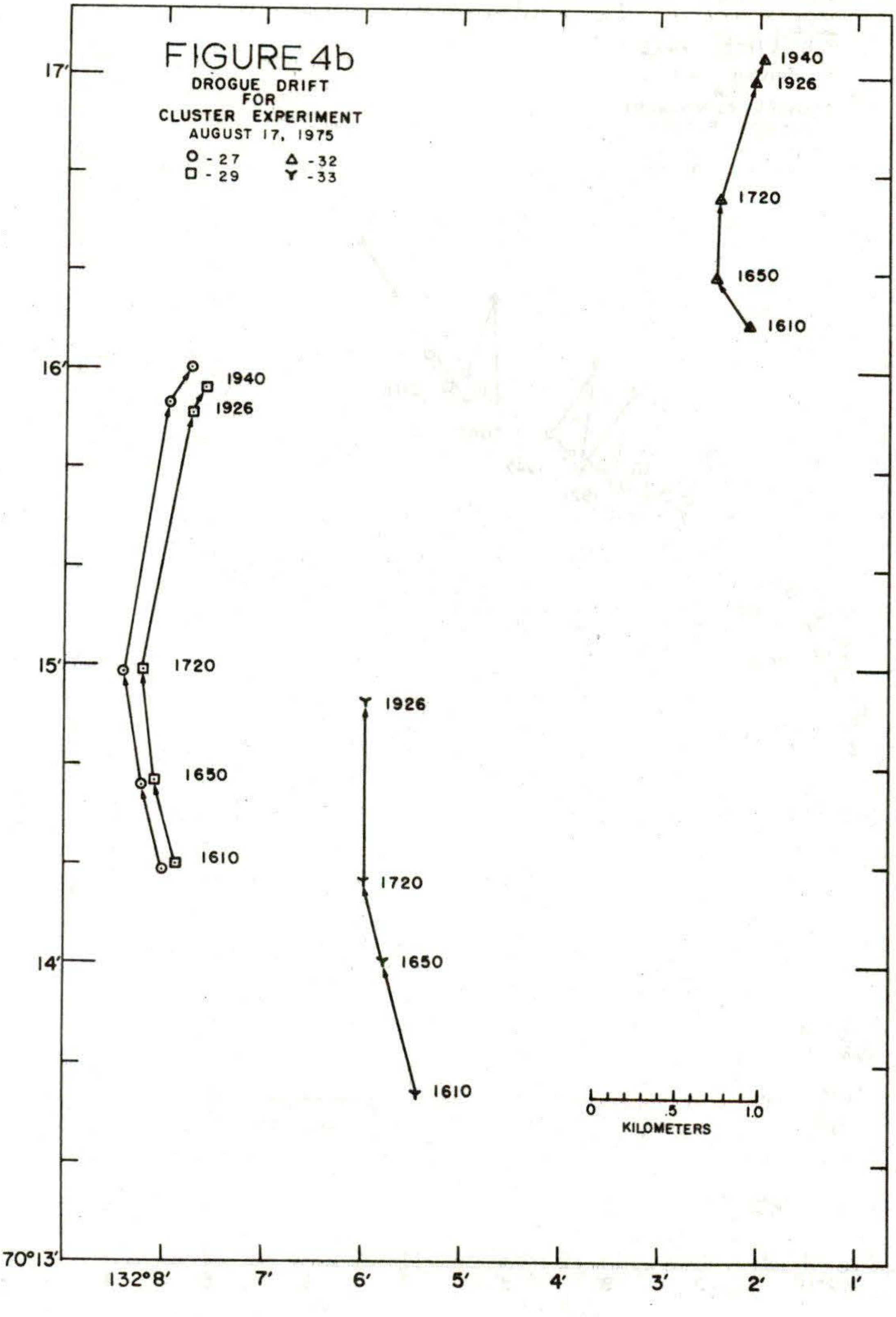


FIGURE 4b
DROGUE DRIFT
FOR
CLUSTER EXPERIMENT
AUGUST 17, 1975
O - 27
□ - 29
△ - 32
Y - 33
1940
1926
1720
1650
1610
KILOMETERS
0
.5
1.0
17′
16′
15′
14′
70°13′
132°8′
7′
6′
5′
4′
3′
2′
1′

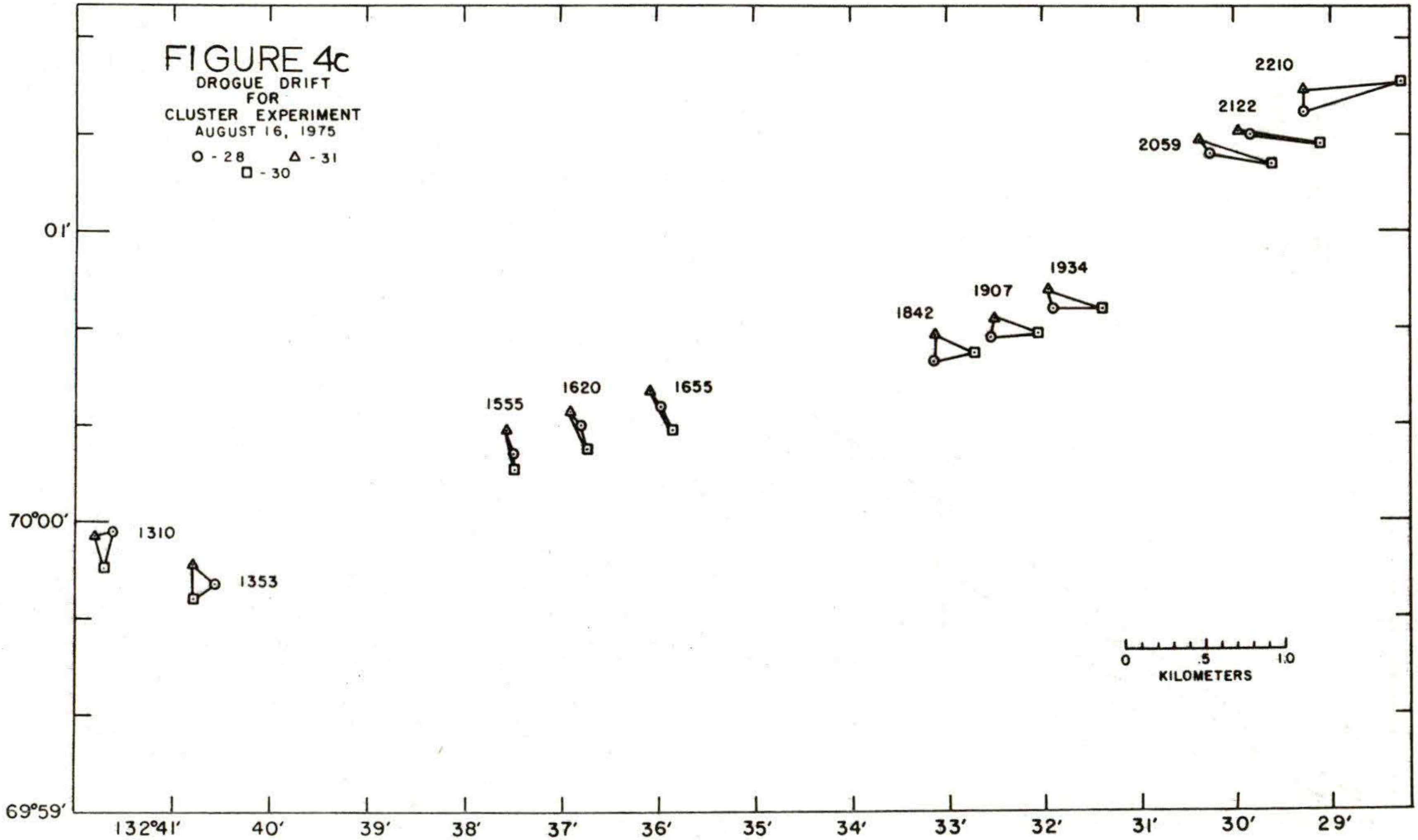


FIGURE 4c
DROGUE DRIFT
FOR
CLUSTER EXPERIMENT
AUGUST 16, 1975
O - 28 Δ - 31
□ - 30
2210
2122
2059
1934
1907
1842
1555
1620
1655
1310
1353
0 .5 1.0
KILOMETERS
01′
70°00′
69°59′
132°41′
40′
39′
38′
37′
36′
35′
34′
33′
32′
31′
30′
29′

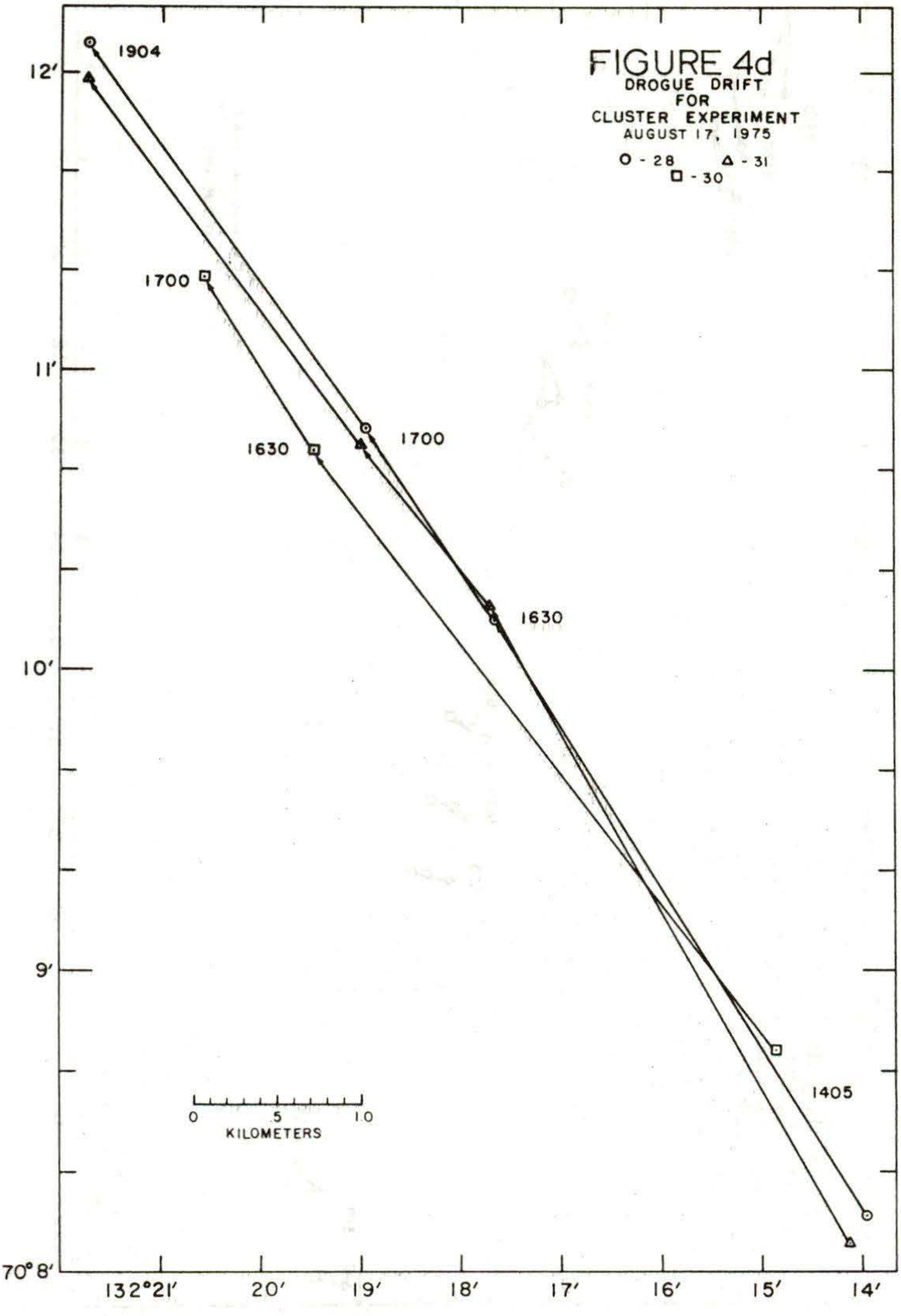


FIGURE 4d
DROGUE DRIFT
FOR
CLUSTER EXPERIMENT
AUGUST 17, 1975
O - 28
Δ - 31
□ - 30
1904
1700
1700
1630
1630
1405
12′
11′
10′
9′
70° 8′
132°21′
20′
19′
18′
17′
16′
15′
14′
0
.5
1.0
KILOMETERS

FIG. 5a

VELOCITY COMPONENTS
FOR
CLUSTER OF FOUR
AUGUST 16, 1975

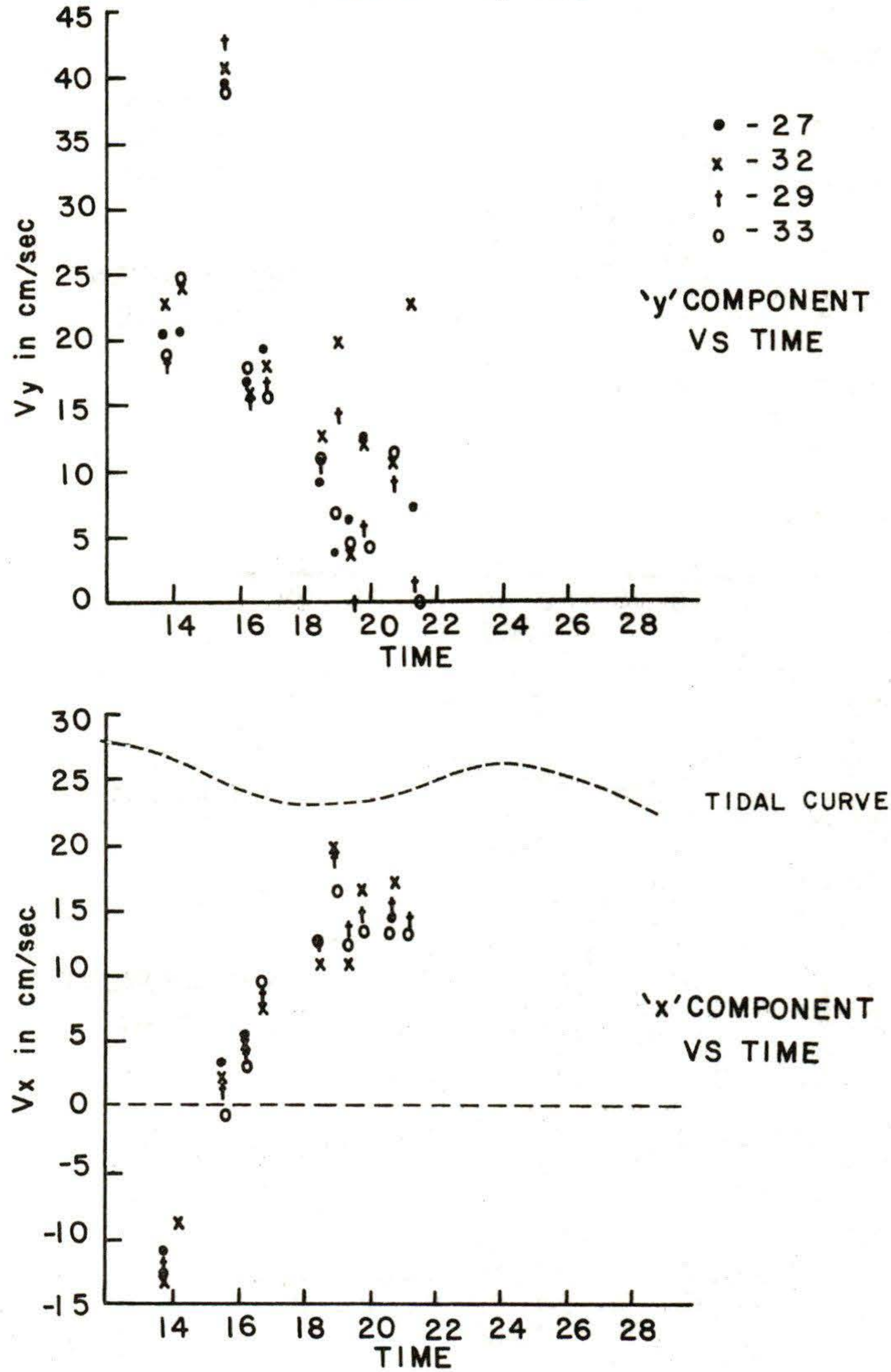


FIG. 5b

VELOCITY COMPONENTS
FOR
CLUSTER OF THREE
AUGUST 16, 1975

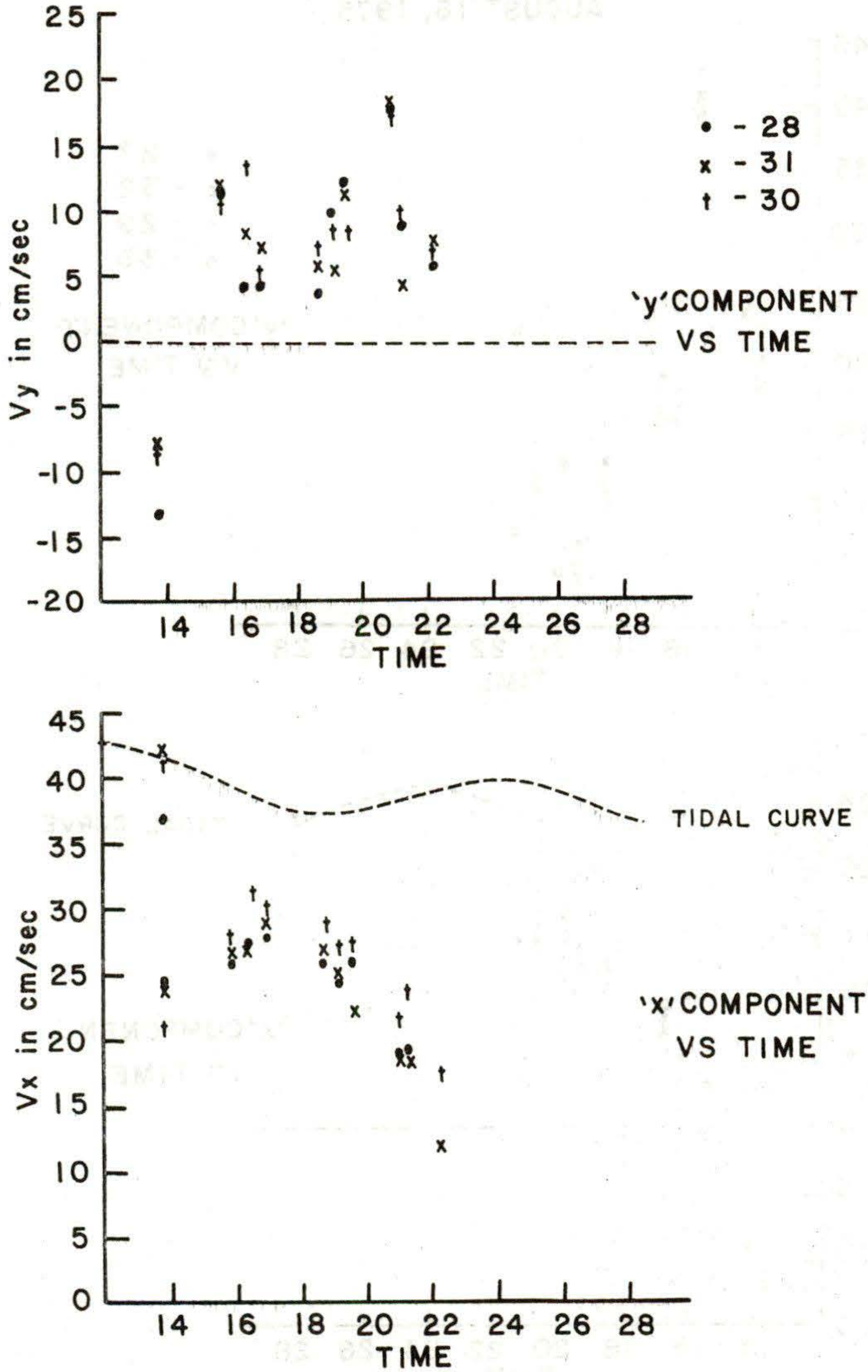
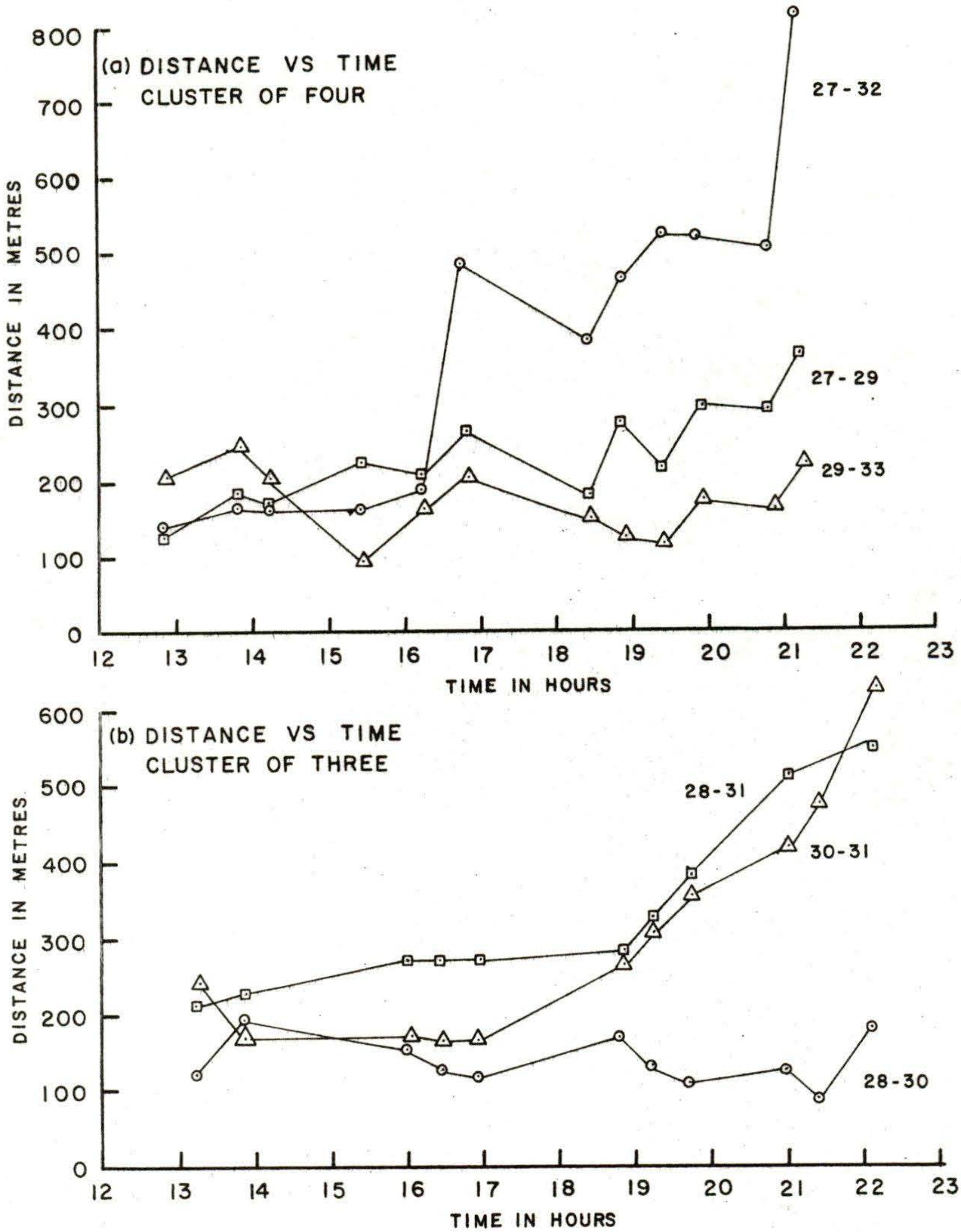


FIG. 6 DISTANCE BETWEEN DROGUE DRIFT PAIRS



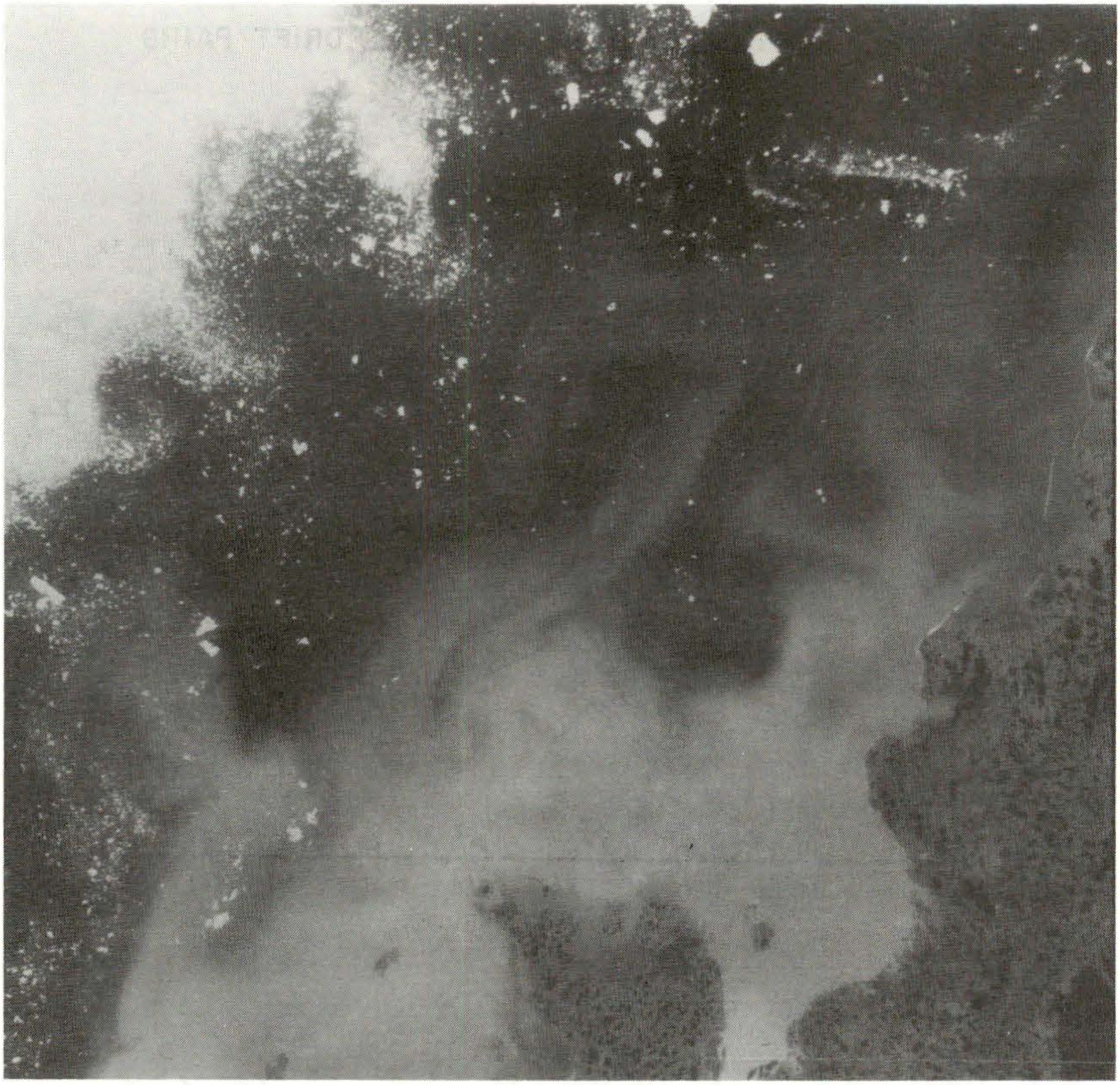


Figure 7a: A large eddy north of Richards Island July 20, 1973

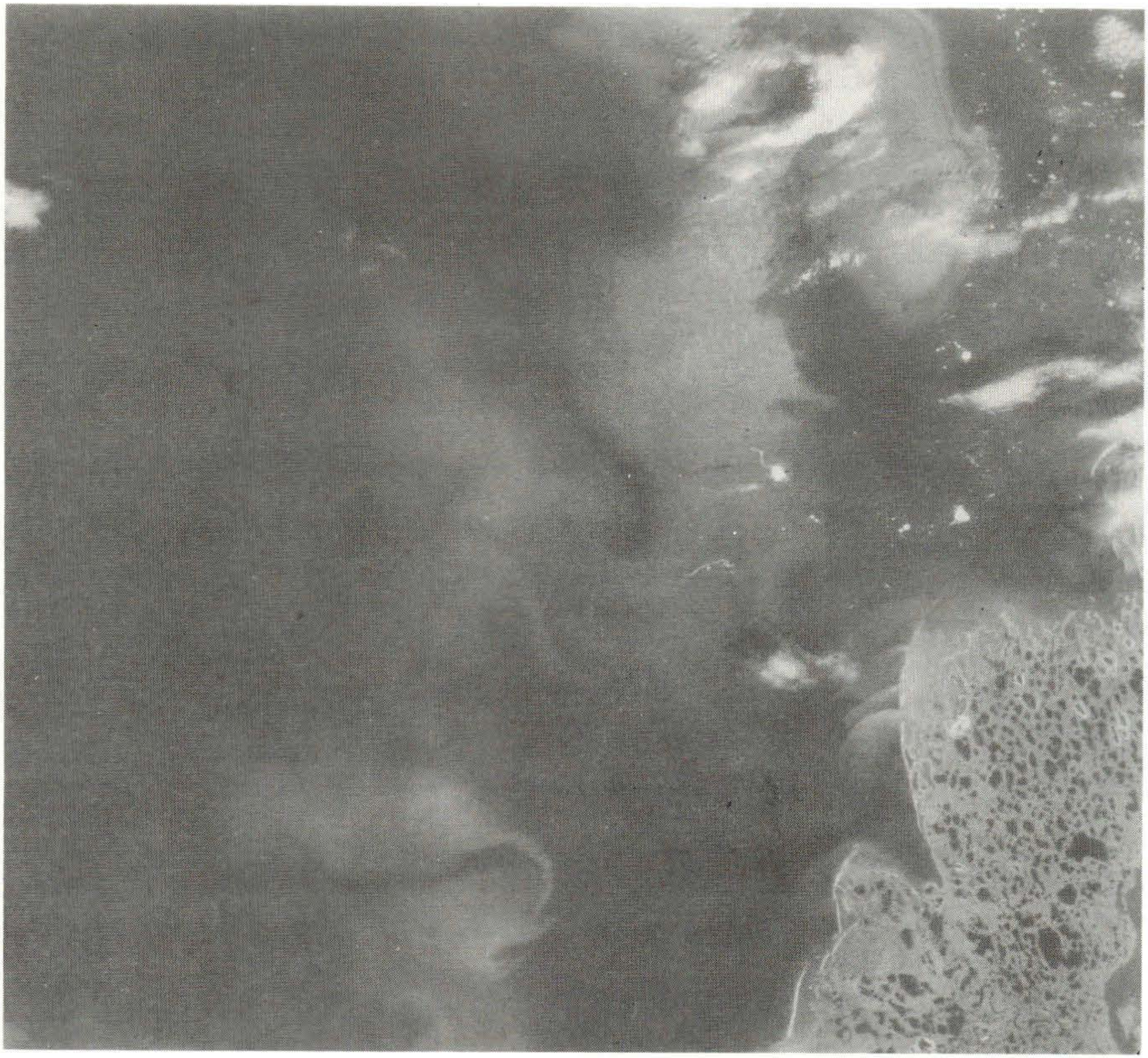


Figure 7b: Eddies north of Tuktoyaktuk Peninsula July 15, 1975

OBSERVED WIND VERSUS GEOSTROPHIC SURFACE WIND

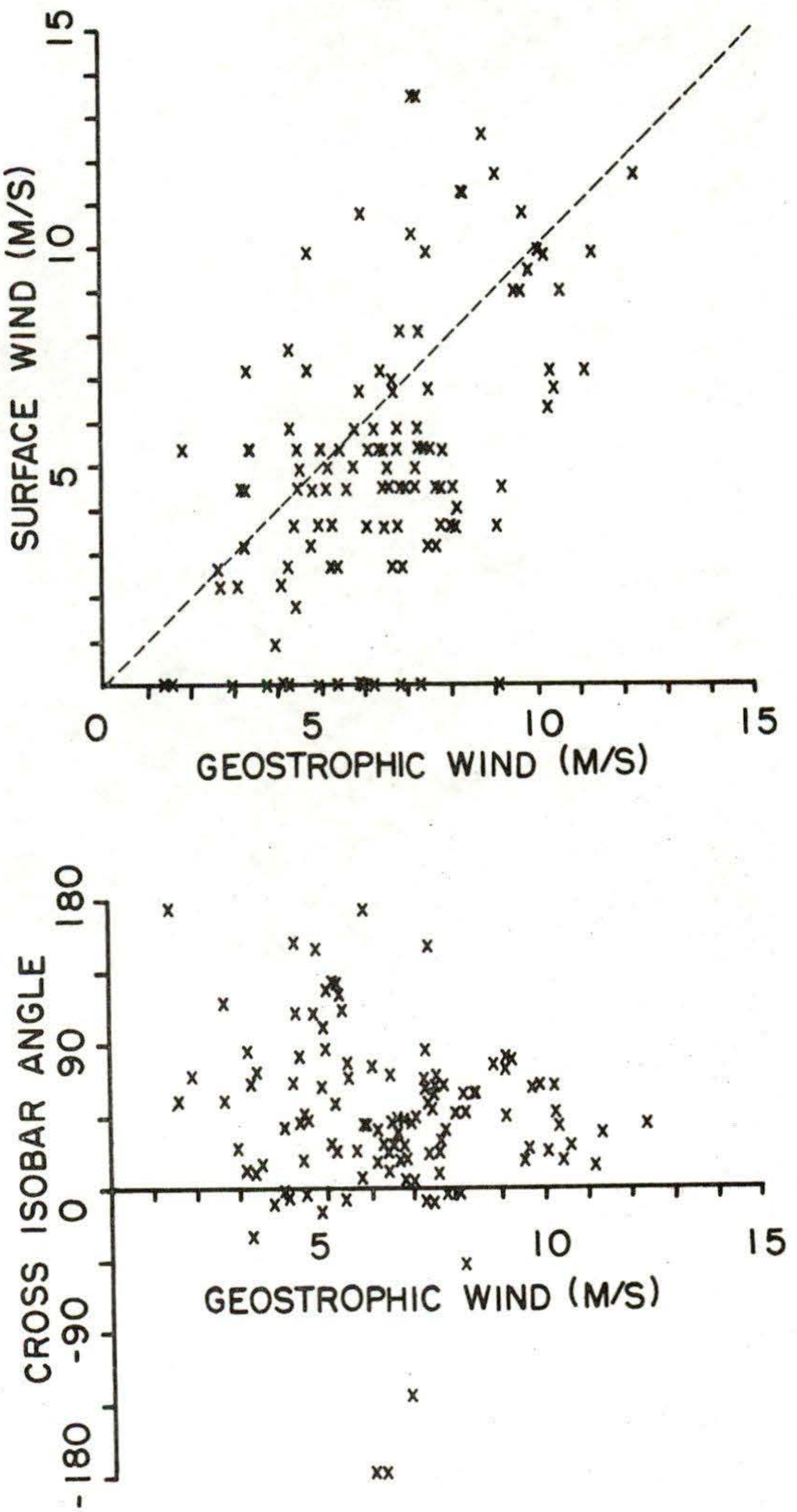


FIG. 8

FIG. 9 SMOOTHED WIND DATA FROM JULY 26 TO SEPT. 10, 1975
FOR IMMERK ARTIFICIAL ISLAND AT 69°35'N, 135°25'W

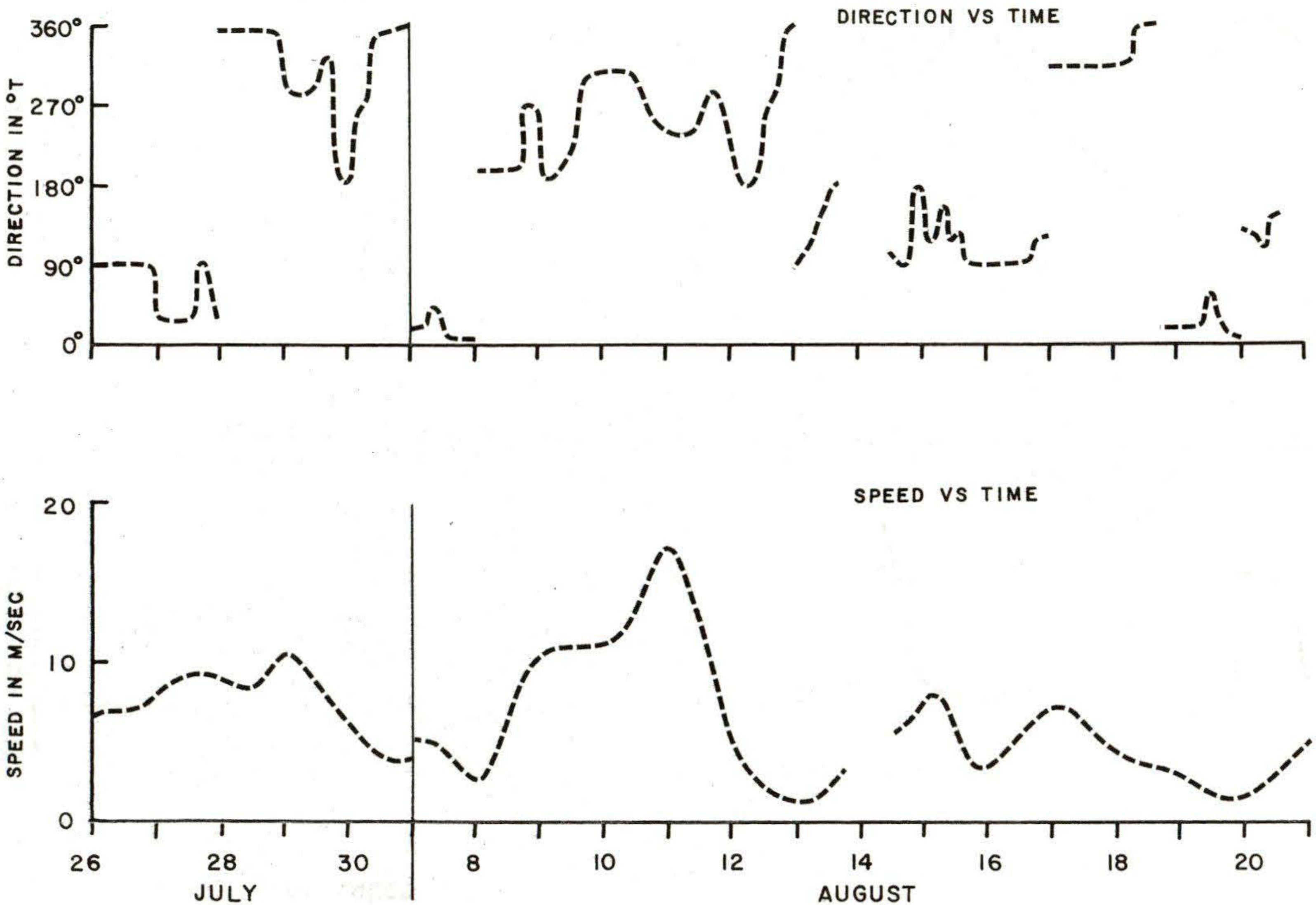
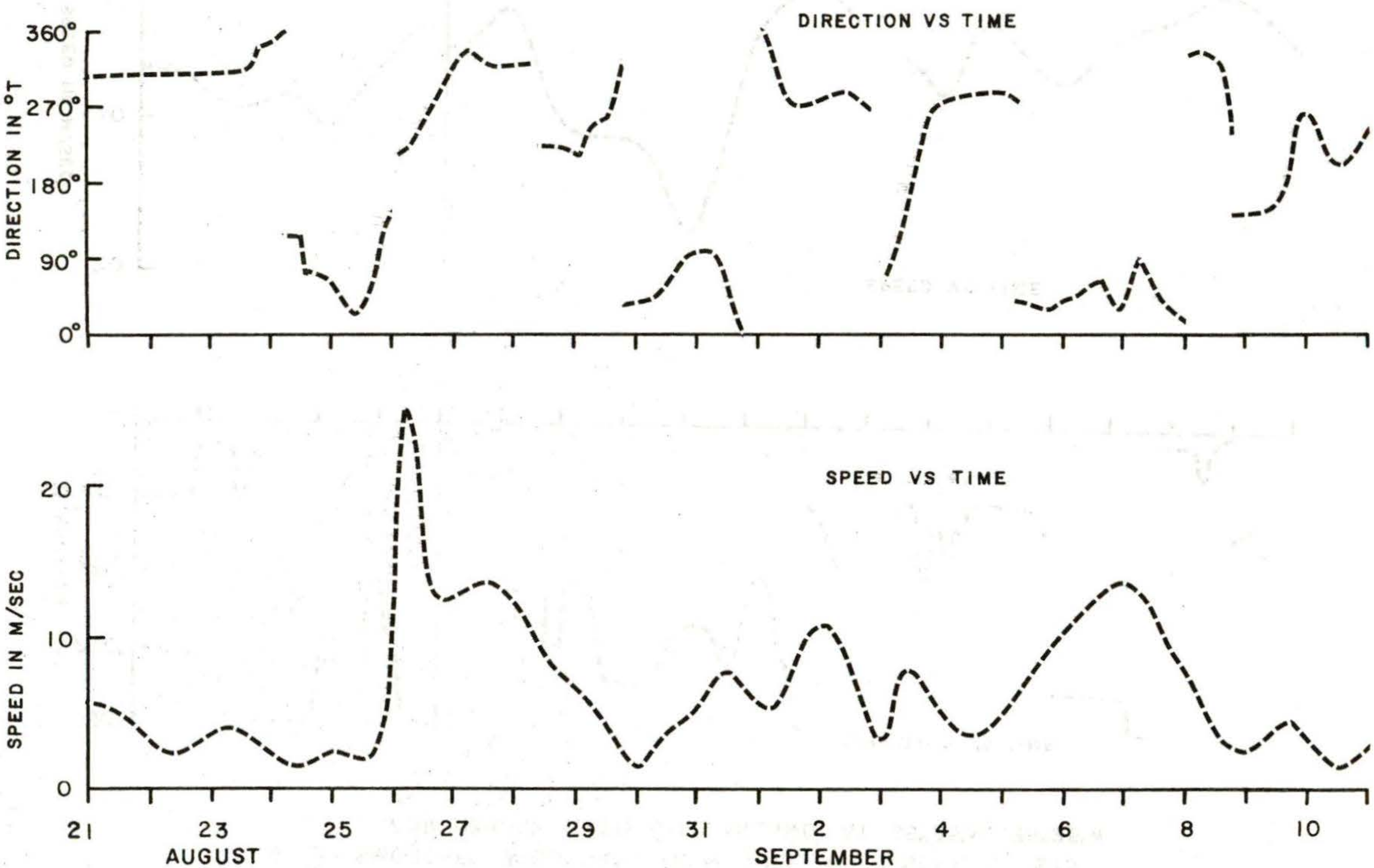


FIG 9 CONTINUED



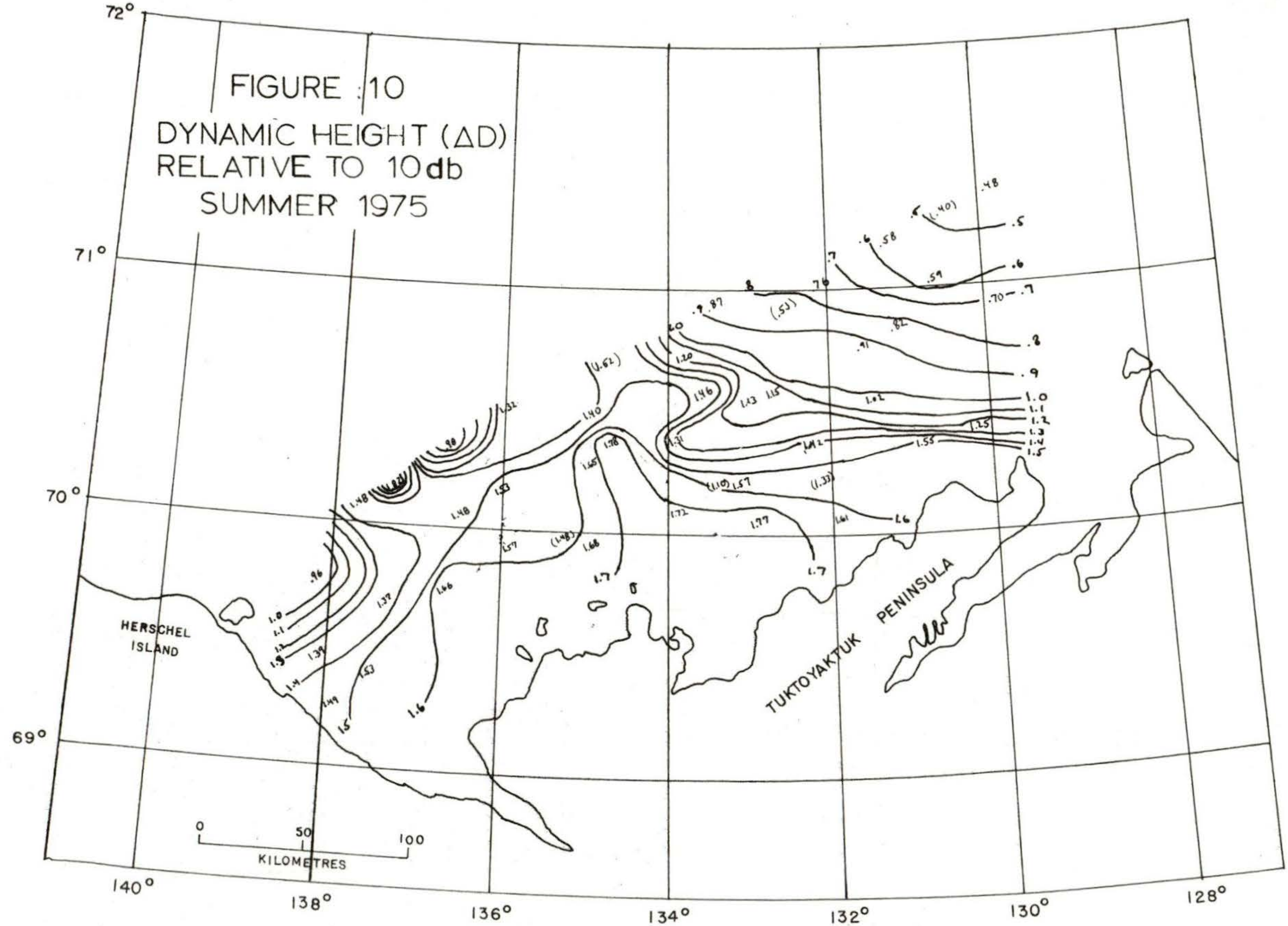


FIGURE 10

DYNAMIC HEIGHT (ΔD) RELATIVE TO 10db SUMMER 1975

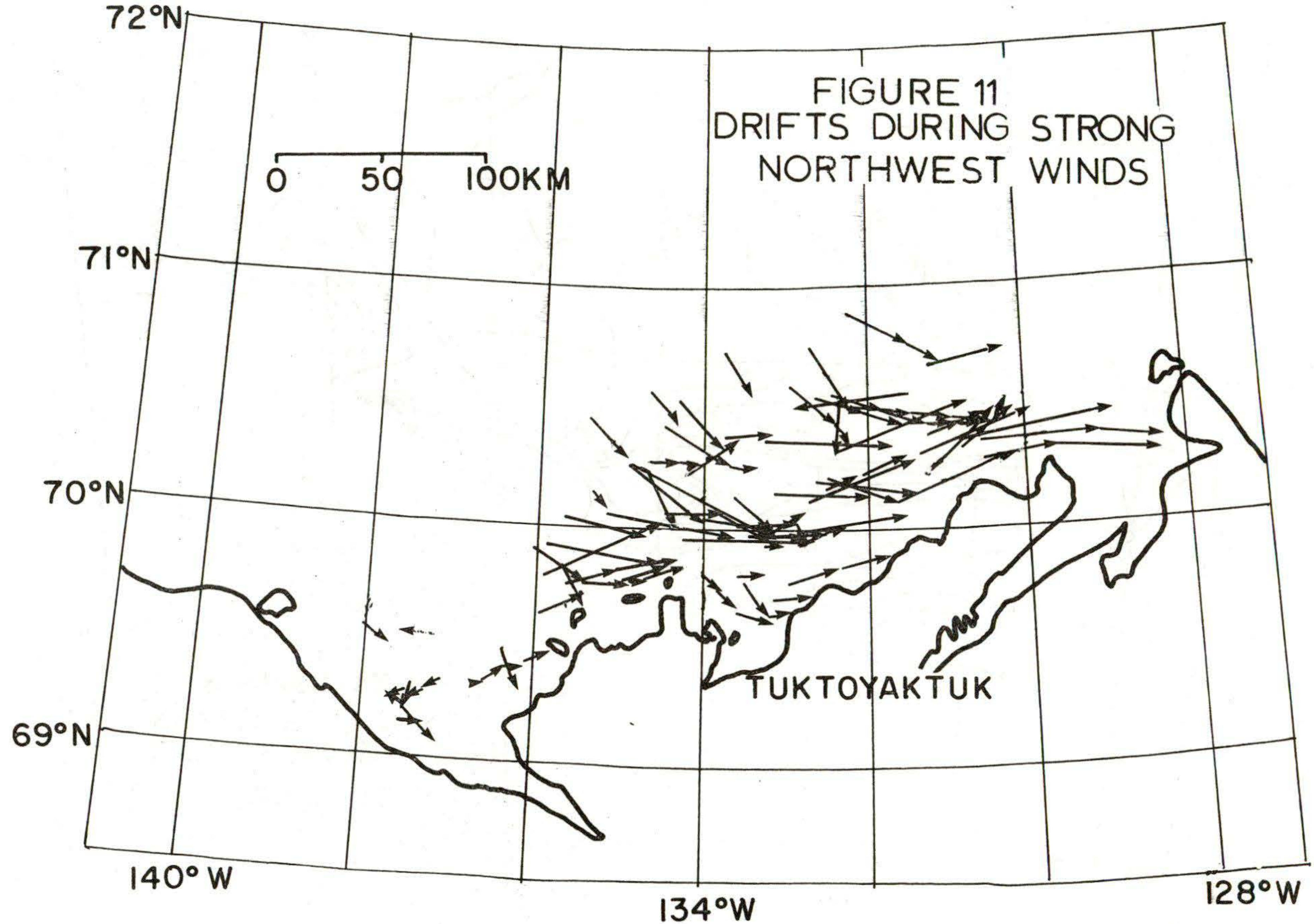


FIGURE 11
DRIFTS DURING STRONG
NORTHWEST WINDS
0
50
100KM
72°N
71°N
70°N
69°N
TUKTOYAKTUK
140° W
134°W
128°W

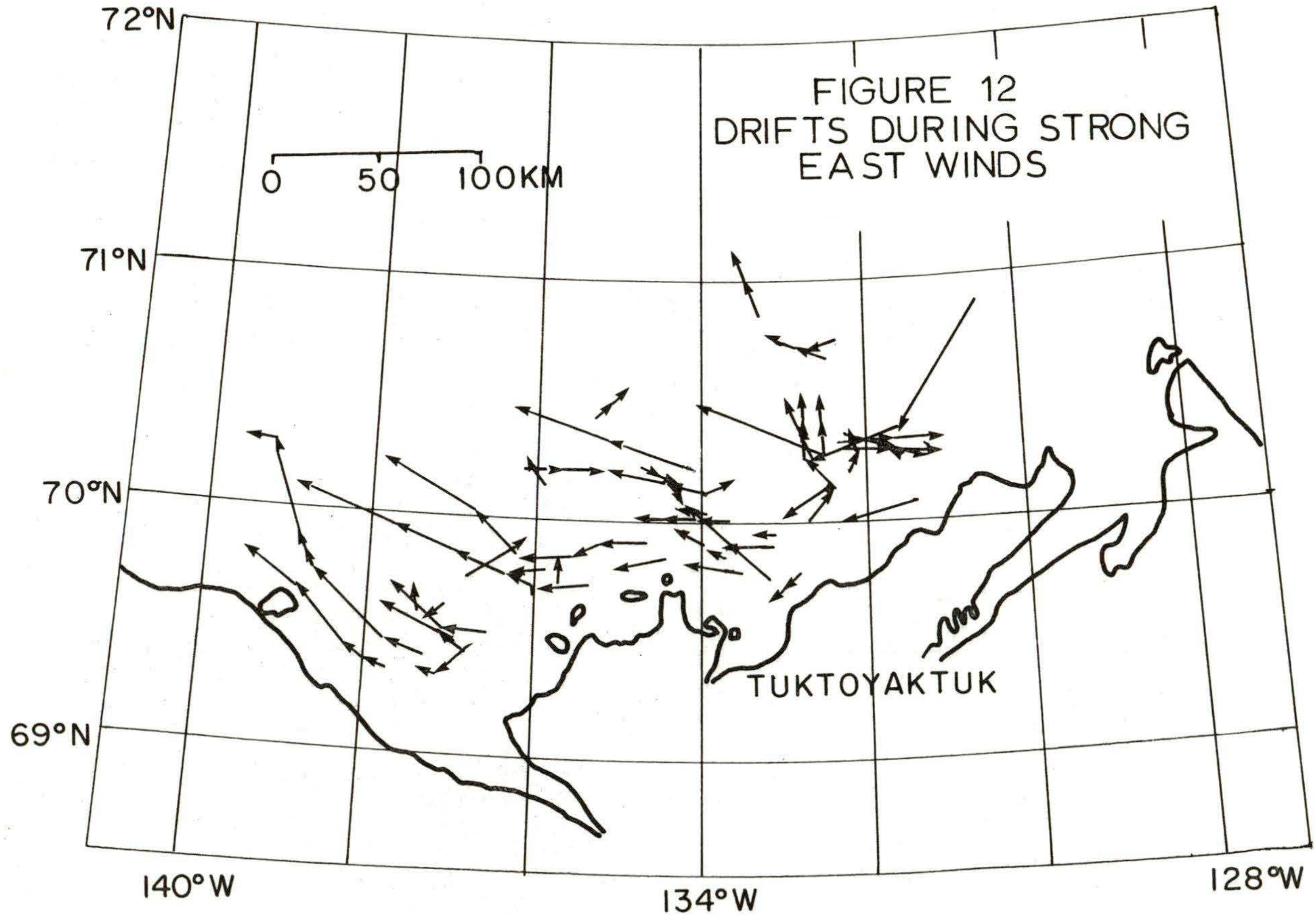


FIGURE 12
DRIFTS DURING STRONG
EAST WINDS

Figure 13a, Joint Distribution of Drift Speed and Observed Wind Speed for All 1975 Observations

OBSERVED WIND m/sec \ DRIFT, cm/sec	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
17.5–20										
15–17.5					1		2			1
12.5–15		2	3	1	1					
10–12.5		1	1	2	1	2	1	1		
7.5–10		1	9	10	6	2	3			1
5–7.5	1	10	8	6	5	1	2			
2.5–5	7	25	19	8	5	4	5	1	1	
0–2.5	6	22	16	11	3	1			1	

Figure 13b, Joint Distribution of Drift Speed and Speed of Wind from Regional Update Model for All 1975 Observations

REGIONAL UPDATE MODEL WIND m/sec \ DRIFT cm/sec	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
17.5–20										
15–17.5										
12.5–15		1	1			1		1		
10–12.5										
7.5–10		3	7	2		2	4			
5–7.5	7	18	9	4	2		2			
2.5–5	3	18	13	11	7	2	1	1	2	
0–2.5	1	4	9	3						

Figure 13c, Drift vs. Observed Winds, Zone D Only

OBSERVED WIND m/sec	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
17.5–20										
15–17.5					1		2			
12.5–15		2	3	1	1					
10–12.5		1	1	1	1	1		1		
7.5–10		1	6	6	6	2	1			
5–7.5	1	7	7	3	2		2			
2.5–5	5	16	15	8	3	1	2			
0–2.5	2	14	9	7	1	1				

DRIFT cm/sec

Figure 13d, Drift vs. Regional Update Model Winds, Zone D

REGIONAL UPDATE MODEL WIND m/sec	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
17.5–20										
15–17.5										
12.5–15		1	1			1		1		
10–12.5										
7.5–10		3	3	2		2	4			
5–7.5	4	16	5	3	2		1			
2.5–5	2	9	8	8	1				2	
0–2.5	1	1	3	2						

DRIFT cm/sec

OSERVED WIND m/sec

Total	12	6	10	19	25	20	25	29	25	22	14	11
17.5–20												
15–17.5						2	2					
12.5–15								4	3			
10–12.5				2	3		3		1			
7.5–10				3	7	2	4	4	6	3	1	1
5–7.5		1	1		3	5	3	9	6	1	4	
2.5–5	7	4	5	6	6	5	10	9	6	11	3	4
0–2.5	5	1	4	8	6	6	3	3	3	7	6	6

-180 -120 -60 0 60 120 180

DRIFT DIRECTION MINUS WIND DIRECTION
Degrees

Figure 14a: Joint Distribution of Observed Wind Speed and Direction of Drift Relative to Wind Direction for All 1975 Observation

REGIONAL UPDATE MODEL WIND m/sec

Total	6	11	16	13	17	19	12	13	14	5	2	11
17.5–20												
15–17.5												
12.5–15					2	2						
10–12.5												
7.5–10		2	4	4	3	4	3	1	2	1		
5–7.5	2	1	2	1	8	5	5	7	6	2		6
2.5–5	4	7	9	5	3	5	2	5	4	2	1	5
0–2.5		1	1	3	1	3	2		2		1	

-180 -120 -60 0 60 120 180

DRIFT DIRECTION MINUS WIND DIRECTION
Degrees

Figure 14b: Joint Distribution of Speeds of Winds from Regional Update Model and Direction of Drift Relative to Wind Direction, All 1975 Data

OBSERVED WIND m/sec												
Total	8	5	4	8	13	11	15	21	19	16	10	10
20 – 17.5												
17.5 – 15						2	2					
15 – 12.5								4	3			
12.5 – 10				1			3		1			
10 – 7.5				1	5	1	2	4	6	2	1	1
7.5 – 5		1	1		2	1	2	5	6		4	
5 – 2.5	6	3	1	3	3	2	5	6	2	9	2	3
2.5 – 0	2	1	2	3	3	5	1	2	1	5	3	6

-180 -120 -60 0 60 120 180

DRIFT DIRECTION MINUS WIND DIRECTION
Degrees

Figure 14c: Joint Distribution of Observed Wind Speed and Relative Direction of Drift for 1975 Zone D Observation

	-180 to -150	-150 to -120	-120 to -90	-90 to -60	-60 to -30	-30 to 0	0 to 30	30 to 60	60 to 90	90 to 120	120 to 150	150 to 180
Total	6	9	7	5	10	15	6	8	10	4	1	9
17.5–20												
15–17.5												
12.5–15					2	2						
10–12.5												
7.5–10		1	2	1	3	3	2	1	1	1		
5–7.5	2	1			5	5	2	5	6	2		5
2.5–5	4	6	4	2		4	1	2	2	1	1	4
0–2.5		1	1	2		1	1		1			

DRIFT DIRECTION MINUS WIND DIRECTION
Degrees

Figure 14d: Joint Distribution of Wind Speed and Relative Direction of Drift for Winds from Regional Update Model and Drifts in Zone D, 1975

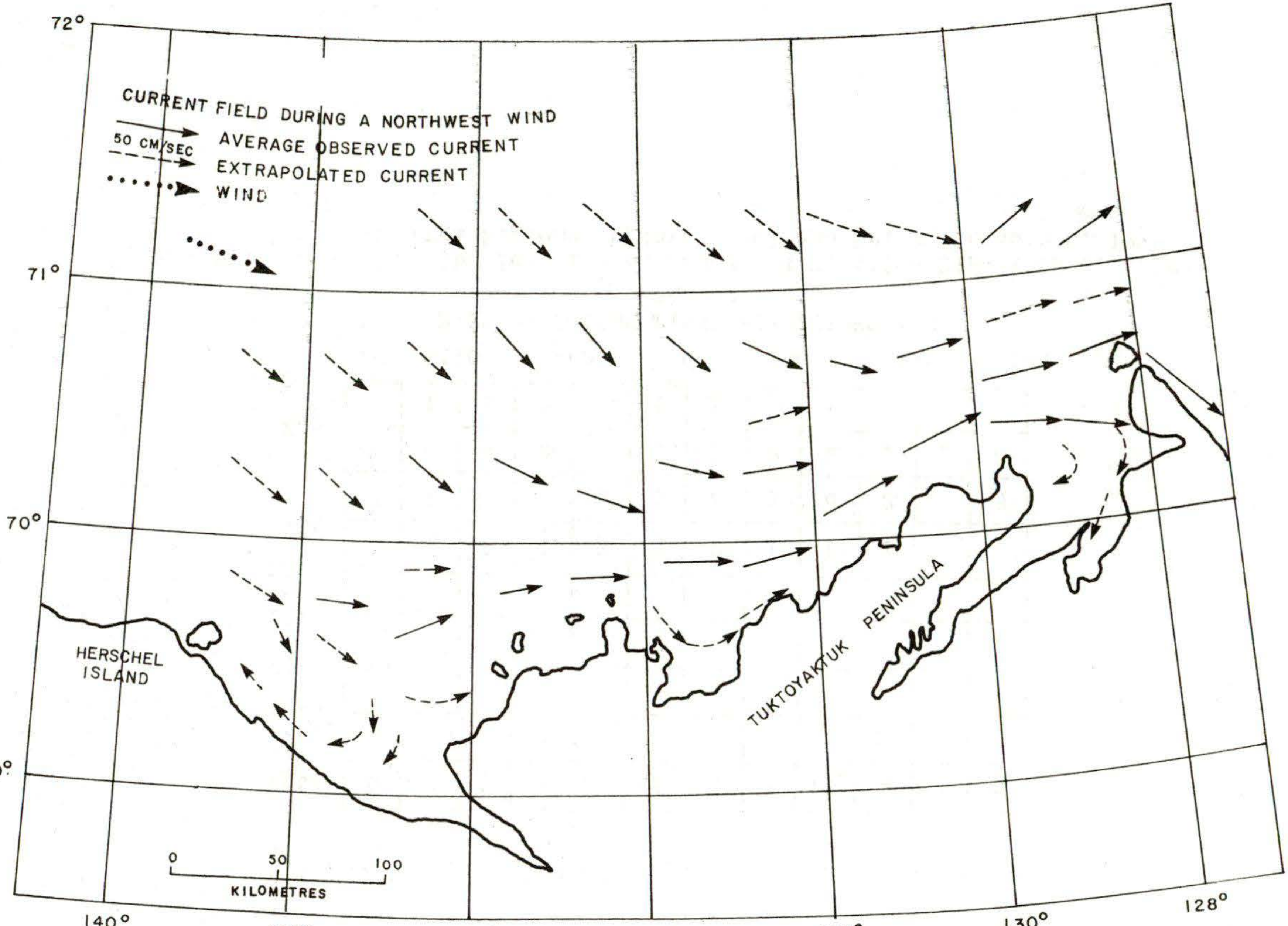

CURRENT FIELD DURING A NORTHWEST WIND
50 CM/SEC
AVERAGE OBSERVED CURRENT
EXTRAPOLATED CURRENT
WIND
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
HERSCHEL ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES

FIGURE 15

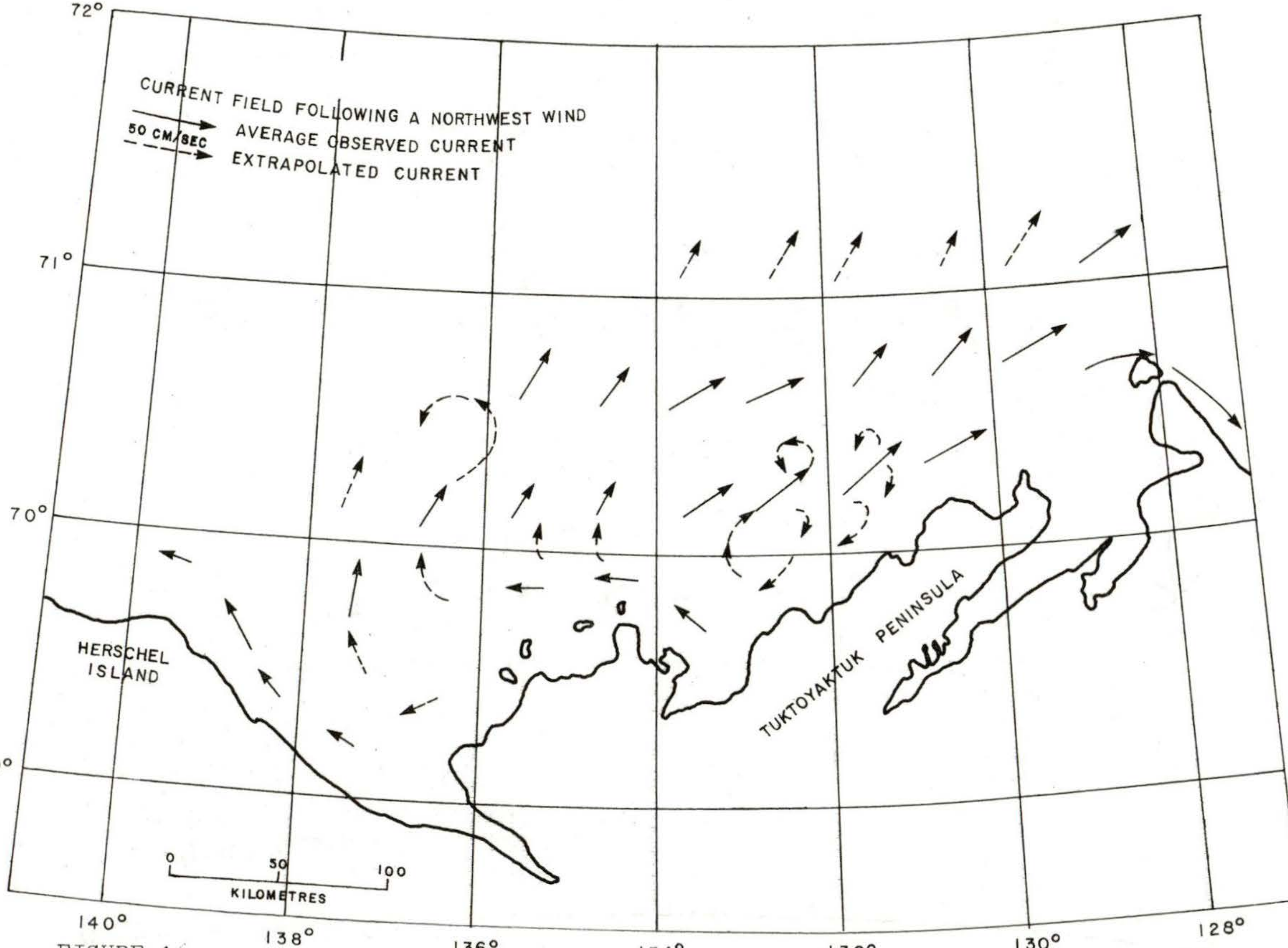
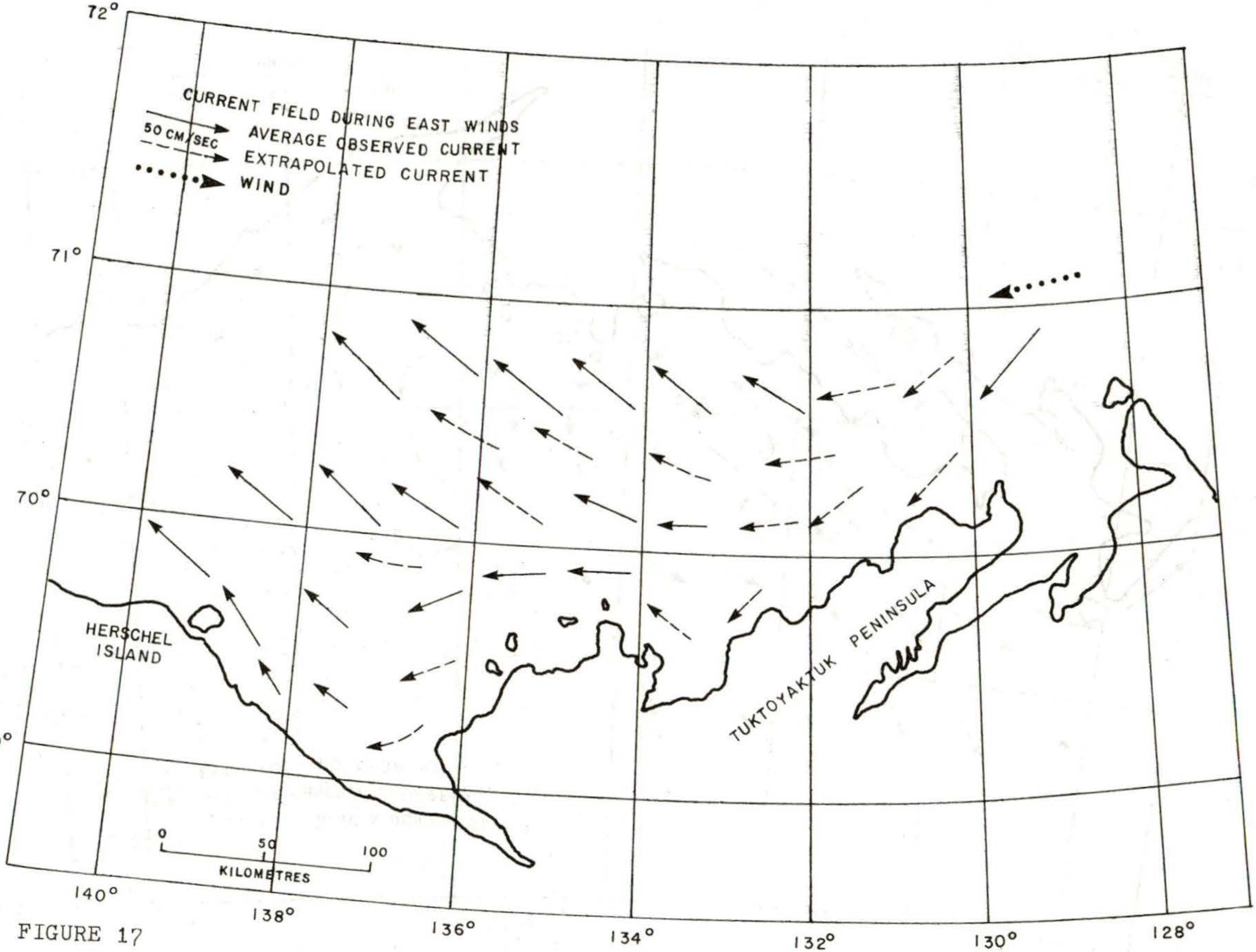

CURRENT FIELD FOLLOWING A NORTHWEST WIND
50 CM/SEC
AVERAGE OBSERVED CURRENT
EXTRAPOLATED CURRENT
72°
71°
70°
69°
HERSCHEL ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES
140°
138°
136°
134°
132°
130°
128°

FIGURE 16



72°
CURRENT FIELD DURING EAST WINDS
50 CM/SEC
AVERAGE OBSERVED CURRENT
EXTRAPOLATED CURRENT
WIND
71°
70°
69°
HERSCHEL ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES
140°
138°
136°
134°
132°
130°
128°

FIGURE 17

APPENDIX A

1974 DATA

The 1974 drogue and ice floe drift data is presented in Figures A-1, A-2 and A-3. Because the data is sparse, it has been collected into three wind periods - northwest wind - Figure A-1; post-northwest wind - Figure A-2; and east wind - Figure A-3. For purposes of visual comparison, each drogue track is plotted as an average velocity vector with the vector origin at the starting position of the track the velocity is averaged over.

TABLE A-1 - 1974

D.B. = Drift Buoy — I.B. = Ice Beacon

DATE	DEPLOYED (REGION)	EVENTUAL RESULT
August 3	D.B. Mackenzie Bay D.B. Kugmallit Bay	Went ashore Aug. 19 Found ashore Atkinson Pt.
August 10	D.B. off Toker Pt.	(Lost Aug. 15)
August 16	3 D.B. Kugmallit Bay D.B. Mackenzie Bay	Blown ashore in big storm August 19th
August 17	D.B. Mackenzie Bay	Blown ashore in big storm August 19th
August 20	3 I.B. North of Hooper	2 fell in water 1 tracked 8 days (70°3'N)
August 20	D.B. off Toker	Found ashore Atkinson Pt. (Lost August 24)
August 20	D.B. off Warren	Caught in ice - Aug. 24
August 22	3 I.B. in Mackenzie Bay	- one aground - one lost after 2 days - one north of Herschel
August 22	D.B. Kugmallit	Lost radio beacon (detached - 4 days)
August 22	D.B. Kugmallit	Aground September 2nd
August 26	2 D.B. Kugmallit, Pelly	Caught in ice August 28
August 28	D.B. Kugmallit 3 D.B. north of Hooper	Caught in ice Lost after 2 days (29th)
August 29	D.B. north of Pullen 3 D.B.	Aground September 2nd Failed to function
September 1	D.B. Mackenzie Bay	Aground September 3rd
September 2	Storm for Northwest	
September 3	D.B. off Toker	Aground September 5th
September 5	3 I.B. north of Toker	-1 quit September 14 -2 in water September 7th
September 6	D.B. northeast Pullen (helicopter)	Went into ice September 9
September 6	3 I.B. north of Toker 3 I.B. Mackenzie Bay	lasted 6-8 days -1 aground -2 northwest of Herschel
September 7	2 D.B. north of Hooper	-In ice September 9
September 9	2 D.B. Mackenzie Bay	Lost - receiver problems
September 13	2 D.B. Mackenzie Bay	-Northwest of Herschel
September 16	4 D.B. Hooper → Atkinson	Tracked to September 19
September 19	Last Day of Operation.	

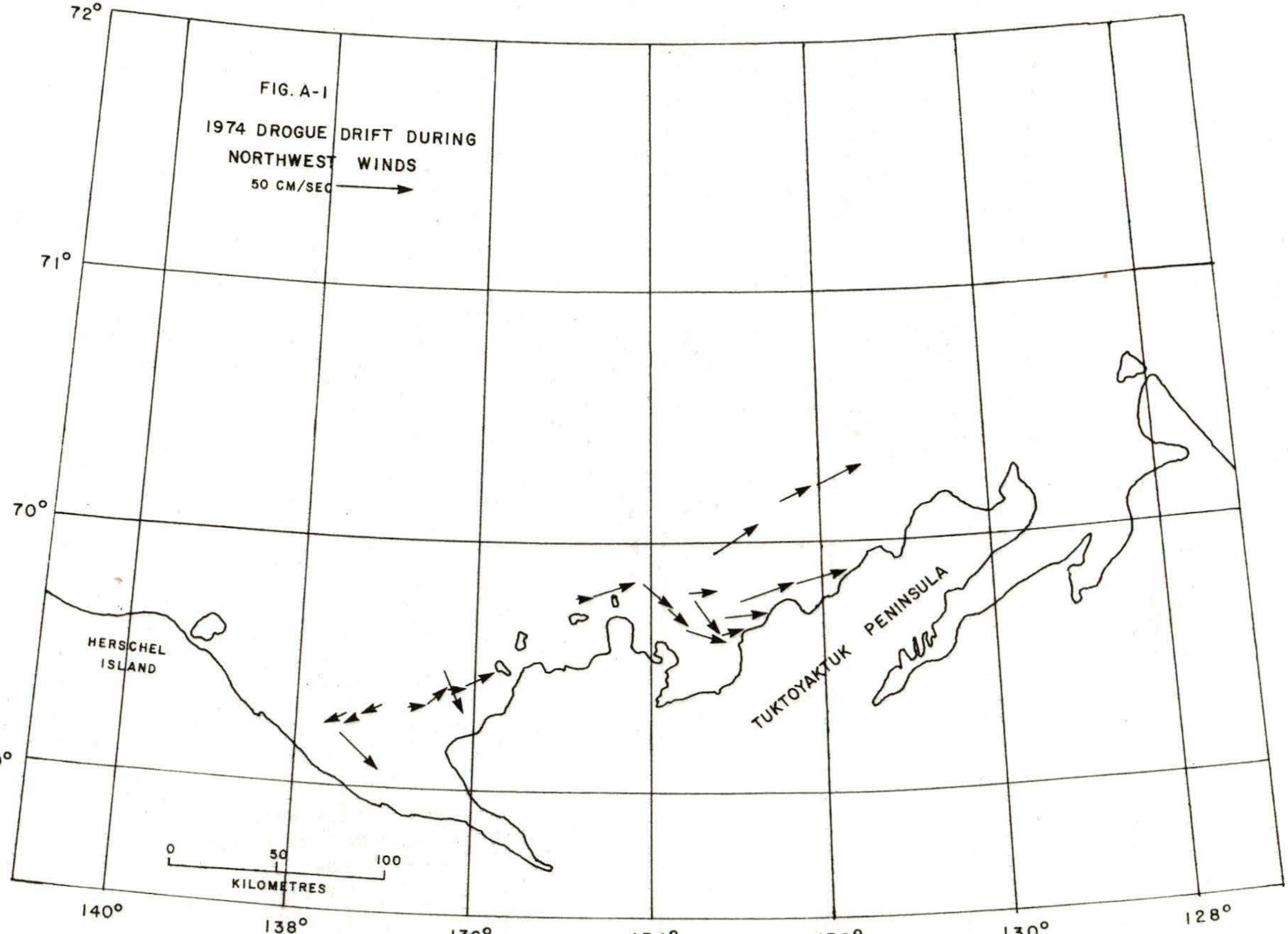


FIG. A-1
1974 DROGUE DRIFT DURING
NORTHWEST WINDS
50 CM/SEC
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
HERSCHEL
ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES

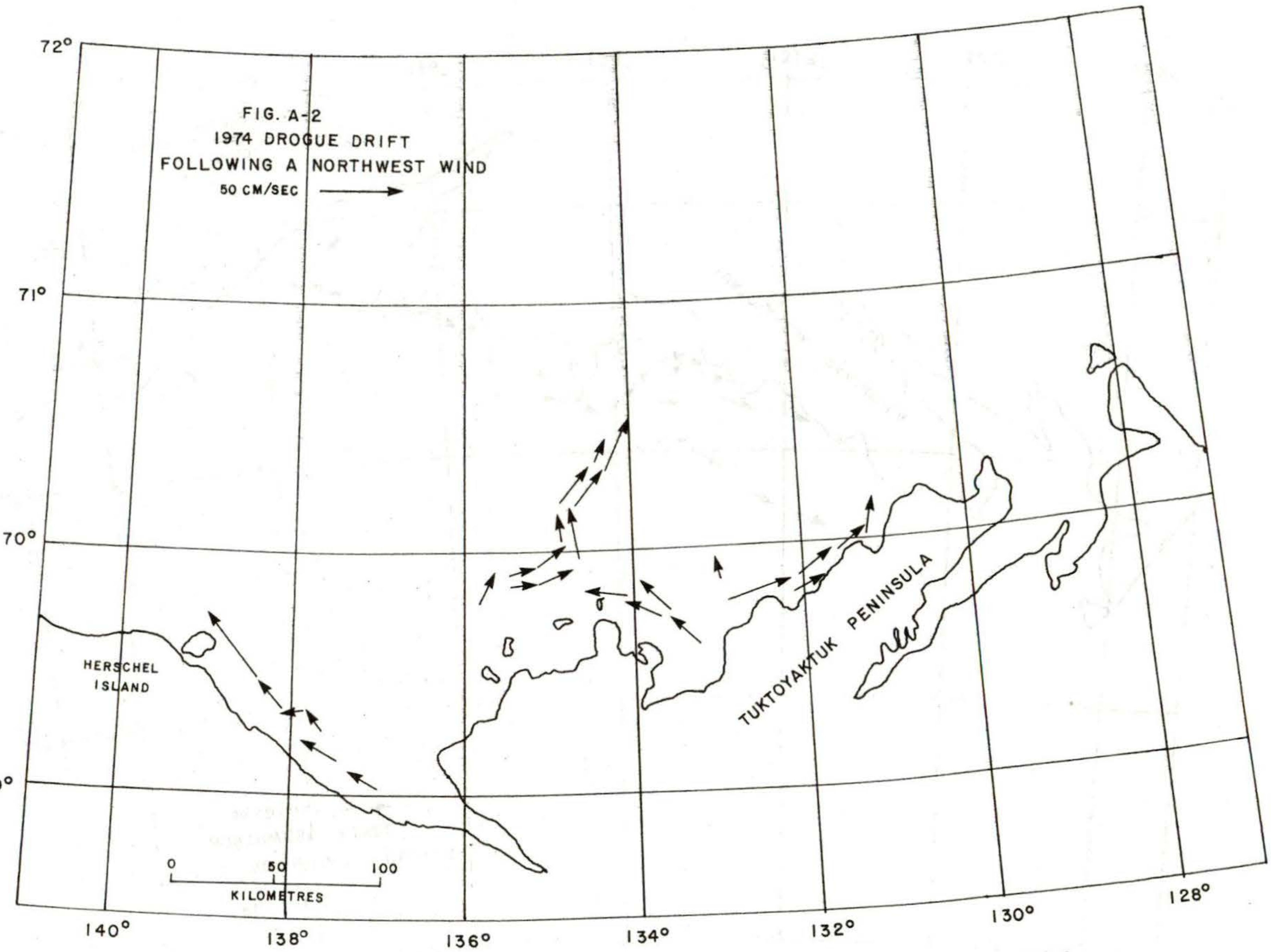


FIG. A-2
1974 DROGUE DRIFT
FOLLOWING A NORTHWEST WIND

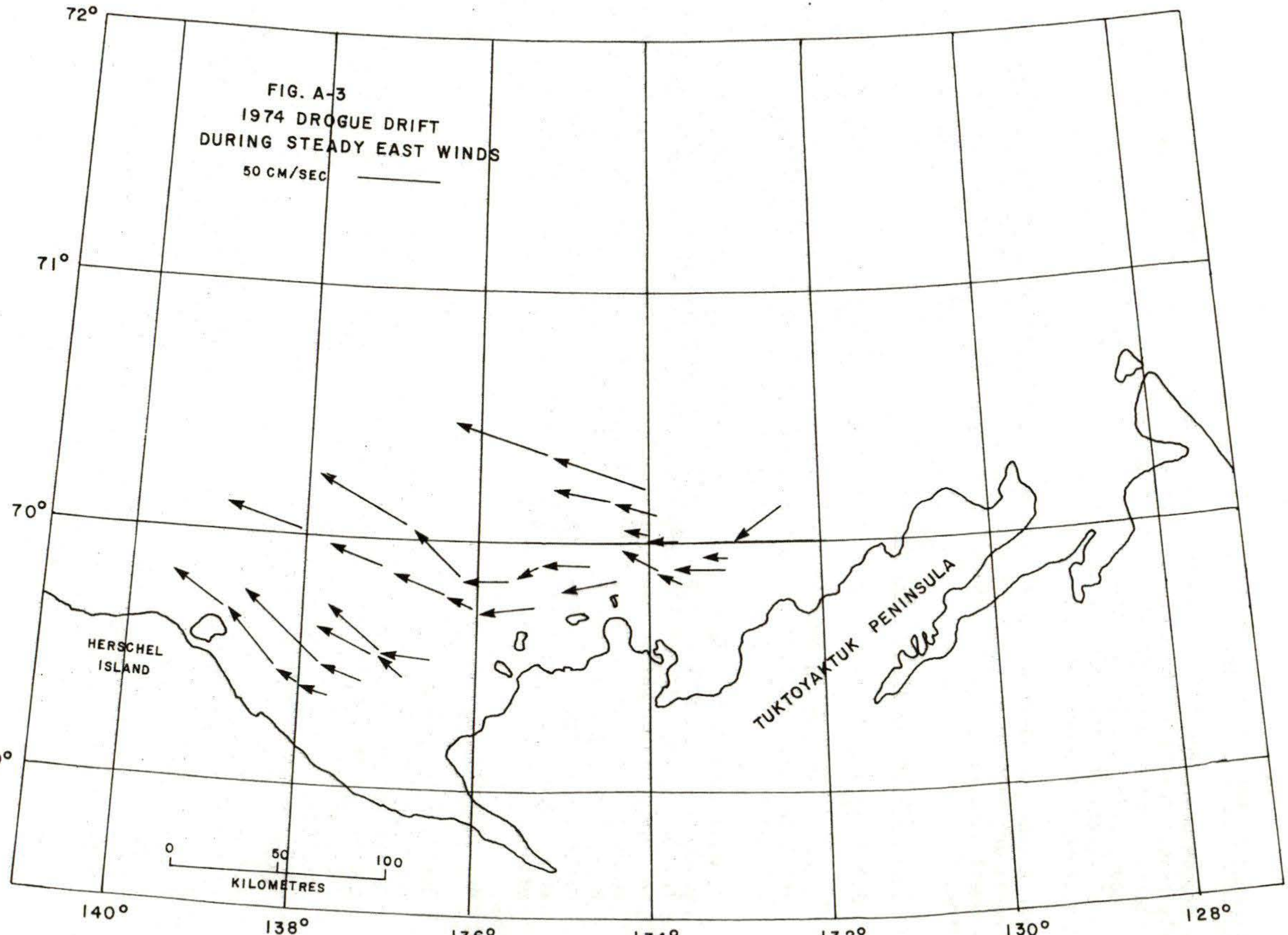


FIG. A-3
1974 DROGUE DRIFT
DURING STEADY EAST WINDS
50 CM/SEC
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
HERSCHEL
ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES

APPENDIX B

PRESENTATION AND DISCUSSION OF 1975 DATA

The drogue drift for 1975 is presented in Figures B-1 to B-26 as plots showing daily drogue positions for successive time intervals. Average wind for several stations for each period appears as a dotted arrow at the station location. The accompanying discussion attempts to present a correlation between meteorological events and the observed drift for the purpose of establishing a coherent picture of the current velocity field.

In the discussion winds are described by the direction they are coming from, currents are described by the direction they are going to. For example, a northwest wind is from the northwest, a northwest current is flowing to the northwest.

B.1 July 28th to August 1st (Figure B-1)

B.1.1 Weather

A low pressure moved down into the northern Beaufort Sea on July 27th which brought with it a steady west wind (beginning in Tuktoyaktuk about 1500 hours, July 27th).

Between observations from the 28th to the 29th, the wind blew at 7-10 m/sec from 270-300°T. From the 29th to the 30th, the wind north of Tuktoyaktuk was blowing 10 m/sec from 290°T until about 0300 hours local (on the 30th) at which time it died off to 5-7 m/sec from 270°T. By 2100 hours on the 30th, the wind had changed direction, and for the last six hours before the times of the drogue positions, the wind was less than 5 m/sec and variable. On the 31st of July, the winds were light and variable, most of the first of August, the winds were from the east at 3-5 m/sec.

B.1.2 Drift

During this period, the drogues were quite obviously driven by the wind. From the 28th to the 29th, they moved at an average of 30 cm/sec (about .03 of wind speed) at an angle of 30-50° to the right of the wind; closer to the shore of the Tuktoyaktuk Peninsula the angle to the wind decreased to 0° as the drogues approached the plume. From the 29th to the 30th, on the third day of the west wind, the drogues as far out as 70°30' north moved approximately parallel to the Tuktoyaktuk Peninsula (50°T) to the left of the wind with an increased speed of 40 cm/sec. The Mackenzie Plume was hugging the shoreline of the peninsula (to about 7 km of the shore - presumably moving east) but the drogues closest to shore did not penetrate inside the plume. In the next two days (July 30th to August 1st), the drogues offshore continued to move east, even though the winds had died down and turned around from the east. The drogue closest to shore was found aground in a large bay just west of Cape Dalhousie - caught in the circulation into the bay when the wind subsided (probably lost its subsurface sail before being drawn into the bay).

B.2 August 2-3 (Figure B-2)

B.2.1 Weather

At approximately 1600 hours on August 1st north of Tuktoyaktuk, a northeast wind of 5-7 m/sec began to blow and continued blowing during the drogue drift of August 2nd to 3rd. A high pressure was centred at 72°N and 133°W.

B.2.2 Drift

The drogue paths of this period are difficult to explain - there appears to be a divergence off the Tuktoyaktuk Peninsula - the fastest speeds being recorded in a northeasterly direction (20 cm/sec) against the wind. The average speeds of the drogues going west and northwest were from 7 to 15 cm/sec. There appears to be some residual northeasterly current from the northwest blow. The movement of the drogues close to shore indicates that the river water was flowing west. Upwelling or large scale eddies caused by the east wind may account for the apparent divergence - the surface salinity distribution plotted by Cameron (1953) during an east wind showed the occurrence of upwelling along the Tuktoyaktuk Peninsula. The other possible cause of the divergence was the high pressure area centred over the Beaufort Sea at this time.

B.3 August 8-10 (Figure B-3)

B.3.1 Weather

A low pressure area again moved down into the northern Beaufort Sea on the 7th of August; a northwest wind began to blow at Tuktoyaktuk between 1200 and 1800 hours heralding a minor storm surge. From August 8th to 9th, the wind averaged 10 cm/sec from 270°T. On August 10th, it veered slightly to the northwest and remained steady at 13 m/sec from 290°T all day to 1800 hours.

B.3.2 Drift

From the 8th to the 9th, the drogues north of Atkinson Point moved shoreward at 30-40° to the right of the wind at an average speed of 30 cm/sec (.02-.03 of wind speed). The two drogues closest to shore moved at 55 cm/sec and 42 cm/sec past Cape Dalhousie heading east. Off Hooper Island, the drogue just outside the plume moved east northeast at 20 cm/sec. From the 9th to the 10th, the drogues continued to move shoreward to the right of the wind but at a slower rate - usually less than 25 cm/sec even though the wind had remained quite constant. On the other hand, the drogues nearest to the shore moved northeast parallel to the shore at increased speed - i.e. north of Hooper, the speed increased to 35 cm/sec (from 20); north of Atkinson the speed increased from 45 cm/sec to 62 cm/sec to 70 cm/sec during the 9th and the 10th. The two drogues off Cape Dalhousie went into Liverpool Bay at about 50 cm/sec. The variations in average speed were probably caused by variations in the wind speed over the averaging period.

B.4 August 10th-11th (Figure B-4)

B.4.1 Weather

The west wind picked up to 15-18 m/sec at 1800 hours on August 10th. At 1200 hours on August 11th the wind dropped to 10-12 m/sec and remained constant for the rest of the day.

B.4.2 Drift

The drogues north of Richards Island and Kugmallit Bay seemed to move south to the edge of the plume and then move east parallel to the coast along the edge of the plume at about 50 cm/sec (north of Hooper Island, the speed toward the east had increased from 35 to 50 cm/sec from the previous day). North of 70° the angle of the current to the wind had decreased as the current moved more nearly parallel to the shore with a greater northeastern component. To the northwest of Cape Dalhousie, the drogue at approximately 70°45' had also picked up more northeasterly component of current.

B.5 August 11th-13th (Figure B-5)

B.5.1 Weather

On the 12th of August, the low pressure moved east out of the Beaufort Sea and for two days the winds over most of the southern sea prevailed from the S to SE at about 5 m/sec.

B.5.2 Drift

East of 134°W (as far north as 70°45') the general movement still seemed to be northeast parallel to the Tuktoyaktuk Peninsula (speeds from 18 to 50 cm/sec), this probably being a continuation of the current set up by the strong northwest wind of the previous four days. West of 135°, the currents were less uniform and more difficult to interpret on the large scale with such a sparse spatial representation. The general movement of the drogues was eastward but north of Hooper, the speeds were slower and there was a southerly component to the movement despite the prevailing light ($\approx$ 5 m/sec) south to southeast wind and the remaining current from the storm surge which should tend to move in a northeast direction (although there was no verification of the speed and direction of the currents north of Mackenzie Bay <u>during</u> the northwest storm). Apparently, something other than the wind was driving the surface water here - possibly a cyclonic circulation into Mackenzie Bay or a large eddy caused by the Mackenzie River discharge. Eddies on the scale of tens of kilometers wide have been observed north of the delta on ERTS satellite photos (Figs. 7a and b).

B.6 August 13th-16th (Figure B-6)

B.6.1 Weather

From the 13th to the 16th the winds were variable and light (around 5 m/sec) - the prevailing direction ranging from S to ESE.

B.6.2 Drift

North of 70°N, the characteristic movement of the drogues (from Mackenzie Bay to Cape Dalhousie) was to the north and northeast during this period. This movement is probably accounted for by two factors: (1) the south wind and (2) northeastward (reverse) current set up by a receding storm surge. From the 15th to the 16th, a drogue at 136°W between 70°30'N and 70°N moved south at 20 cm/sec, against the wind. This may have been caused by a large eddy or cyclonic gyre into Mackenzie Bay set up by the movement of Mackenzie River water out of Kugmallit Bay northwestward past Pelly Island where it converged with the water receding northwestward out of Mackenzie Bay. The westward inshore circulation can be seen in the drogue drifts north of Warren Point and in Mackenzie Bay (10-25 cm/sec) with the fastest westward inshore current running northwest past Herschel Island between the 15th and the 16th. The path of drogue movement in Mackenzie Bay almost looked like part of a cyclonic gyre around the bay. The other prominent feature of the circulation during this period was the strong current evidently running southeast along the Bathurst Peninsula from around Baillie Island.

B.7 August 16th-18th (Figure B-7)

B.7.1 Weather

North of Tuktoyaktuk Peninsula, the recorded winds were east and northeast from 2-8 m/sec for the entire period. In Mackenzie Bay and the Delta region, the winds were predominantly northwest about 2 m/sec.

B.7.2 Drift

An east wind would explain the dominant movement of the offshore drogues northwest. A divergent area again appeared north of Richards Island as a gyral type motion, perhaps due to the convergence of the two winds. Two clusters of drogues north of Warren Point moved east with small average speeds from the 16th to the 17th; from visual observations made from the Bell 206, they appeared to be caught up in a system of eddies (of order 2-14 km wide each) formed by the Mackenzie River water under the influence of an east wind. These eddies were clearly visible from the air as far north as 70°40'N of Atkinson Point. Not shown in this plot is the continued drift of a drogue southward along the Bathurst Peninsula.

The drift in Mackenzie Bay does not seem to be associated with the wind which was light from the northwest.

B.8 August 18th-20th (Figure B-8)

B.8.1 Weather

The winds were from the northeast (40°T) at about 5 m/sec for the first 15 hours of this period. The remainder of the three days was virtually calm.

B.8.2 Drift

During this period, there seems to be little correlation between wind speed and direction and drogue drift, probably because of the variability of the wind. Several circulation patterns do stand out though - one being the increased speed to the northwest (from 8 to 40 cm/sec) of the drogue north of Herschel Island, then its movement due west at 25 cm/sec; another being the apparent persistence of the cyclonic gyral motion west and north of Richards Island. An ERTS satellite photograph taken at this time illucidates the apparent gyral motion as an eddy from the Mackenzie plume moving in an anti-cyclonic manner, i.e. the drogue, moving west at 70°N, 134°W is associated with the eddy but the other drogues north of Richards Island are part of the mean eastward movement. This demonstrates how deceptive the drogue movements can be when attempting to decipher smaller scale phenomena.

Note the divergence in Mackenzie Bay.

B.9 August 20th-22nd (Figure B-9)

B.9.1 Weather

The wind was light until a southwest wind (of 5 m/sec) began to blow at 0300 hours (135°W) on the 21st. At 1800 hours on the 21st, it became a northwest wind (veering to 280°T then 300°T) of about 5 m/sec (steady till the last observation on the 22nd of August).

B.9.2 Drift

North of Herschel the drogue continued west at reduced speed (15 cm/sec). East of 137°W, the pattern of drogue movement resembled that of other northwest winds with shoreward speeds of up to 30 cm/sec. Of interest is the drogue indicated by the dotted arrow - it had lost its underwater sail so was affected by the movement of top metre of water and the wind only - its average speed was 1/2 that of the drogues close by with sails intact. The absence of any mean drift in the two-day average motion of the two drogues due north of Atkinson Point may be caused by an eddy from the Mackenzie River discharge.

B.10 August 22nd-24th (Figure B-10)

B.10.1 Weather

(At 136°W) a 5 m/sec wind prevailed from the northwest ($\approx$ 300°T) for the entire period.

B.10.2 Drift

Due to fog preventing deployment of drogues, the spatial density of the drogues had become very sparse so the overall picture lacks coherence but the overall motion of the drogues was eastward, parallel to the coast at speeds of 10 to 25 cm/sec - the speeds being generally smaller than the day before. The two drogues north of Atkinson Point that had very little mean drift from the 20th to the 22nd continued to stay in the same spot with no appreciable average movement in any one direction.

B.11 August 24th-25th (Figure B-11)

B.11.1 Weather

The winds were light and very variable from August 24th to 25th.

B.11.2 Drift

There appeared to be a convergence at 135°W north of Hooper Island. This could not be accounted for by the wind or pressure systems.

B.12 August 25th-26th (Figure B-12)

B.12.1 Weather

The period began with light variable winds over the whole area which continued for about six hours. At 1800 hours on August 25th, the winds became steady from the southeast at approximately 7.5 m/sec; on August 26th at 0300 hours, the winds swung around to the southwest. The wind speed in Mackenzie Bay increased to 15 m/sec although winds at Tuktoyaktuk remained at 5-7 m/sec. These strong southwest winds (up to 25 m/sec in Mackenzie Bay) continued for most of the duration of the period - Tuktoyaktuk winds also picking up to 13 m/sec at 0600 hours on August 26th - although wind reports from 70°10'N, 133°W indicated southeast winds at 15 m/sec during this period. For the last six hours of the interval the winds were west northwest at 12 m/sec.

B.12.2 Drift

The drift looked characteristic of a westerly blow. The fastest drogue speeds were recorded north of Mackenzie Bay when the strontest southwest winds blew. Drogues 35 and 36 moved at about 40 cm/sec. The slowest speeds - 15 cm/sec, were recorded by drogues 27 and 28, north of the Tuktoyaktuk Peninsula. The wind record from Atkinson Point shows that the strong southwest wind did not reach Atkinson until 0900 on August 26th.

B.13 August 26th-27th (Figure B-13)

B.13.1 Weather

Steady northwest winds of 10-20 m/sec blew for the entire period.

B.13.2 Drift

The drift of the drogues was similar to previous northwest wind situations. The speeds were greatest - 50 cm/sec - in the longshore movement of drogues 31 and 27 north of Atkinson Point.

B.14 August 27th-28th (Figure B-14)

B.14.1 Weather

The wind continued to blow from the west northwest with a reduced speed of 7-10 m/sec.

B.14.2 Drift

The drift was still characteristic of a northwest wind situation. There was a more longshore component of velocity apparent; speeds were similar to the previous day.

B.15 August 28th-29th (Figure B-15)

B.15.1 Weather

a) 0000-1500 hours - winds southwest at 5-7 m/sec;
b) 1500 hours - winds north of Tuktoyaktuk switched to northwest;
c) 2100 hours - whole Beaufort Sea - north northwest winds at 5-7 m/sec.

B.15.2 Drift

The drift was again characteristic of a northwest wind situation, with unusually high speeds (57 and 55 cm/sec for drogues #46 and #47 respectively) with a large offshore gradient recorded north of Richards Island. Note the crossing of paths of drogues #46 and #47.

Drogue #42 in Mackenzie Bay moved west. This may have been due to the relaxation of the speed of the wind from 15 to 7 m/sec or the fact that it had become surrounded by heavy ice. It points to a divergence in Mackenzie Bay again.

B.16 August 29th-30th (Figure B-16)

B.16.1 Weather

Light wind conditions prevailed - chiefly northeast winds less than 5 m/sec.

B.16.2 Drift

The drift pattern was similar to the post northwest wind drift of August 13th-16th - a drift offshore to the west in Mackenzie Bay; westward drift just north of Pelly Island and northeast drift around 70°N, north of Pullen Island. There was apparently still a strong northeast current of about 50 cm/sec north of Warren Point although drogue #38 at 70°20'N moved southwest at 25 cm/sec which was likely due to a large eddy set up by the northeast wind acting on the Mackenzie River water.

B.17 August 30th-31st (Figure B-17)

B.17.1 Weather

Winds began light easterly (less than 5 m/sec) in most regions. At 70° 10'N and 133°W they were east 10 m/sec from 1200-2400. At 1500 hours in Mackenzie Bay, the winds swung to northwest, becoming light and this trend moved eastward reaching Richards Island by 0200 hours, September 1. The change in winds was caused by passage of a low pressure system over the area.

B.17.2 Drift

East of 135° the drift was predominantly north at slow speeds under an east wind and fairly calm conditions. The crossing of paths of drogues #37 and #29 indicates some eddies may have been generated north of Atkinson Point. Note the divergence of drogues #42 and #43 in Mackenzie Bay. Drogue #51 moved out of Kugmallit Bay at 15 cm/sec which was characteristic of northwest wind relaxation and east wind conditions.

B.18 August 31st-September 1st (Figure B-18)

B.18.1 Weather

Northwest winds of 7-10 m/sec prevailed for this period of time.

B.18.2 Drift

Fairly typical drift for a northwest wind condition. Note that drogue #42 moved southwest at 17 cm/sec. Drogue #52 exhibited an unusually high speed; drogue #48 must have been caught in an eddy.

B.19 September 1st-2nd (Figure B-19)

B.19.1 Weather

Northwest winds of 10 m/sec persisted over the whole region.

B.19.2 Drift

The two highest drift rates encountered ran against the wind. #52 and #37 drifted with speeds of 90 and 50 cm/sec respectively in directions contrary to expected for a northwest wind condition. The observations of the positions for these two drogues appear correct but their drift is not explainable by meteorological observations.

B.20 September 2nd-3rd (Figure B-20)

B.20.1 Weather

a) winds were calm to light southeast;
b) some light northwest in Mackenzie Bay near Herschel.

B.20.2 Drift

Small drift speeds were encountered. There were too few observations to determine whether or not a steady field existed.

B.21 September 3rd-4th (Figure B-21)

B.21.1 Weather

a) September 4 - light changing to northwest winds at 0300 on September 4th;
b) Mackenzie Bay - northwest 5-7 m/sec for entire period.

B.21.2 Drift

Drogue #53 may have lost its sail considering the strong onshore component of its drift. Note again the southwest rather than southeast motion of drogue #42 in Mackenzie Bay.

B.22 September 5th-8th (Figures B-22,23,24)

B.22.1 Weather

Strong northeast winds persisted for three days.

B.22.2 Drift

Between the 5th and 6th, drogues #54 and #52 offshore moved southwest toward the Tuktoyaktuk Peninsula under a northeast wind. Closer to the shore, drogues #46 and #57 moved parallel to the coast toward the west. On the 6th the wind became more easterly, causing drogues #52 and #54 to drift more parallel to the coast. Drogue #59 moved to the northwest offshore and #60 which was an ice floe moved with a more northerly component. Note the divergence of the ice floe and drogue. The low speeds in Mackenzie Bay may be due to the presence of heavy pack ice.

B.23 September 8th-9th (Figure B-25)

B.23.1 Weather

Calm conditions and very light variable winds prevailed.

B.23.2 Drift

The sudden reversal in the movement of drogues #59 and #54 and ice floe 60 may have been due to relaxation of the east wind or may have been associated with the high pressure centred over the Beaufort Sea.

B.24 September 9th-10th (Figure B-26)

B.24.1 Weather

The wind was west to southwest about 5 m/sec.

B.24.2 Drift

The drift was a "westwind" type of drift with slower speeds due to the lighter winds.

TABLE B-1 - 1975

DHT = Twin Otter Aircraft KGO = Bell 206 Helicopter

DROGUE #	DATE IN	DATE OUT	DAYS TRANSMITTING	DEPLOYED BY (AIRCRAFT)
1	July 27	July 28	1	DHT
2	July 27	August 1	5	DHT
3	July 27	August 2	6	DHT
4	July 28	August 2	5	DHT
5	July 28	August 1	4	DHT
6	July 31	August 8	8	KGO
7	August 2	August 11	9	KGO
8	August 2	August 11	9	KGO
9	August 2	August 3	1	KGO
10	August 2	August 13	11	KGO
11	August 2	August 13	9	KGO
12	August 2	August 13	9	DHT
13	August 9	August 21	12	DHT
14	August 9	August 20	11	DHT
15	August 9	August 20	11	DHT
16	August 9	August 14	5	DHT
17	August 9	August 18	9	DHT
18	August 9	August 15	6	DHT
19	August 12	August 28	16	DHT
20	August 12	August 24	12	DHT
21	August 12	August 24	12	DHT
22	August 12	August 14	2	DHT
23	August 12	August 19	7	DHT
24	August 12	August 12	0	DHT
25	August 14	-	-	DHT
26	August 14	August 21	7	DHT
27	August 16	August 27	11	KGO
28	August 16	August 26	11	KGO
29	August 16	September 3	17	KGO
30	August 16	August 24	8	KGO
31	August 16	August 28	12	KGO
32	August 16	August 24	8	KGO
33	August 16	August 17	1	KGO

TABLE B-1 - 1975 (continued)

DHT = Twin Otter Aircraft KGO = Bell 206 Helicopter

DROGUE #	DATE IN	DATE OUT	DAYS TRANSMITTING	DEPLOYED BY (AIRCRAFT)
34	August 23	August 24	1	KGO
35	August 23	September 3	10	KGO
36	August 23	August 28	5	KGO
37	August 24	September 3	9	KGO
38	August 24	September 1	7	KGO
39	August 24	August 24	1	KGO
40 - Was not activated on deployment				
41	August 28	September 3	5	DHT
42	August 28	September 6	8	DHT
43	August 28	September 6	8	DHT
44	August 28	August 28	0	DHT
45	August 28	September 4	6	DHT
46	August 28	September 6	8	DHT
47	August 28	August 31	3	DHT
48	August 28	September 3	6	DHT
49	August 29	August 29	0	DHT
50	August 29	September 6	8	DHT
51	August 29	September 3	5	DHT
52	August 29	September 9	11	DHT
53	September 3	September 4	1	DHT
54	September 3	September 12	9	DHT
55	September 4	September 13	9	DHT
56	September 4	September 8	4	DHT
57	September 4	September 8	4	DHT
58	September 4	September 8	4	DHT
59	September 6	September 14	8	DHT
60	September 6	September 14	8	KHQ
61	September 8	September 8	0	KHQ
62	September 8	September 14	6	KHQ
63	September 9	September 14	5	KHQ
64	September 9	September 14	5	KHQ
65	September 9	September 14	5	KHQ
66	September 9	September 14	5	KHQ
67	September 10	September 14	4	DHT

Key to

Figures B-1 to B-11

Drogue Drift From July 8 to August 25, 1975

1 → 2 Drogue track from 1st to 2nd

Regional Update Model	Wind	Observed
	0-2.5 m/sec	
	2.5-5 m/sec	
	5-7.5 m/sec	
	7.5-10 m/sec	
	10-12.5 m/sec	
	12.5-15 m/sec	
	15-17.5 m/sec	

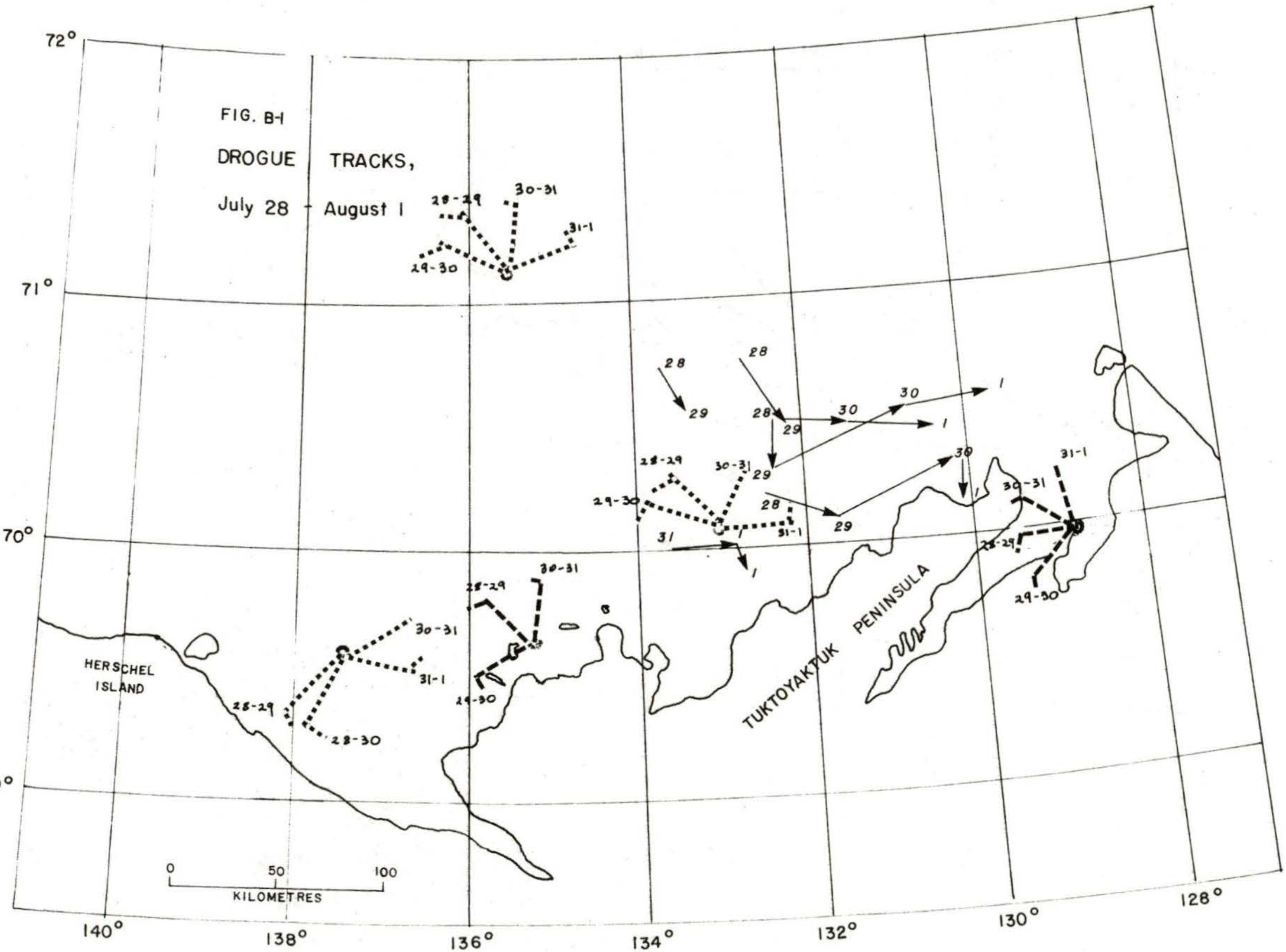


FIG. B-1
DROGUE TRACKS,
July 28 - August 1

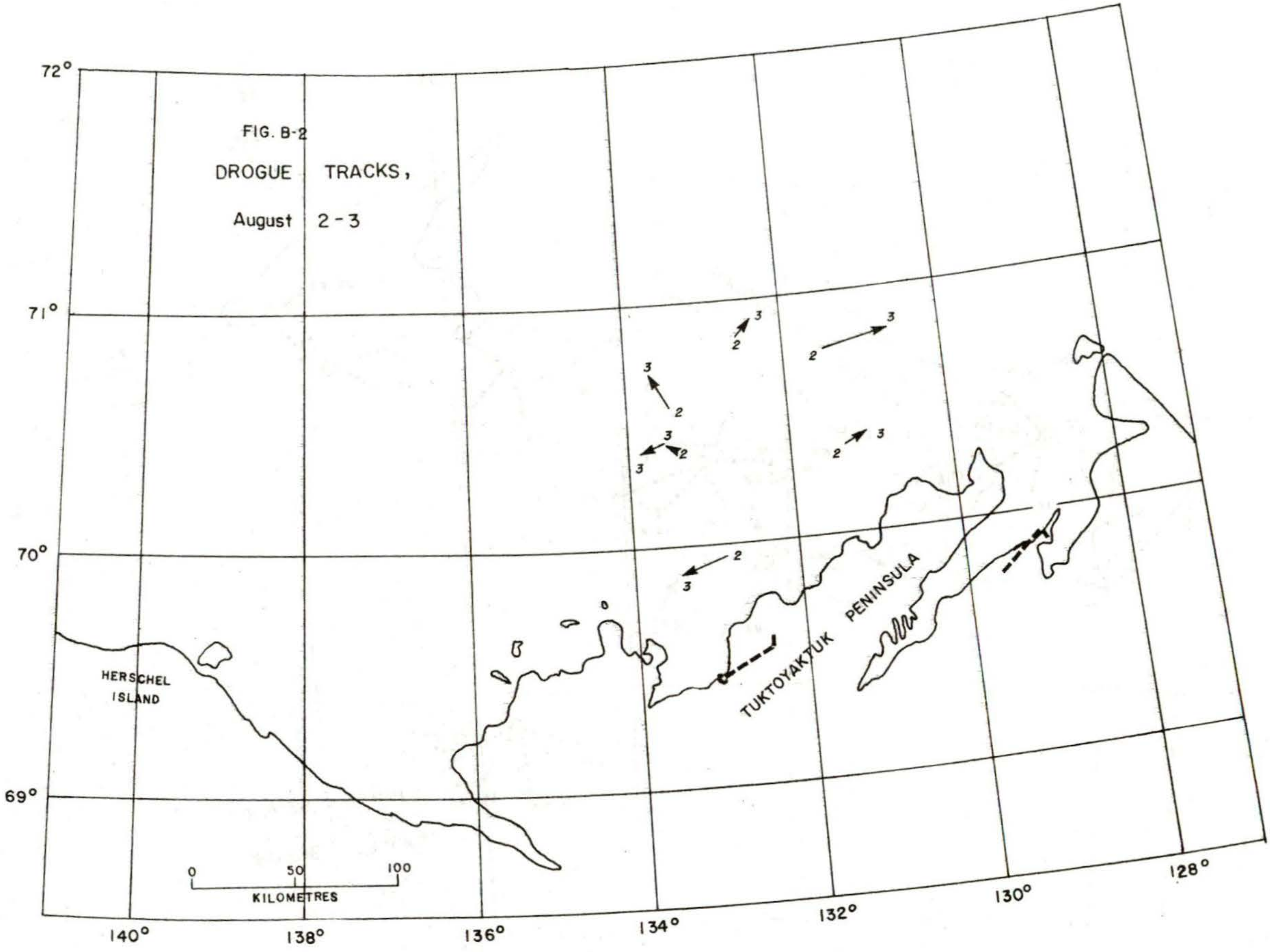


FIG. B-2

DROGUE TRACKS,

August 2 - 3

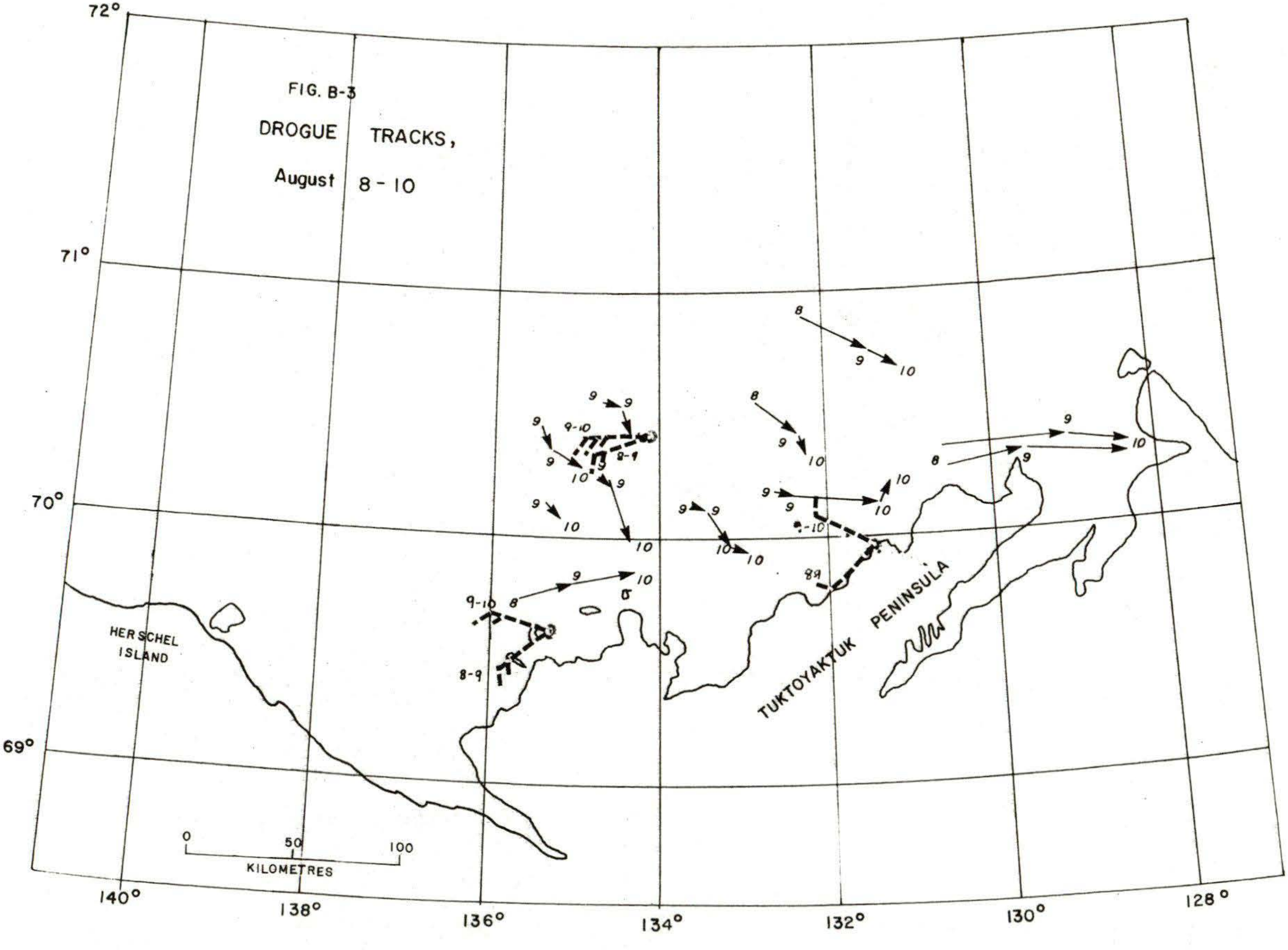


FIG. B-3
DROGUE TRACKS,
August 8 - 10
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
HERSCHEL ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES

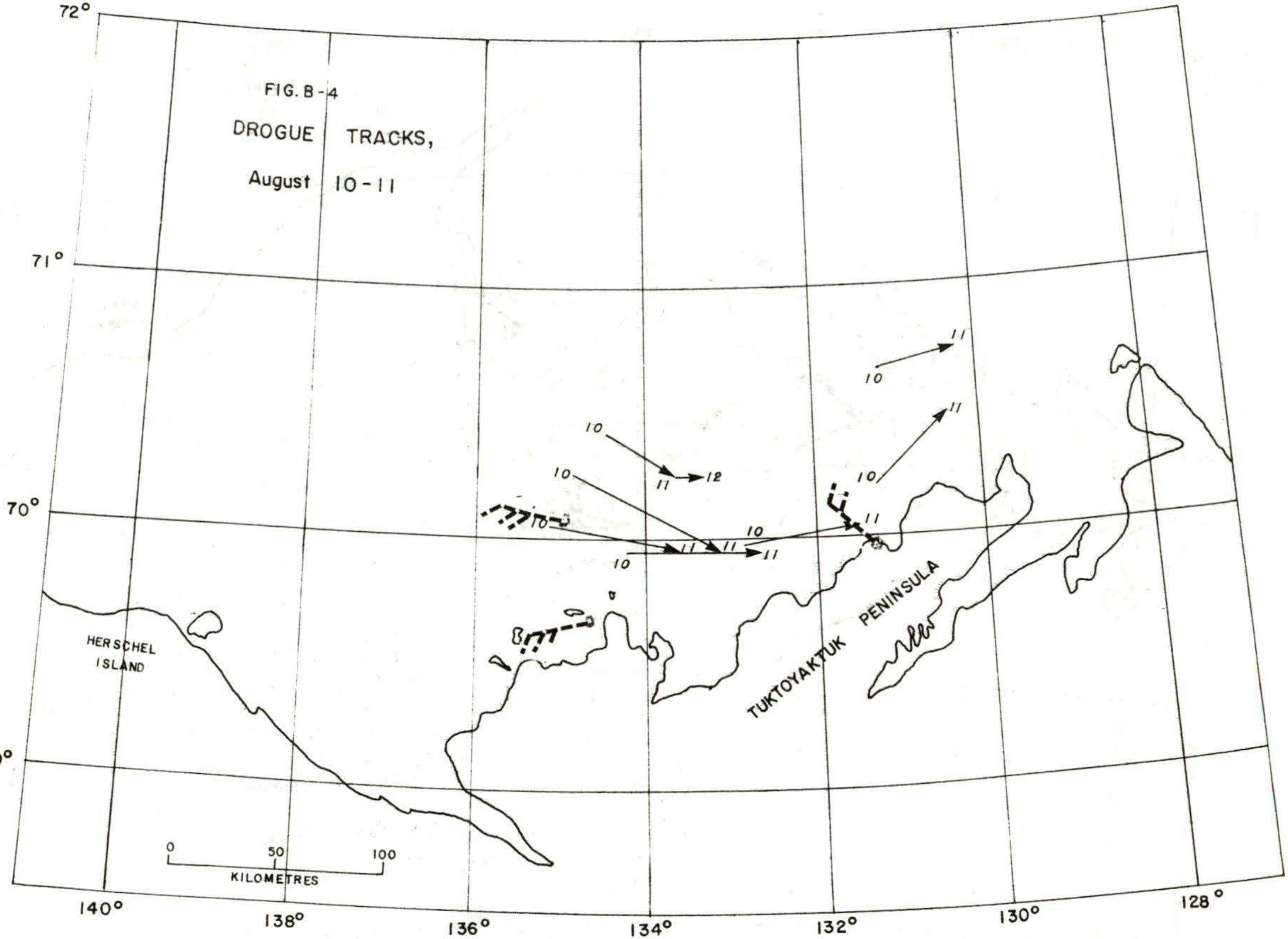
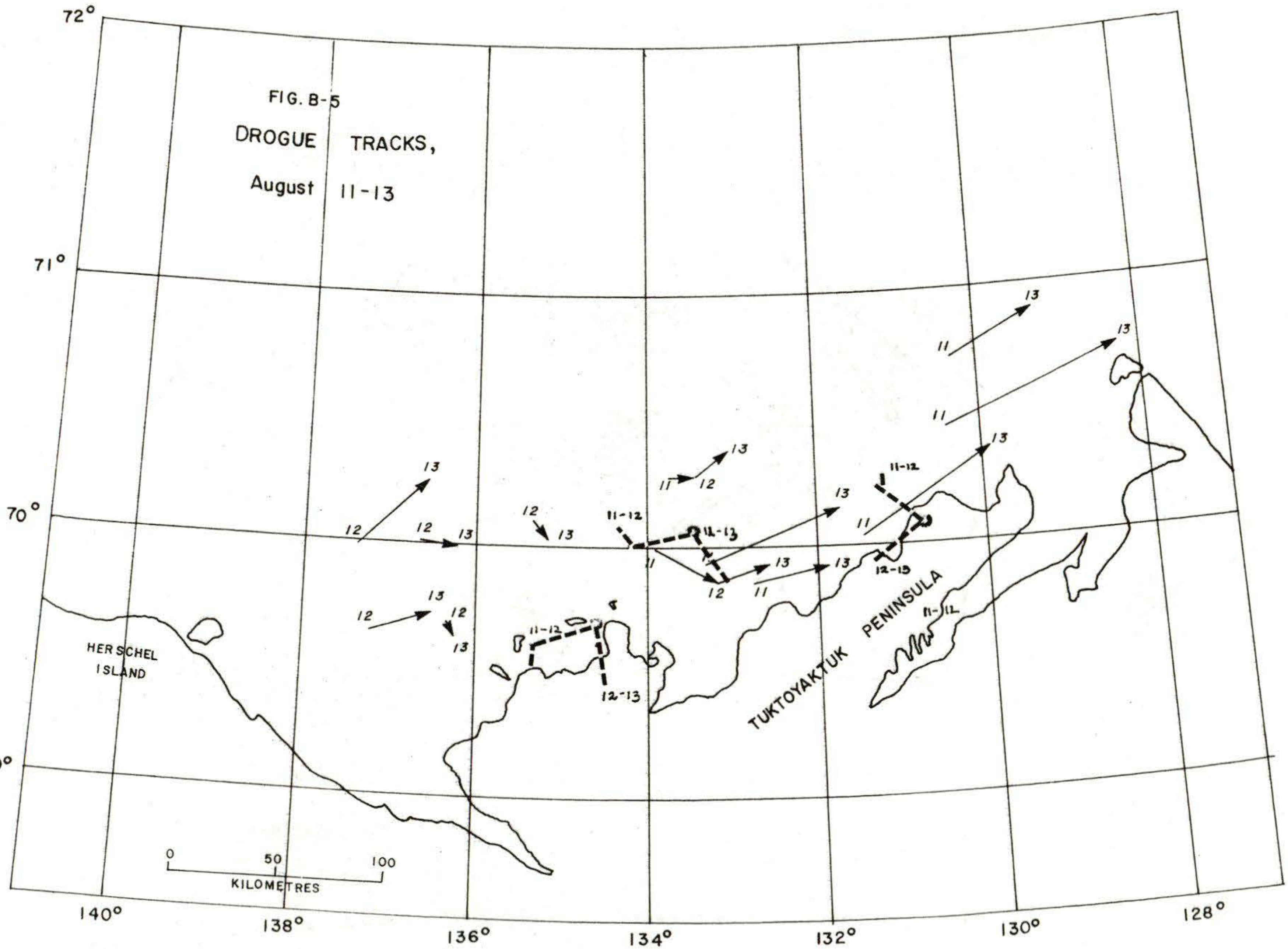


FIG. B-4
DROGUE TRACKS,
August 10-11
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
HERSCHEL ISLAND
TUKTOYAKTUK PENINSULA
0
50
100
KILOMETRES

FIG. B-5

DROGUE TRACKS, August 11-13



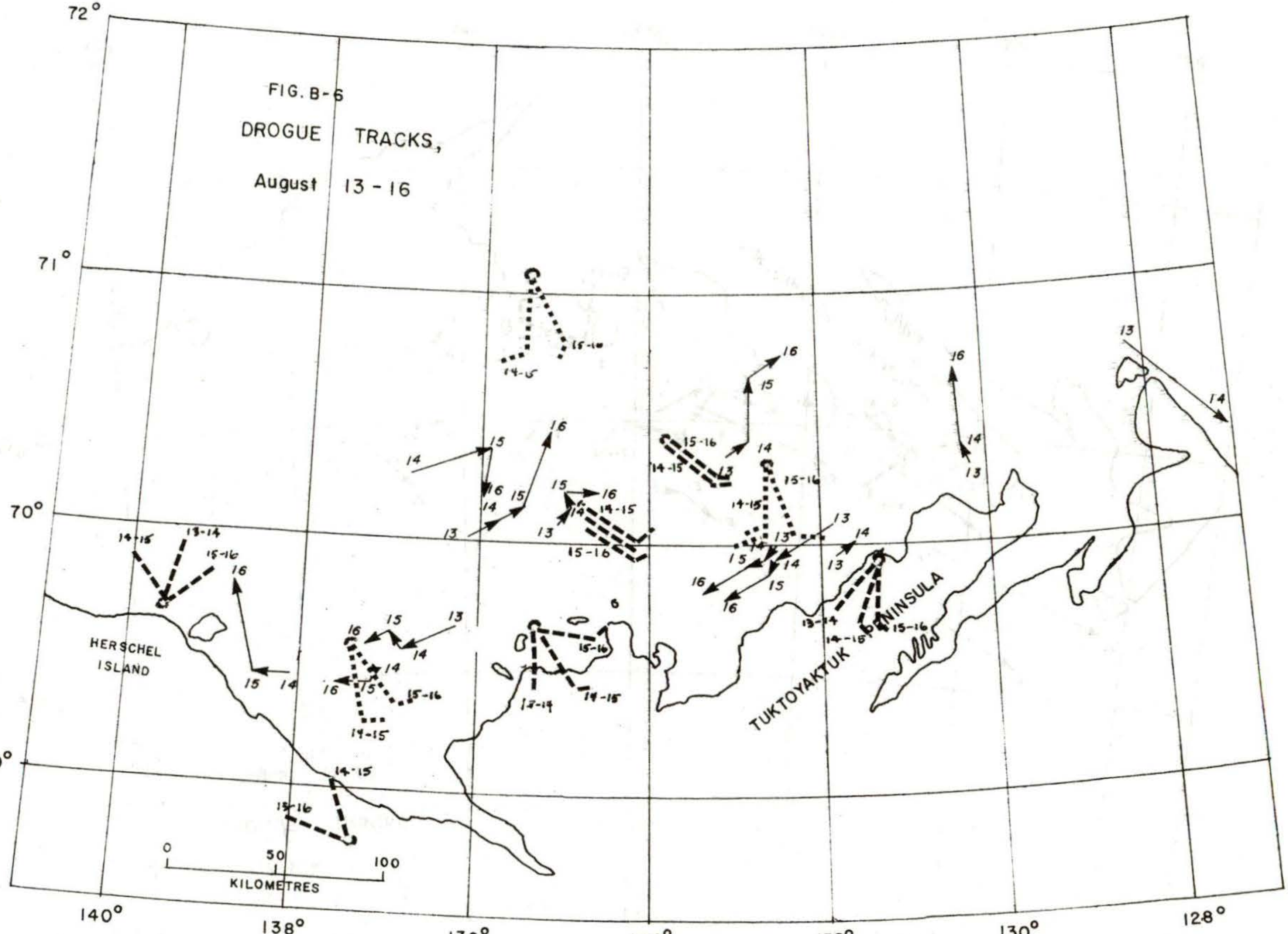


FIG. B-6
DROGUE TRACKS,
August 13 - 16

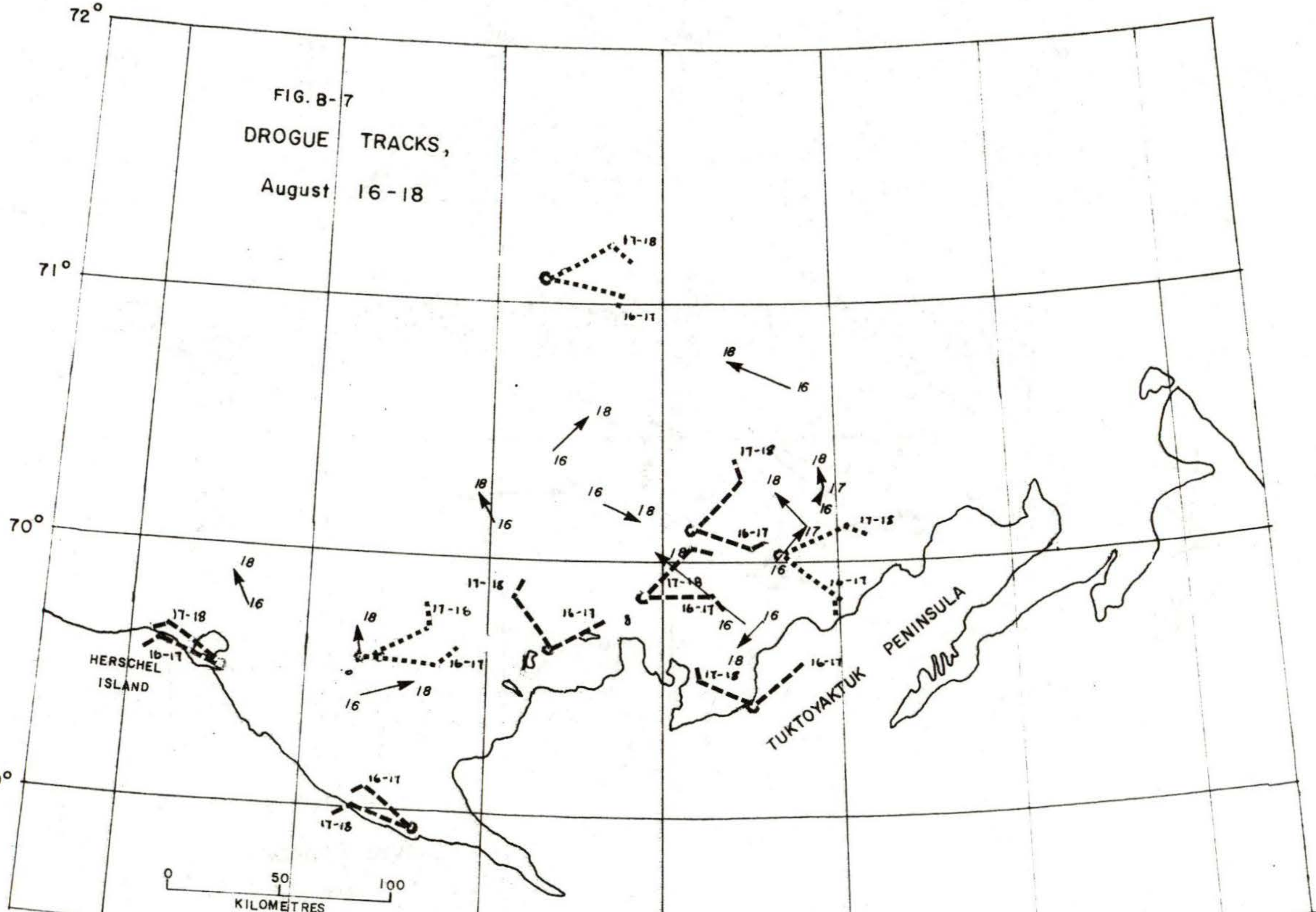


FIG. B-7
DROGUE TRACKS,
August 16-18
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
HERSCHEL ISLAND
TUKTOYAKTUK PENINSULA
KILOMETRES
0
50
100

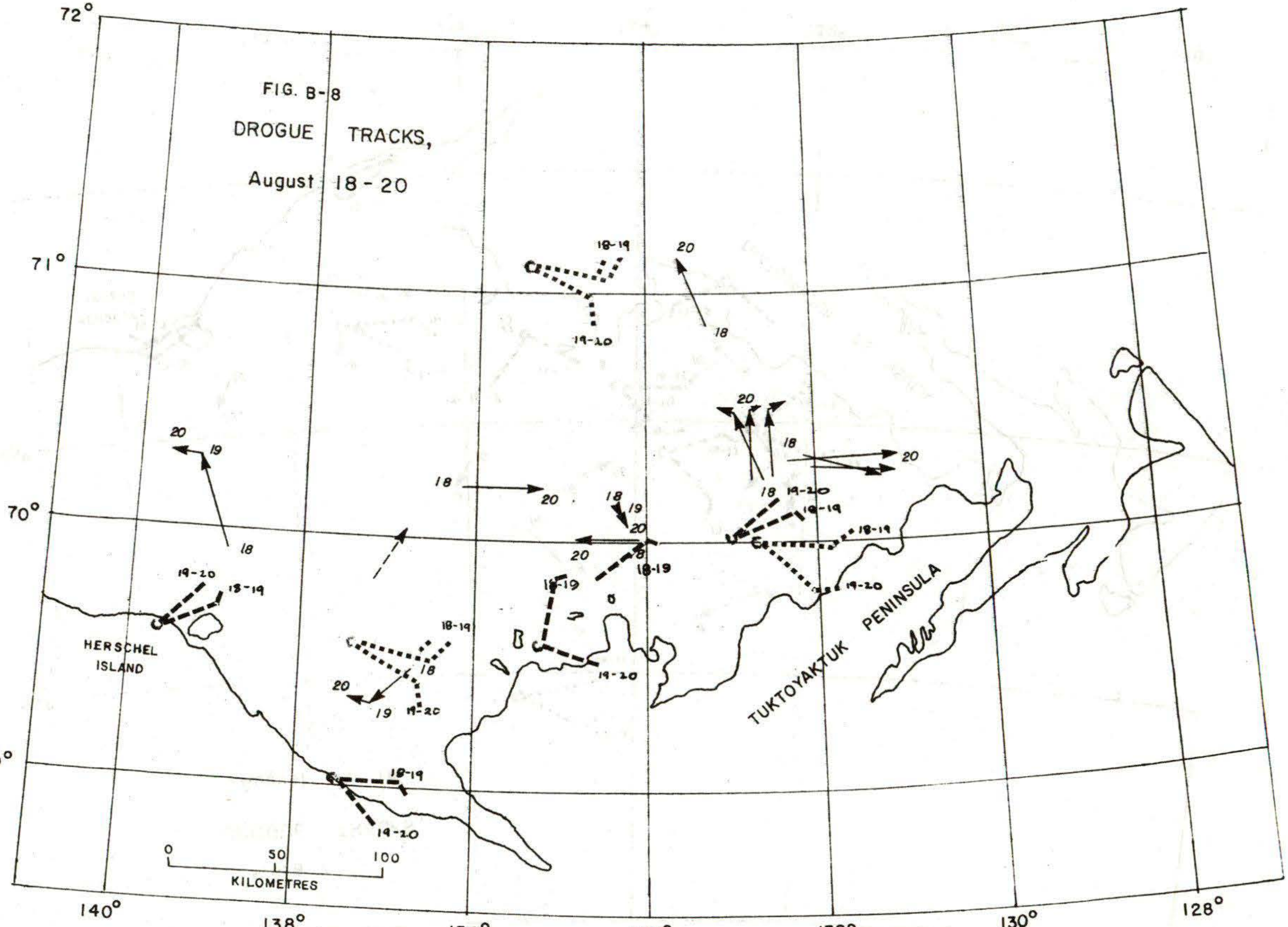


FIG. B-8
DROGUE TRACKS,
August 18 - 20

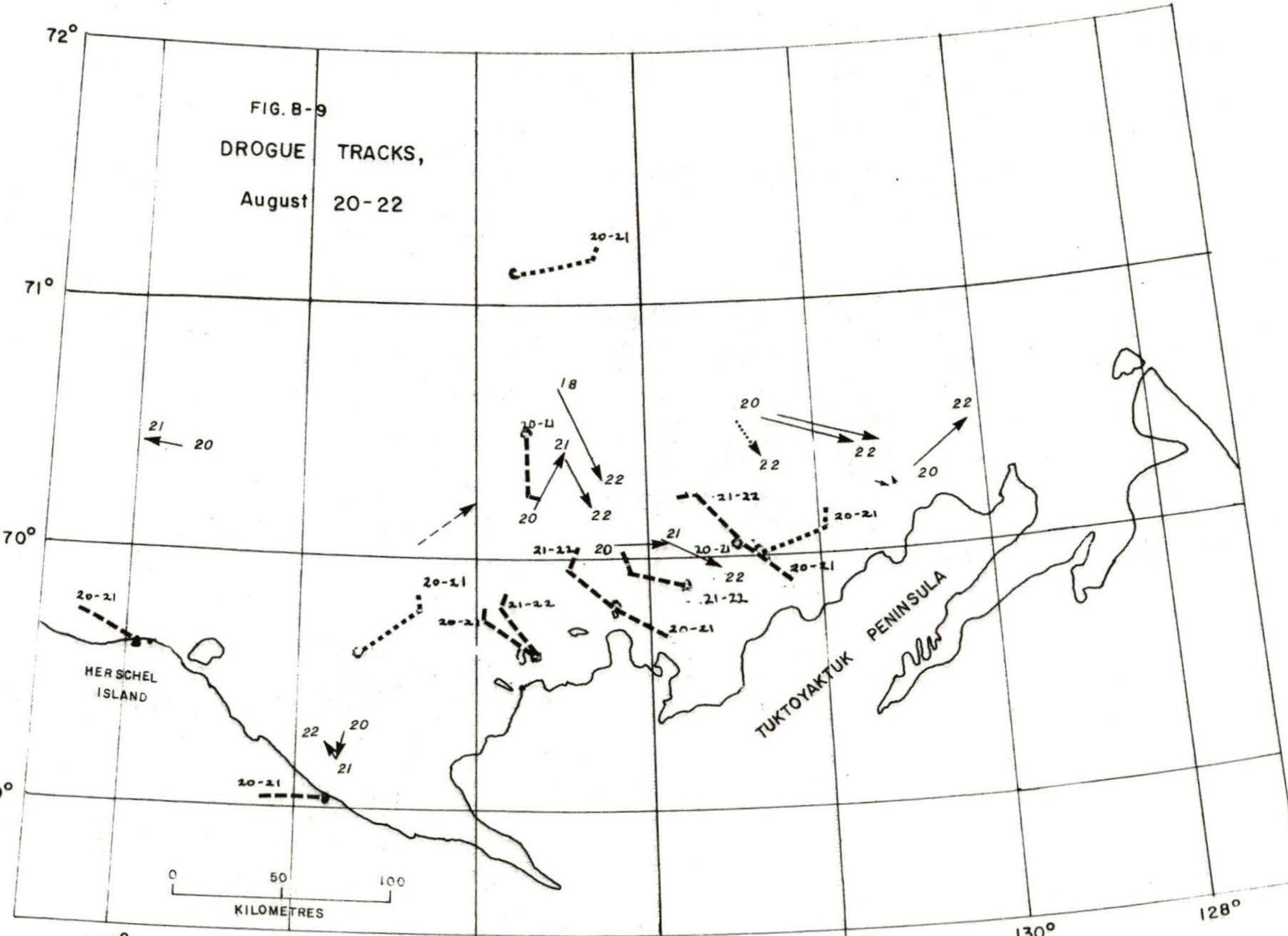


FIG. B-9
DROGUE TRACKS,
August 20-22

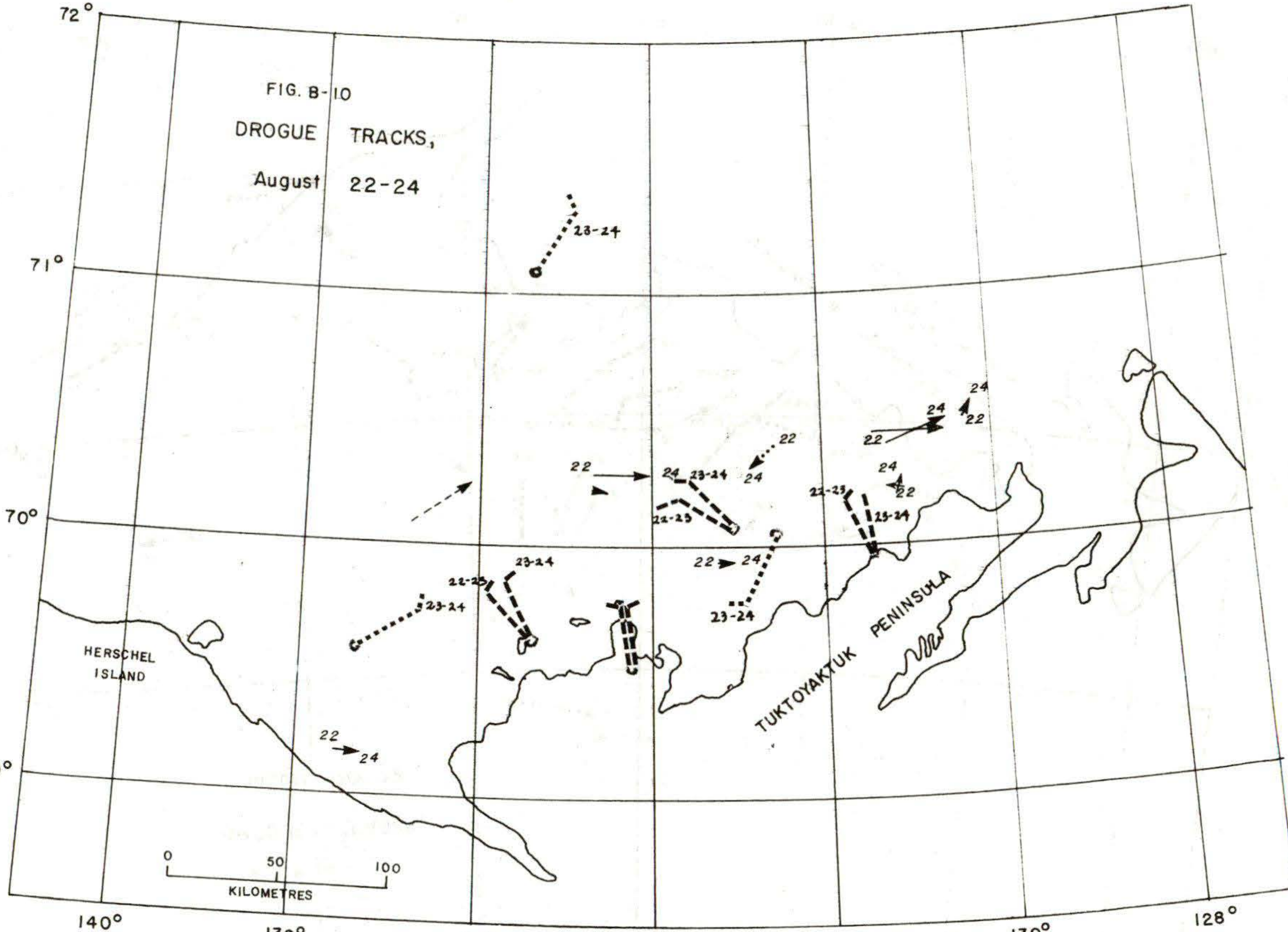


FIG. B-10
DROGUE TRACKS,
August 22-24

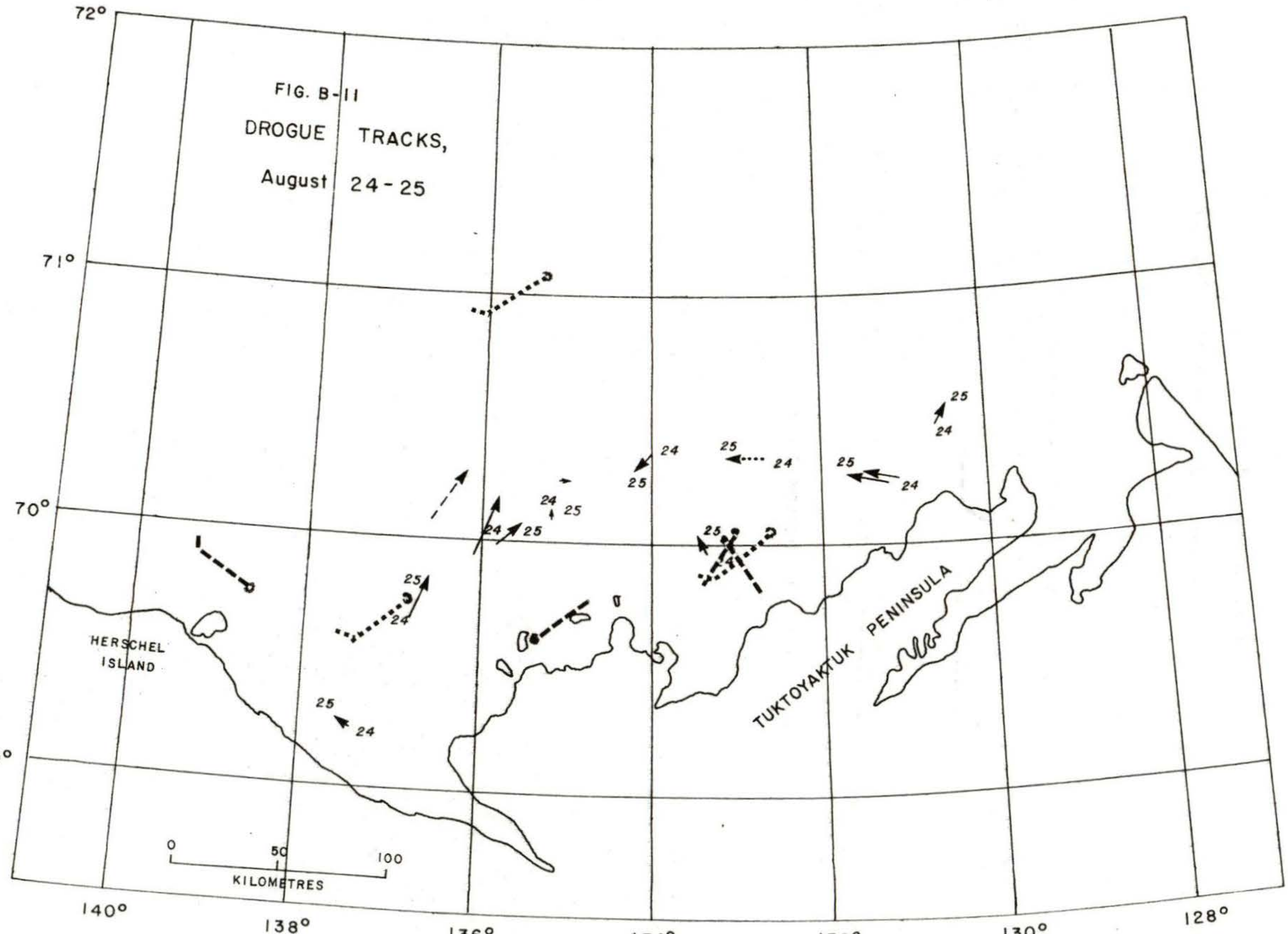


FIG. B-11
DROGUE TRACKS,
August 24-25

Figures B-12 to B-26

Drogue Drift From August 24 to September 10, 1975

15 ⟶ Drogue track for drogue #15

Wind

---------------- Isobars

Ice beacon track

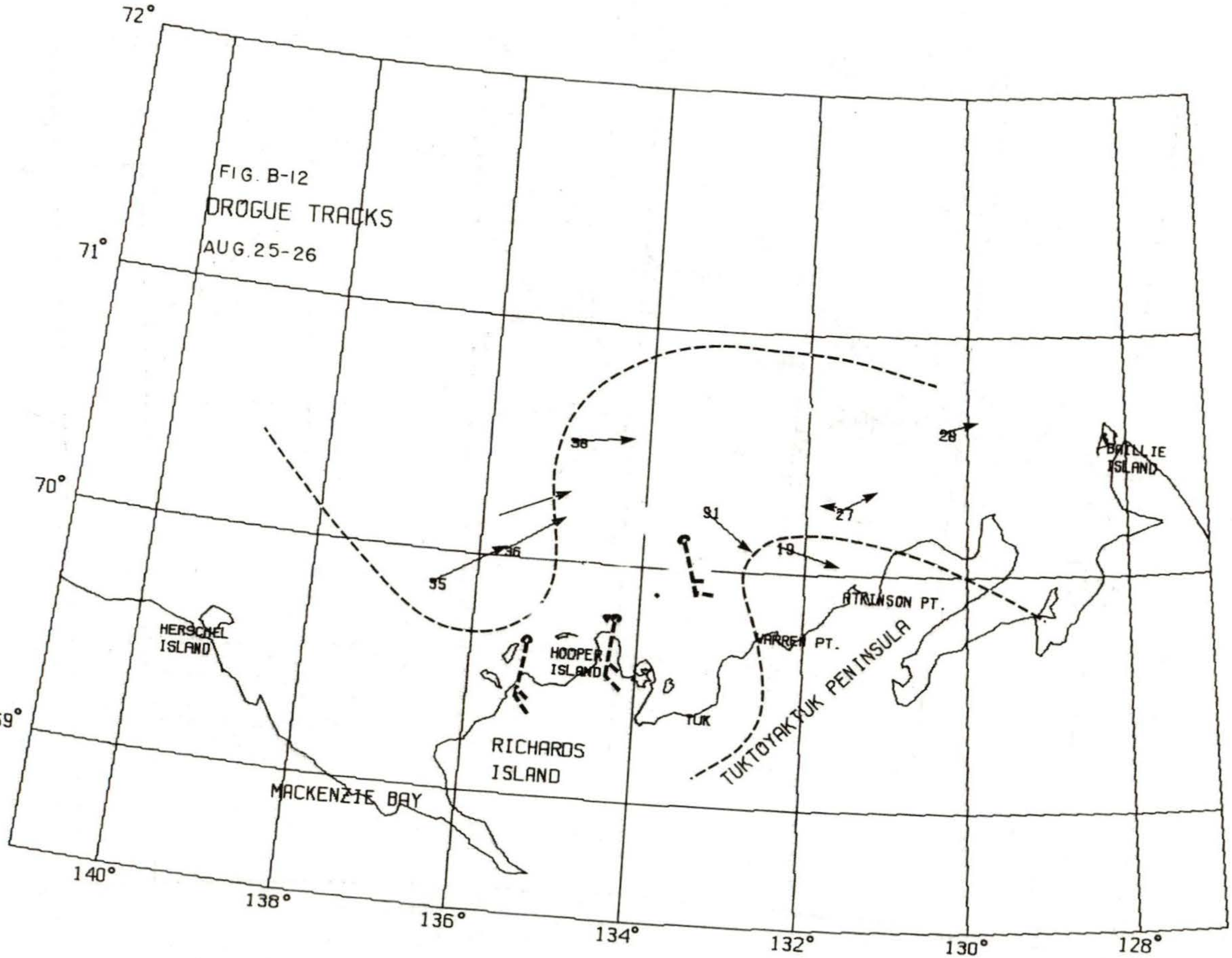


FIG. B-12
DROGUE TRACKS
AUG.25-26

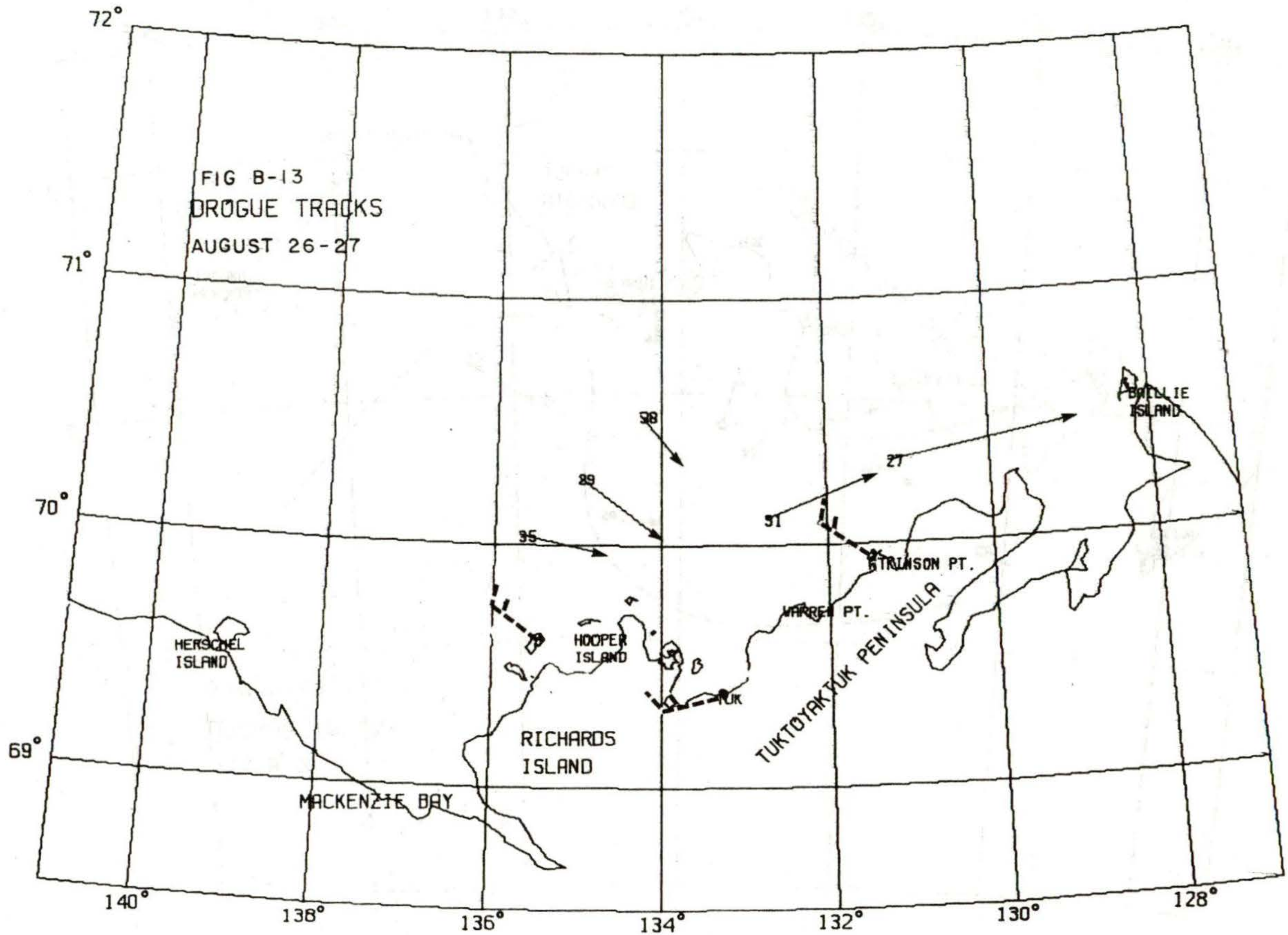
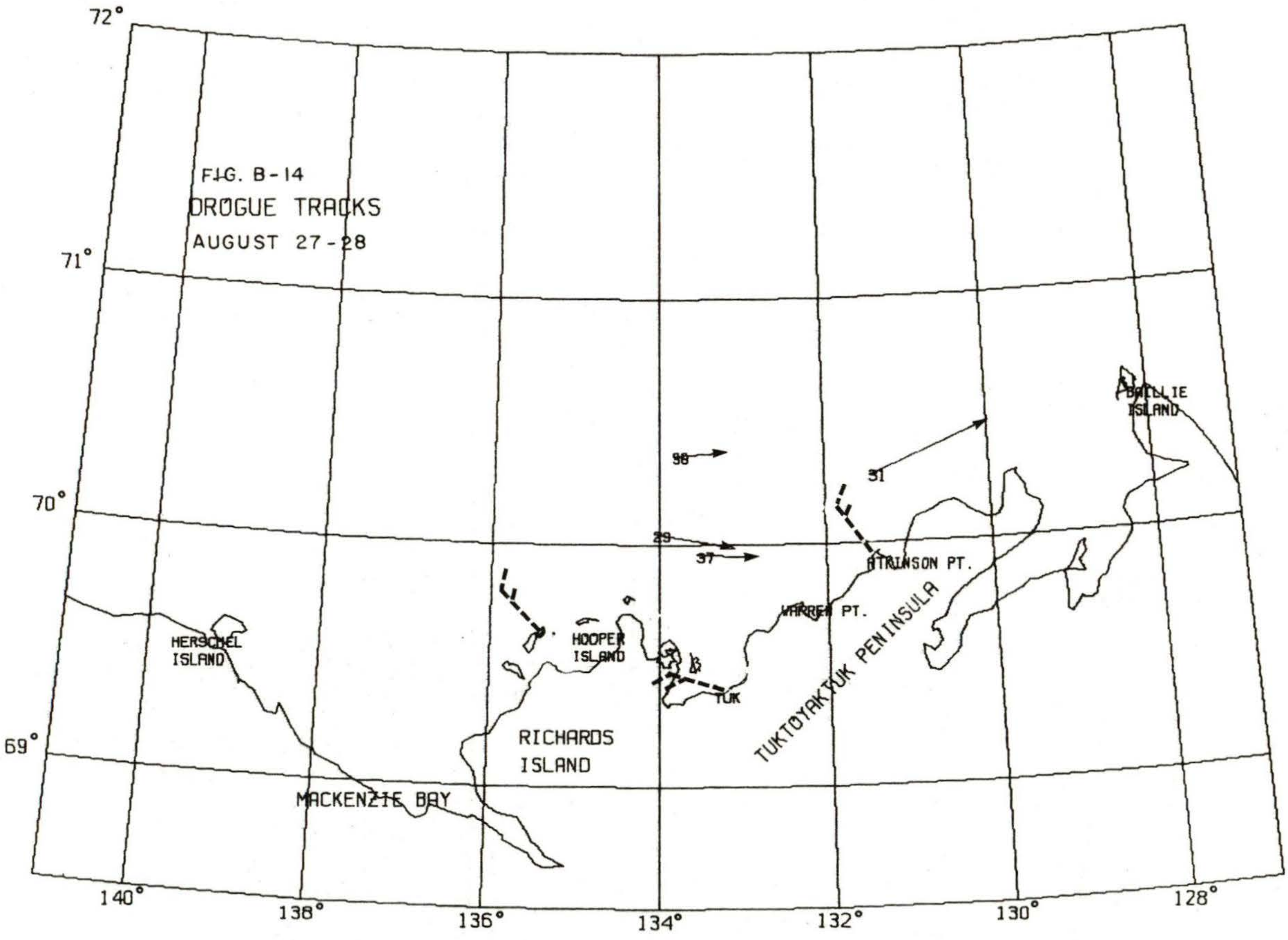


FIG B-13
DROGUE TRACKS
AUGUST 26-27



72°
71°
70°
69°
FIG. B-14
DROGUE TRACKS
AUGUST 27-28
HERSCHEL ISLAND
HOOPER ISLAND
RICHARDS ISLAND
MACKENZIE BAY
TUK
TUKTOYAKTUK PENINSULA
WARREN PT.
ATKINSON PT.
BAILLIE ISLAND
38
29
37
31
140°
138°
136°
134°
132°
130°
128°

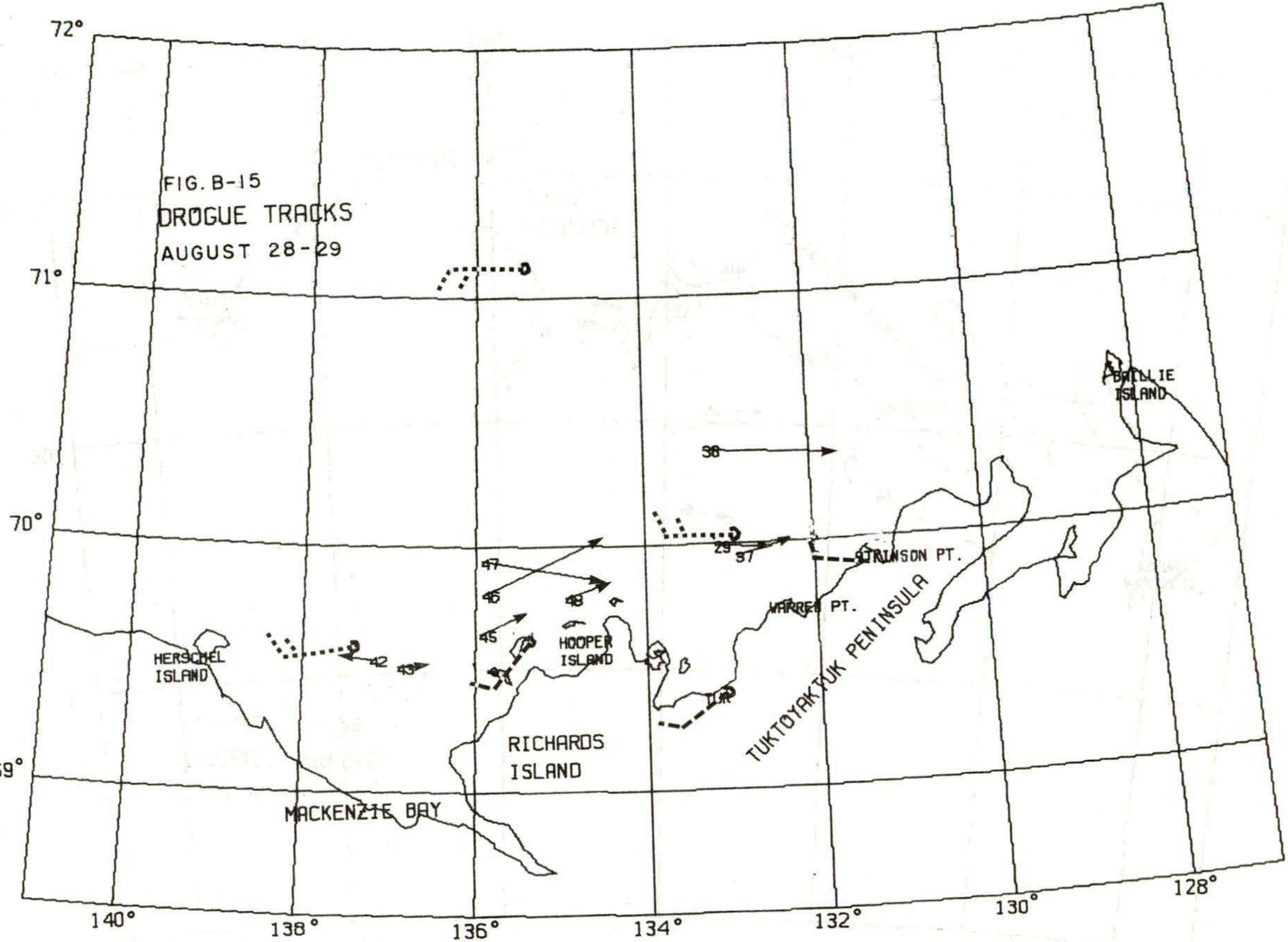


FIG. B-15
DROGUE TRACKS
AUGUST 28-29

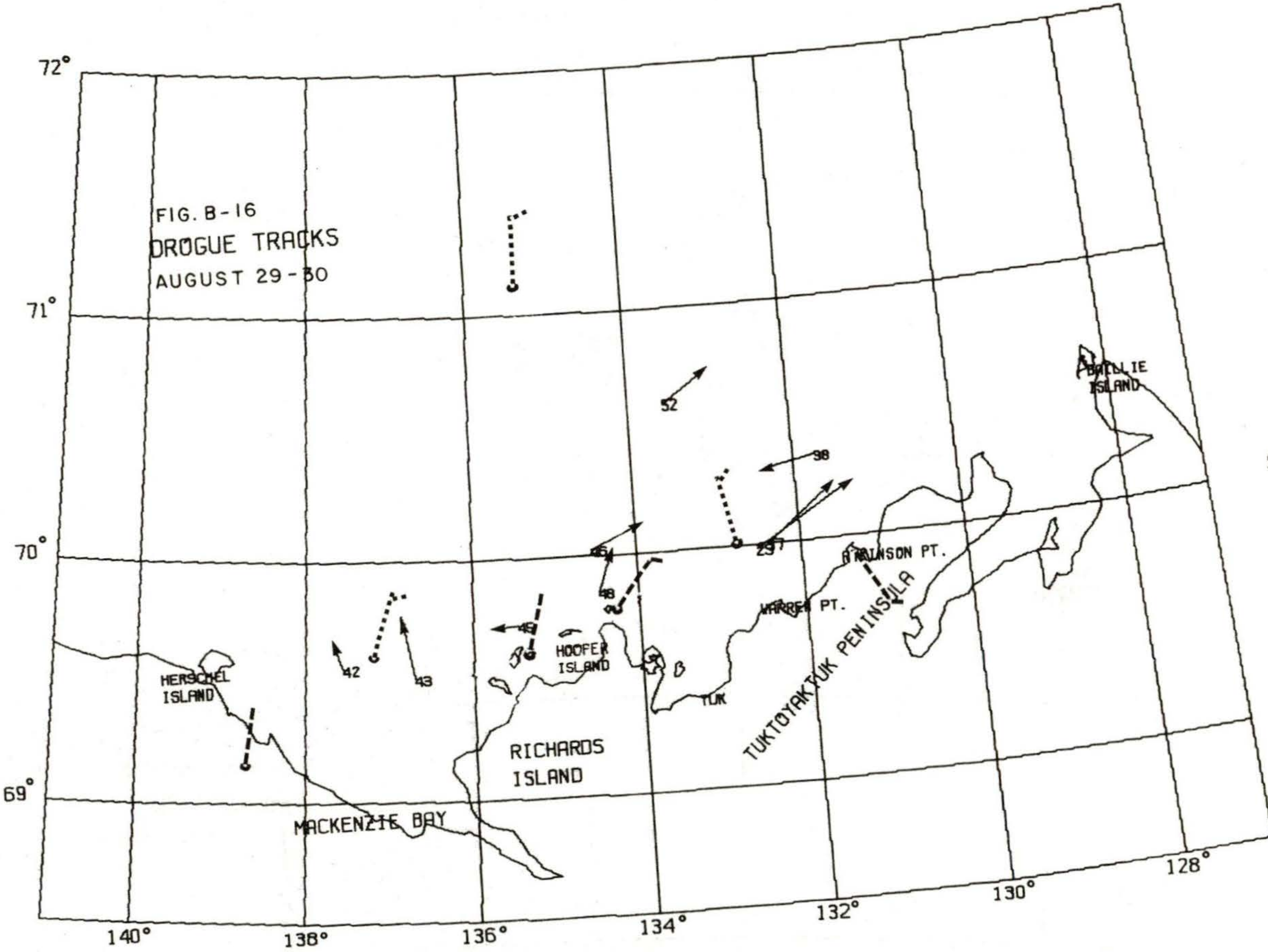


FIG. B-16
DROGUE TRACKS
AUGUST 29-30

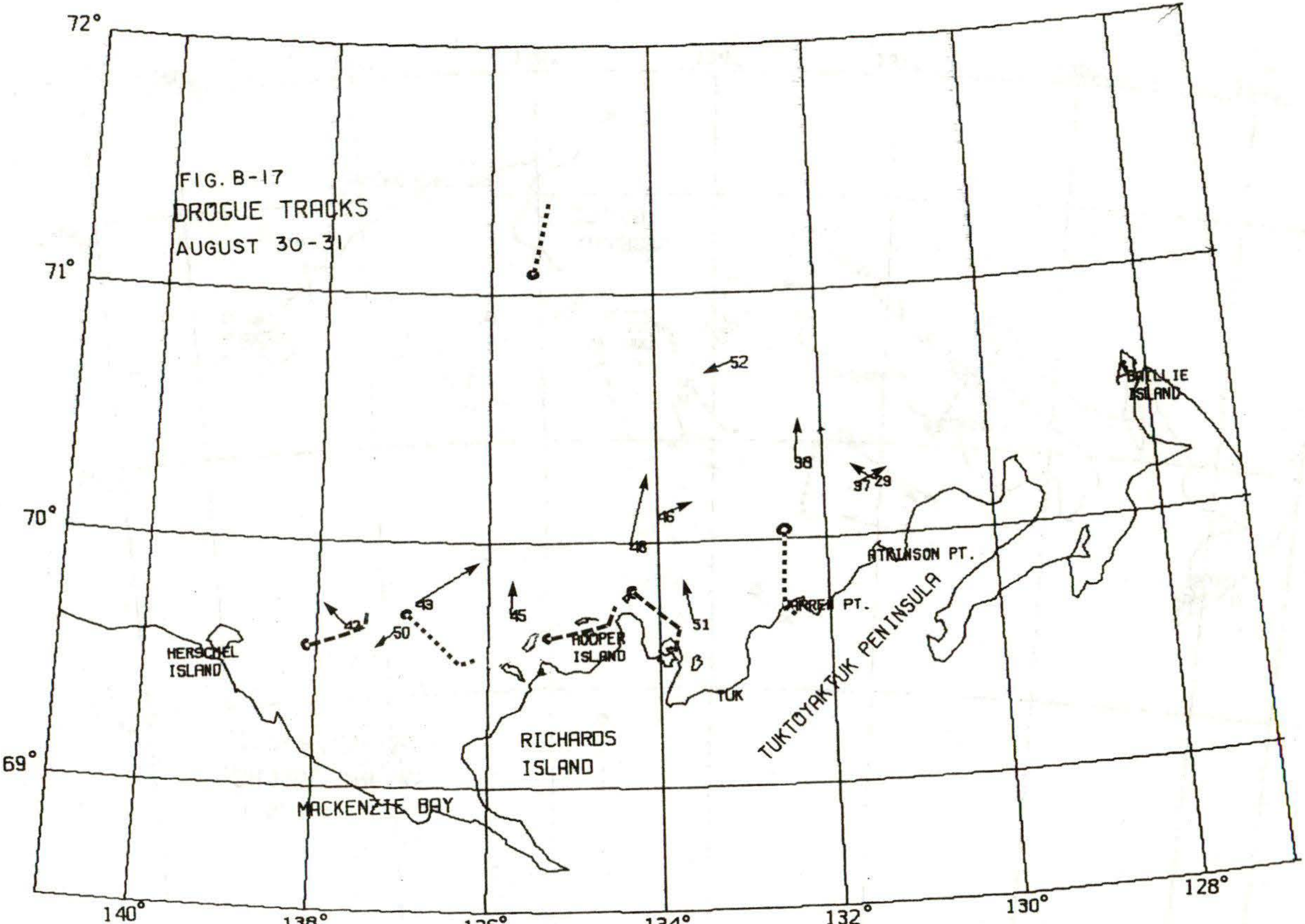


FIG. B-17
DROGUE TRACKS
AUGUST 30-31

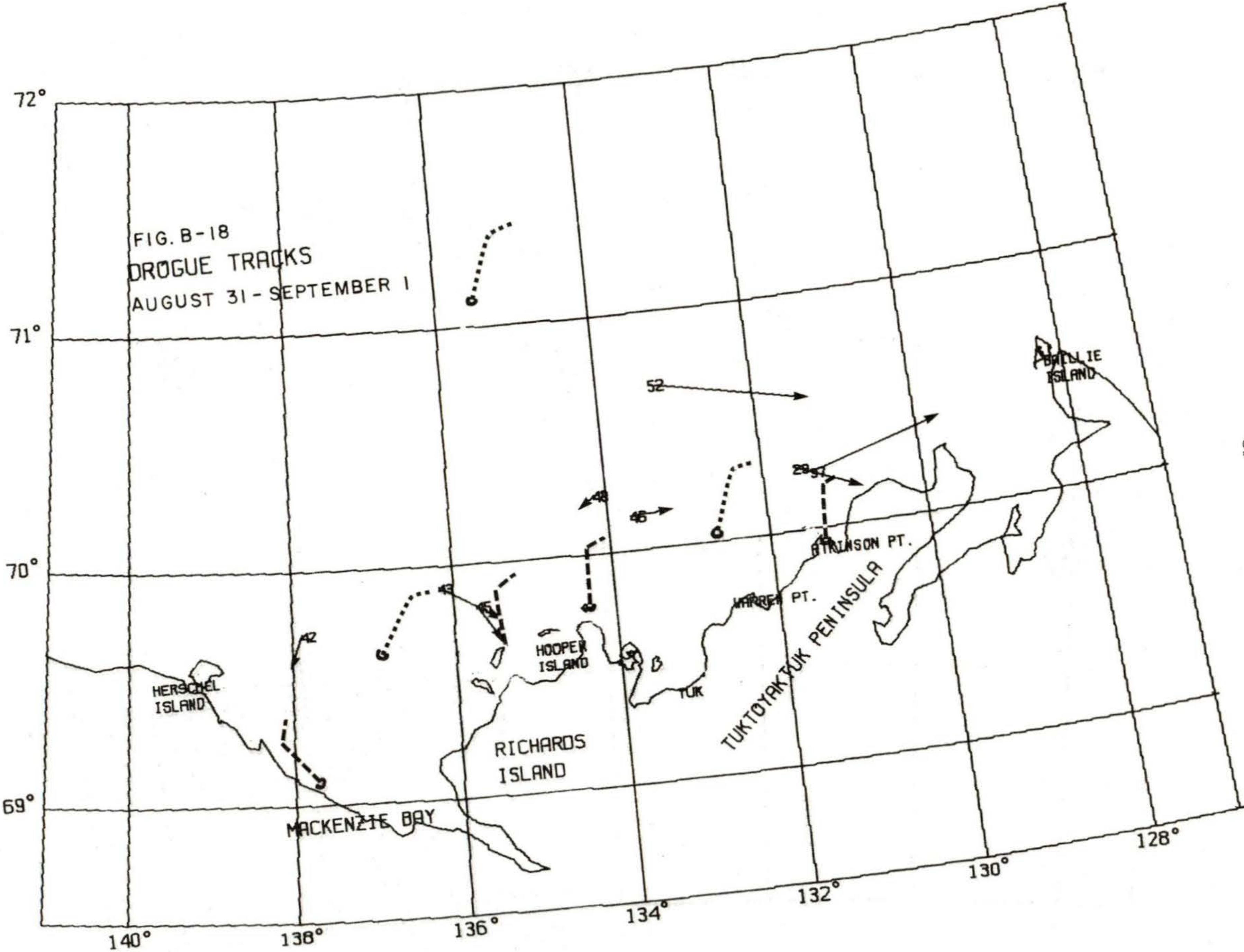


FIG. B-18
DROGUE TRACKS
AUGUST 31 - SEPTEMBER 1

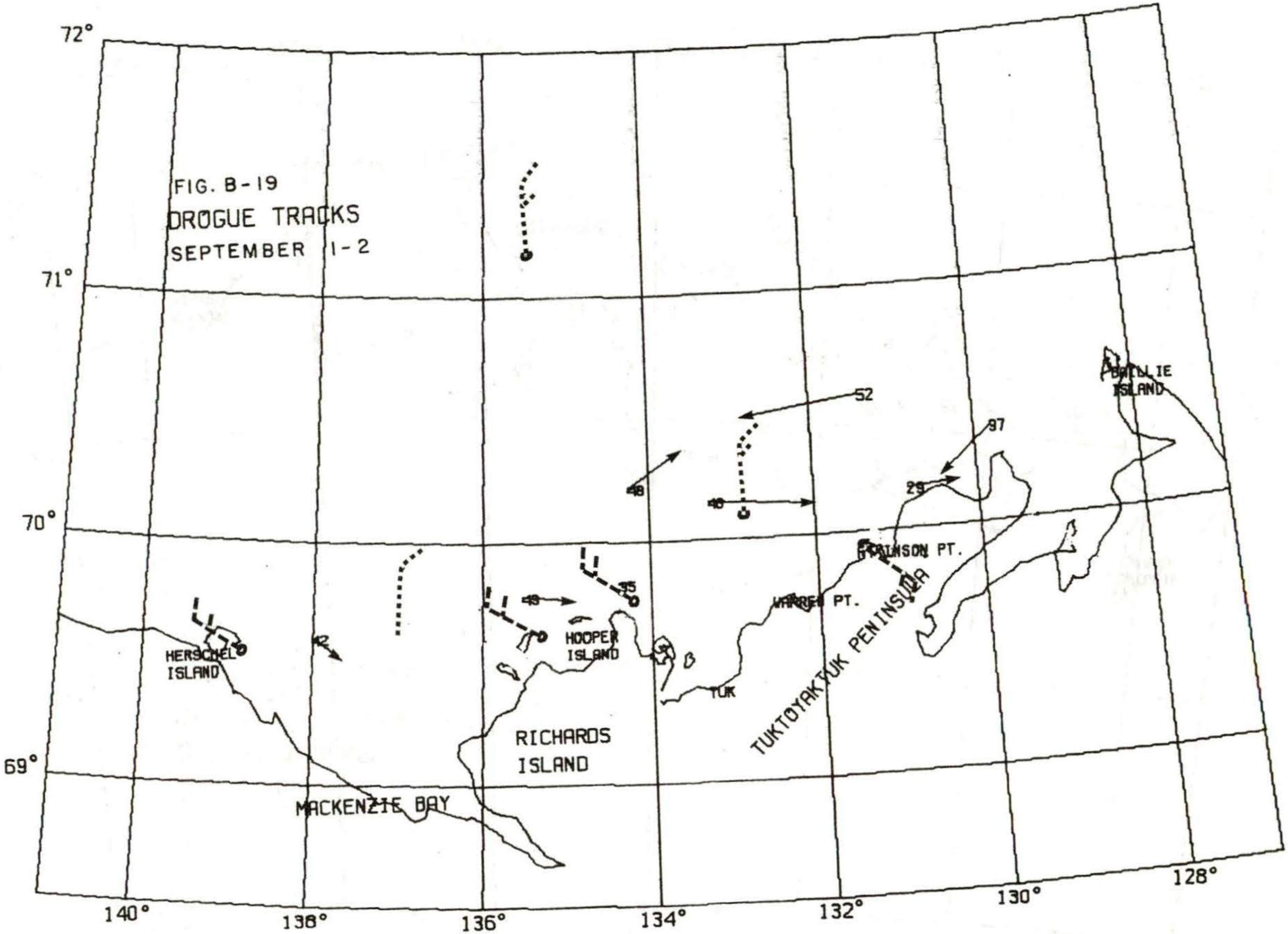
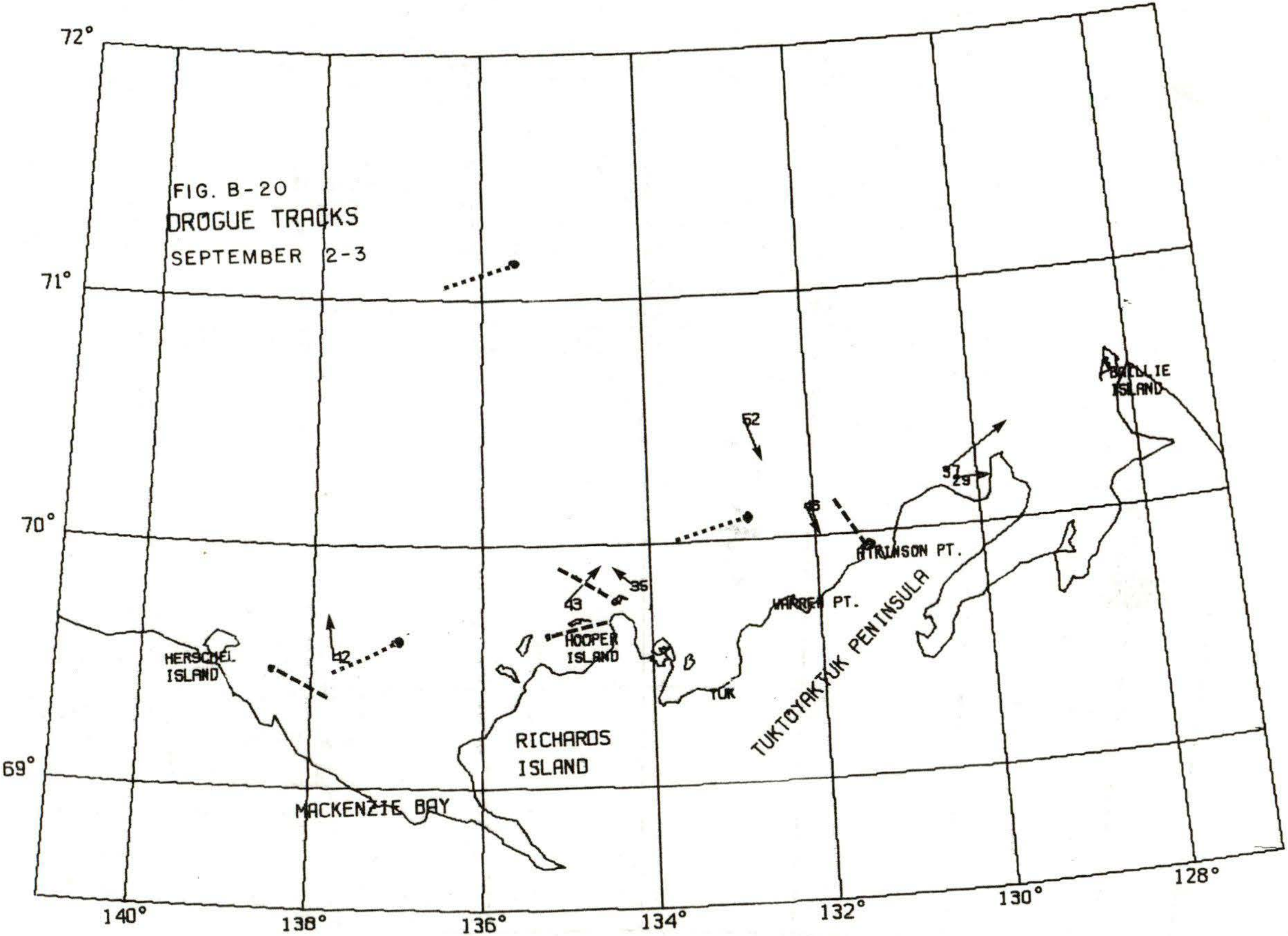


FIG. B-19
DROGUE TRACKS
SEPTEMBER 1-2
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
BAILLIE ISLAND
52
97
29
46
48
ROBINSON PT.
WARREN PT.
TUKTOYAKTUK PENINSULA
35
49
42
HOOPER ISLAND
HERSCHEL ISLAND
TUK
RICHARDS ISLAND
MACKENZIE BAY

FIG. B-20
DROGUE TRACKS
SEPTEMBER 2-3



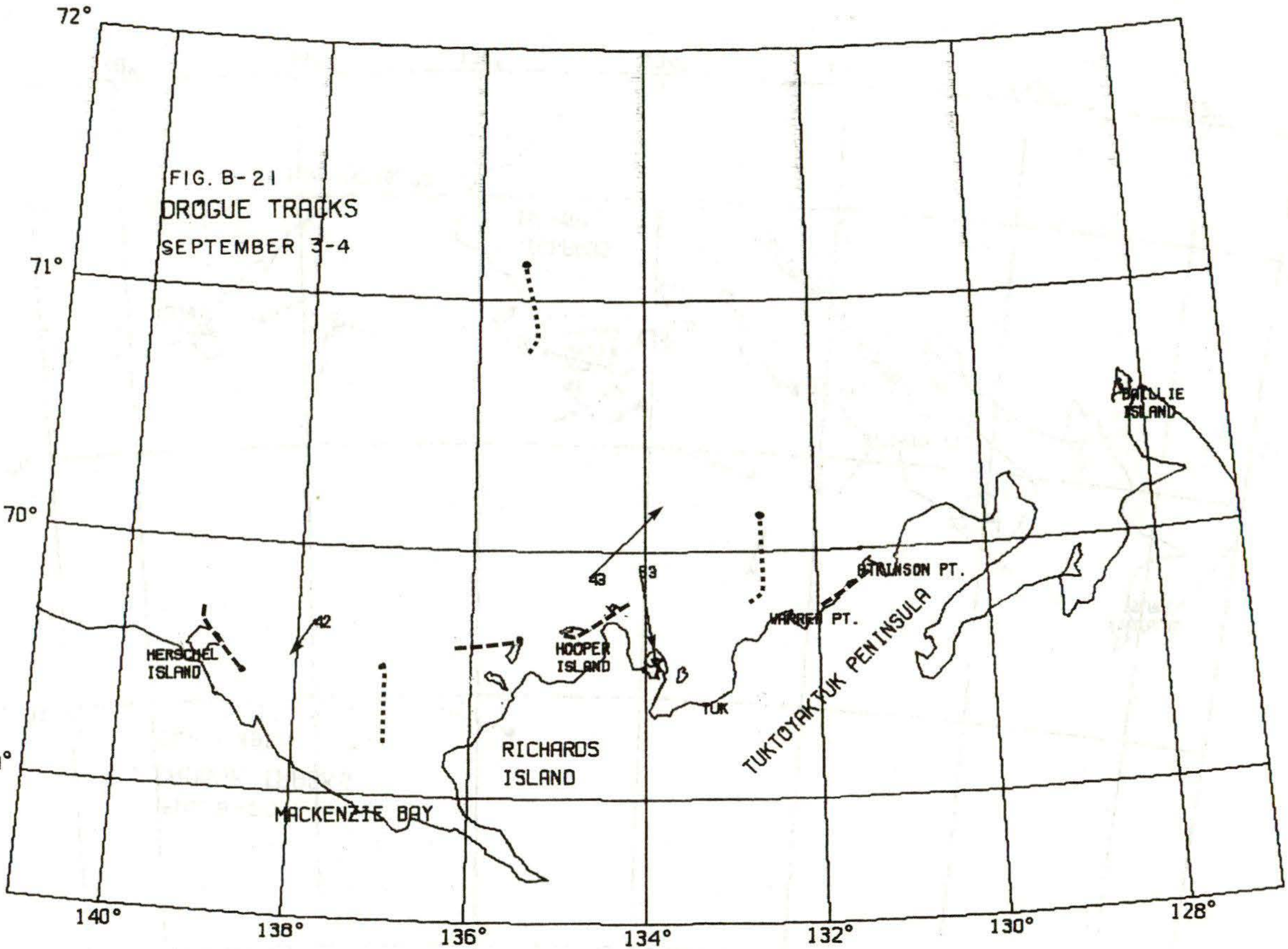


FIG. B-21
DROGUE TRACKS
SEPTEMBER 3-4

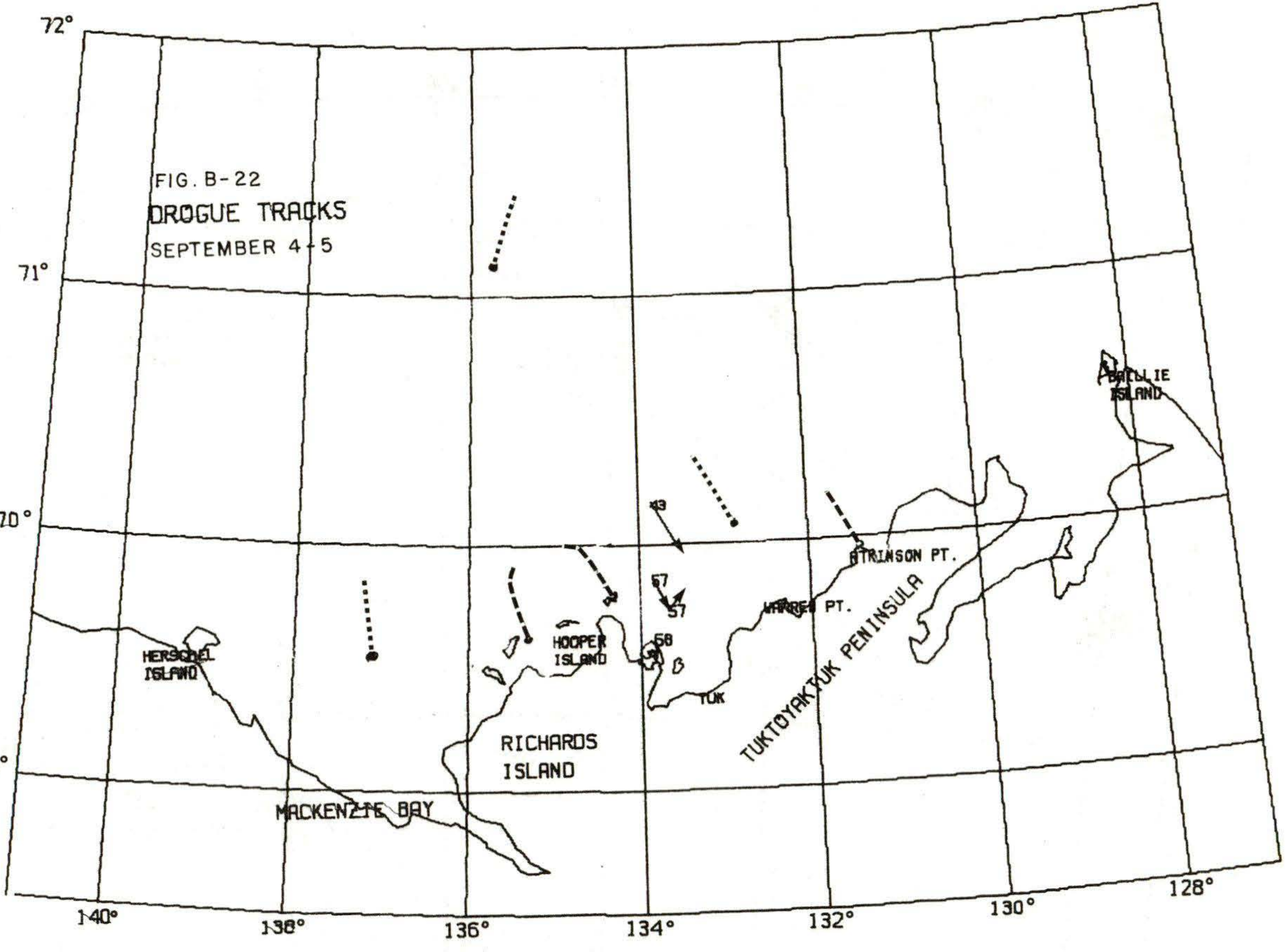


FIG. B-22
DROGUE TRACKS
SEPTEMBER 4-5
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
43
57
57
58
HERSCHEL ISLAND
HOOPER ISLAND
RICHARDS ISLAND
MACKENZIE BAY
TUK
WARREN PT.
ATKINSON PT.
TUKTOYAKTUK PENINSULA
BAILLIE ISLAND

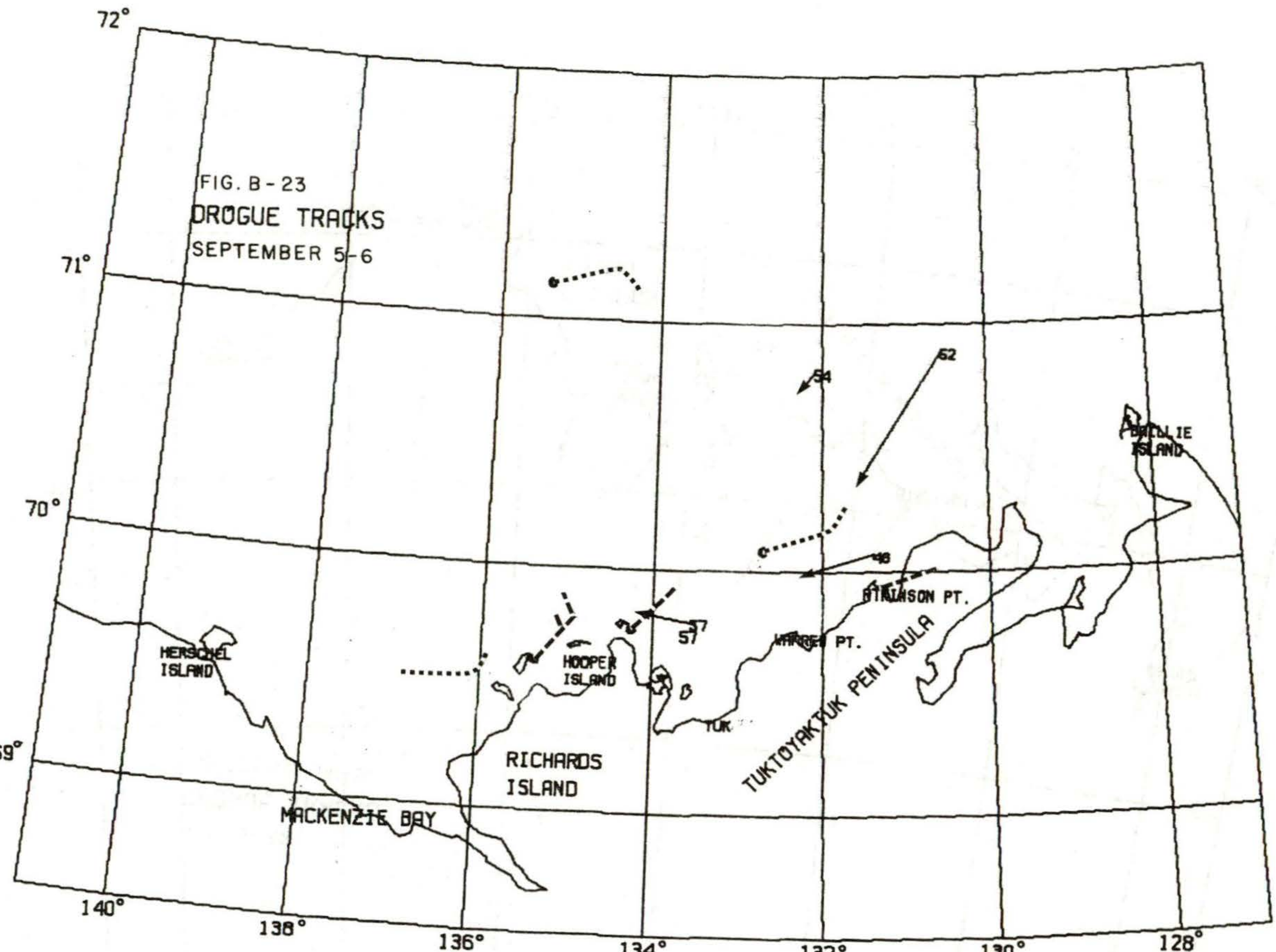


FIG. B-23
DROGUE TRACKS
SEPTEMBER 5-6
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
62
54
48
57
57
BAILLIE ISLAND
ATKINSON PT.
WARREN PT.
HERSCHEL ISLAND
HOOPER ISLAND
TUK
TUKTOYAKTUK PENINSULA
RICHARDS ISLAND
MACKENZIE BAY

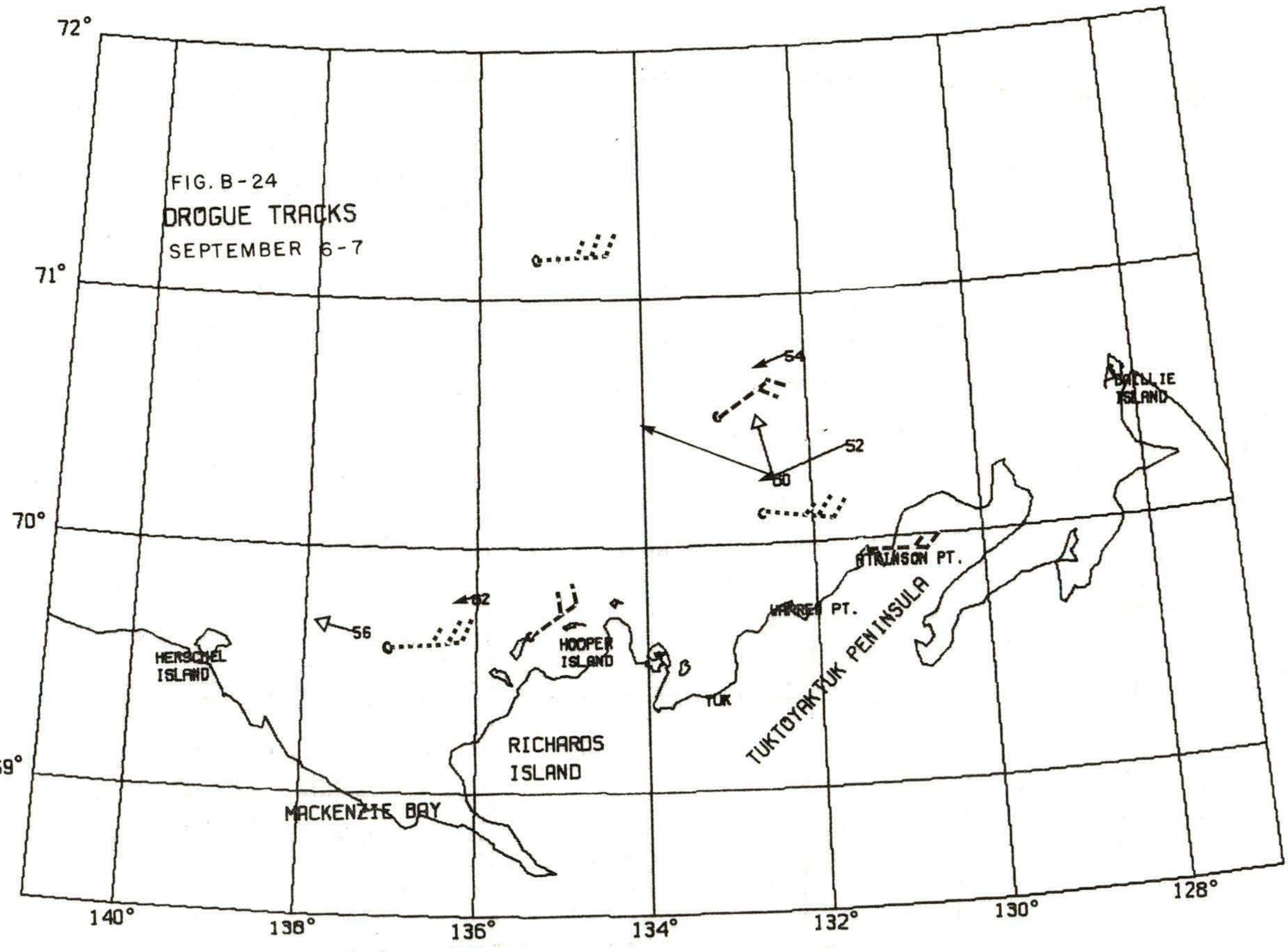


FIG. B-24
DROGUE TRACKS
SEPTEMBER 6-7
72°
71°
70°
69°
140°
138°
136°
134°
132°
130°
128°
54
52
50
62
56
BAILLIE ISLAND
ATKINSON PT.
WARREN PT.
TUKTOYAKTUK PENINSULA
HOOPER ISLAND
HERSCHEL ISLAND
TUK
RICHARDS ISLAND
MACKENZIE BAY

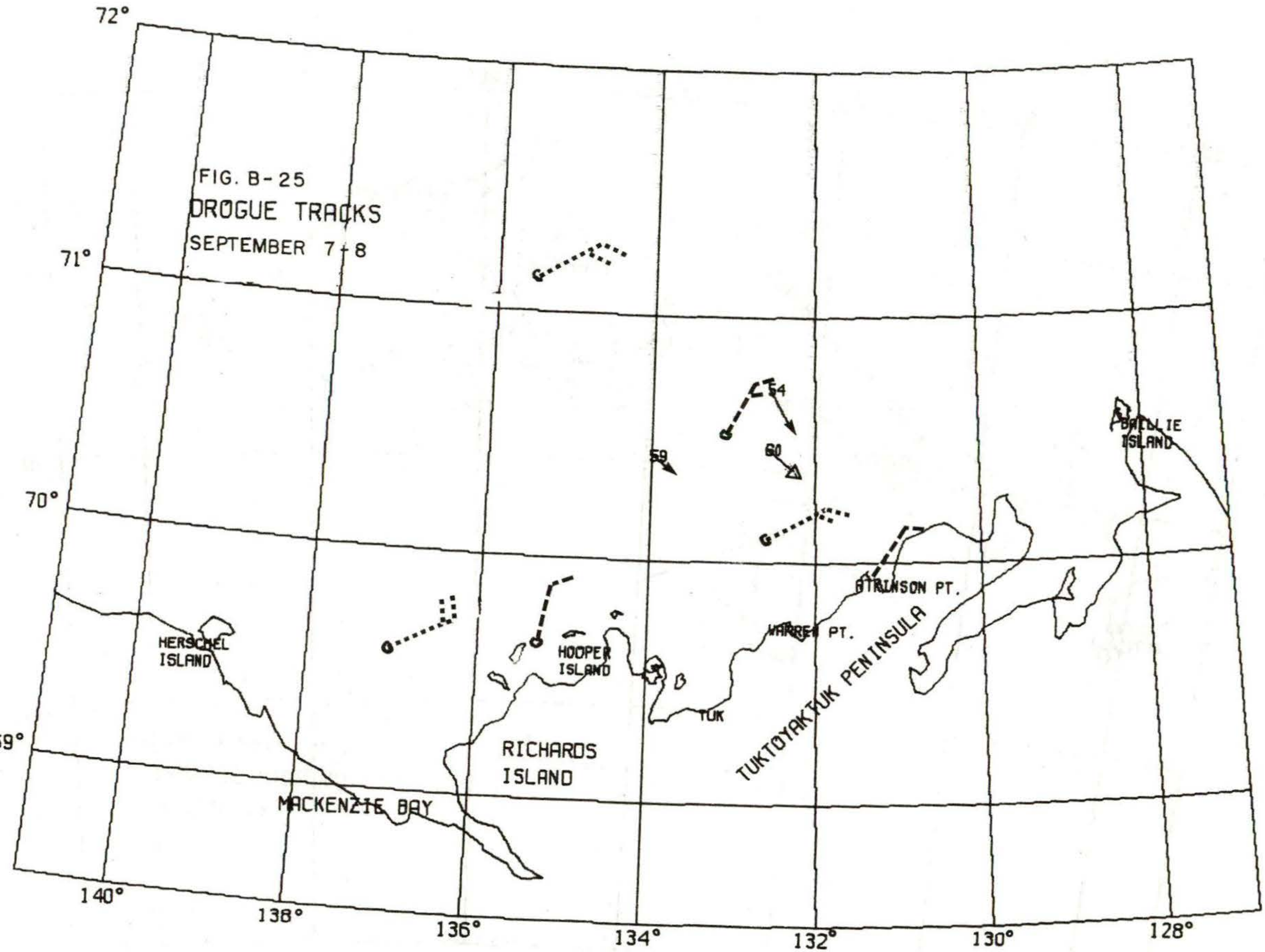


FIG. B-25
DROGUE TRACKS
SEPTEMBER 7-8

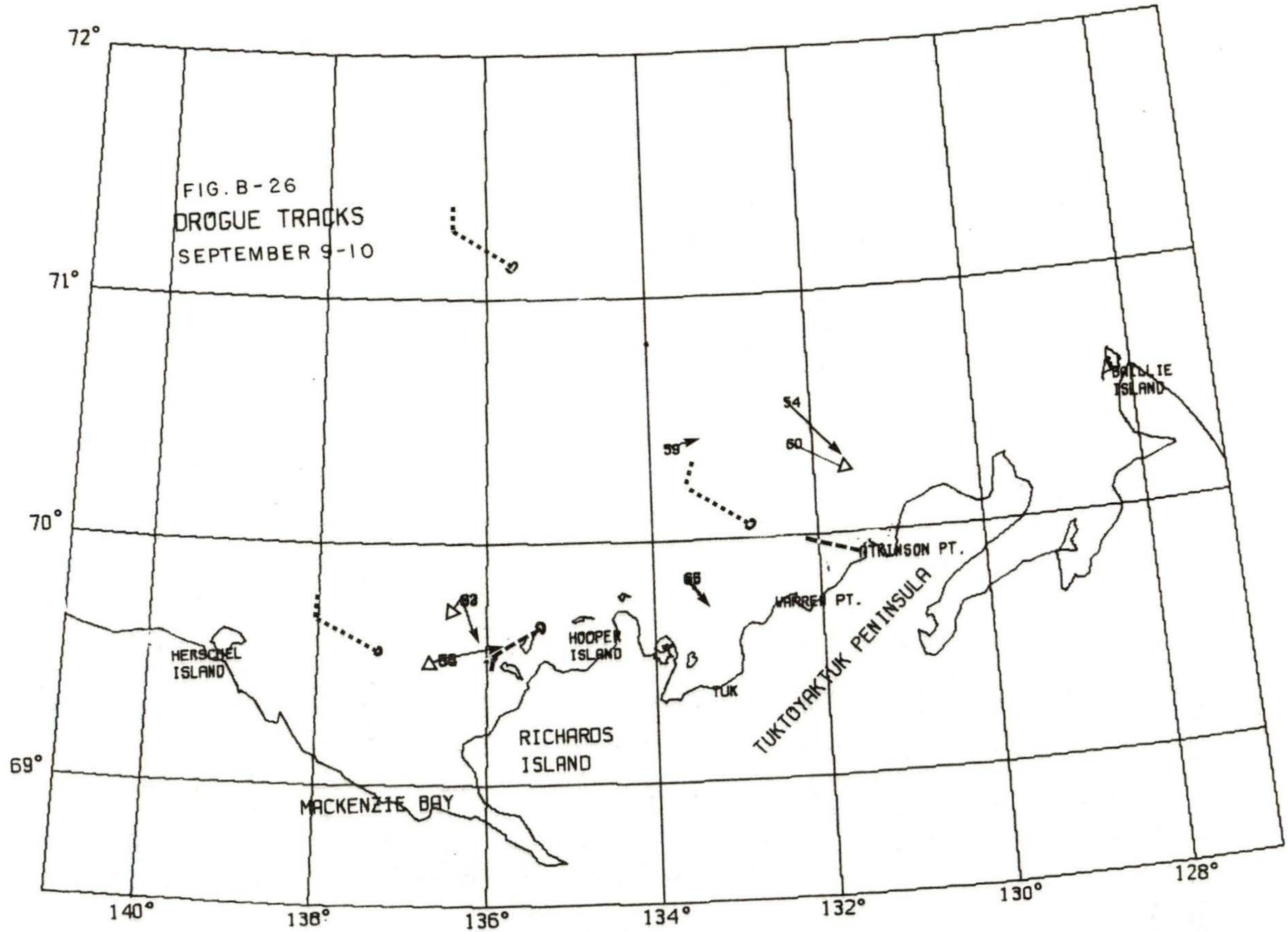


FIG. B-26
DROGUE TRACKS
SEPTEMBER 9-10

APPENDIX C

RADIOBEACON TRACKING SYSTEM

C.1 Radiobeacon Buoys

These buoys were developed and produced by Radio Engineering Products of Montreal. They consist of a 1 watt VHF transmitter, a modulator and timer as shown in Figure D-1. This circuit board and the two 6 volt Manganese Alkaline lantern batteries (Mallory) were supplied in a cylindrical aluminum buoy, as shown in Figure D-2. The total weight of the buoy was about 10 lbs.

The timer was designed so that the buoy transmitted pulses with a duty cycle of 10%, i.e., the pulse length was 10% of the interval between pulses. With this duty cycle the batteries provided enough power for three weeks operation.

The buoys were designed to be independently air deployable without a parachute at speeds of 100 knots from 100 feet altitude.

Eight different frequencies were used so as to be able to tell the drifters apart. These were 152.990, 153.080, 153.170, 153.260, 153.350, 153.440, 153.530, 153.650 MHz. Although the supplier did not supply sufficient technical information to permit formal licensing of these beacons, the Department of Communications was extremely cooperative in permitting their operation in the study area on a non-interference basis for the limited period required. To further improve our ability to discriminate among the beacons, two pulse rates were used, one and two pulses per second. Thus, there were 16 distinct beacon characteristics.

C.2 Receiver

The receiver used in the aircraft was a Realistic Patrolman PRO-88 VHF/OHF FM scanning monitor receiver, available from Radio Shack for less than $200.00. It was modified slightly to incorporate a meter to indicate the strength of the received signal. The receiver was mounted in a small cabinet which also held the receiver battery pack (3 6-volt alkaline lantern batteries), the signal strength meter, an antenna selector switch, and a set of attenuators. A block diagram of the whole system is shown in Figure D-3.

C.3 Antenna System

The antenna system was based on one developed for use on smaller aircraft. It consisted of a quarter-wave antenna mounted on each wing strut with stainless steel hose clamps, with the antenna cable taped to the strut and the side of the aircraft with glass filament tape. The antenna cables were led in the doors and forward to the receiver, with some care being taken to ensure that the antenna leads were the same length. The only mechanical problems with this installation were that the antenna leads could be easily cut or broken closing the door, and that stones flying up when landing or taking off chipped off the insulation of the cable running along the trailing edge of the strut. These were solved by protecting the cable with another larger one at the door and moving it on to the top of the struts.

The directional pattern obtained with such an arrangement depended on the position of the antenna on the strut, as shown in Figure D-4.

C.4 Search Technique

The aircraft would start toward the expected position of the beacon, with the radio observer switching from one antenna to another occasionally to determine which side gave the greatest signal. Usually not too much effort was made to direct the aircraft towards the beacon by nulling the signal because of the uncertainty of the antenna patterns for directions nearly directly ahead. After a while, the signal strength from one of the antennas would be observed to gradually increase. If the rate of increase was very slow and the signal strength low, this indicated that the beacon was very distant and not being approached directly. After a few minutes the aircraft would be turned so as to equalize the strengths of the signals from the two antennas. Otherwise the signal strength would be observed, adding attenuation as required to keep the needle near the centre of the meter, until it reached a maximum and began to drop off slowly. The aircraft would then make a 90° turn toward the side showing maximum signal strength and the procedure would be repeated: when attenuation was 50 db or greater, the beacon should be within one half mile of the aircraft and a visual search would be begun. Figure D-5 shows the signal strength as a function of flying time headed away from the buoy. For this heading the antennas had about half their maximum sensitivity.

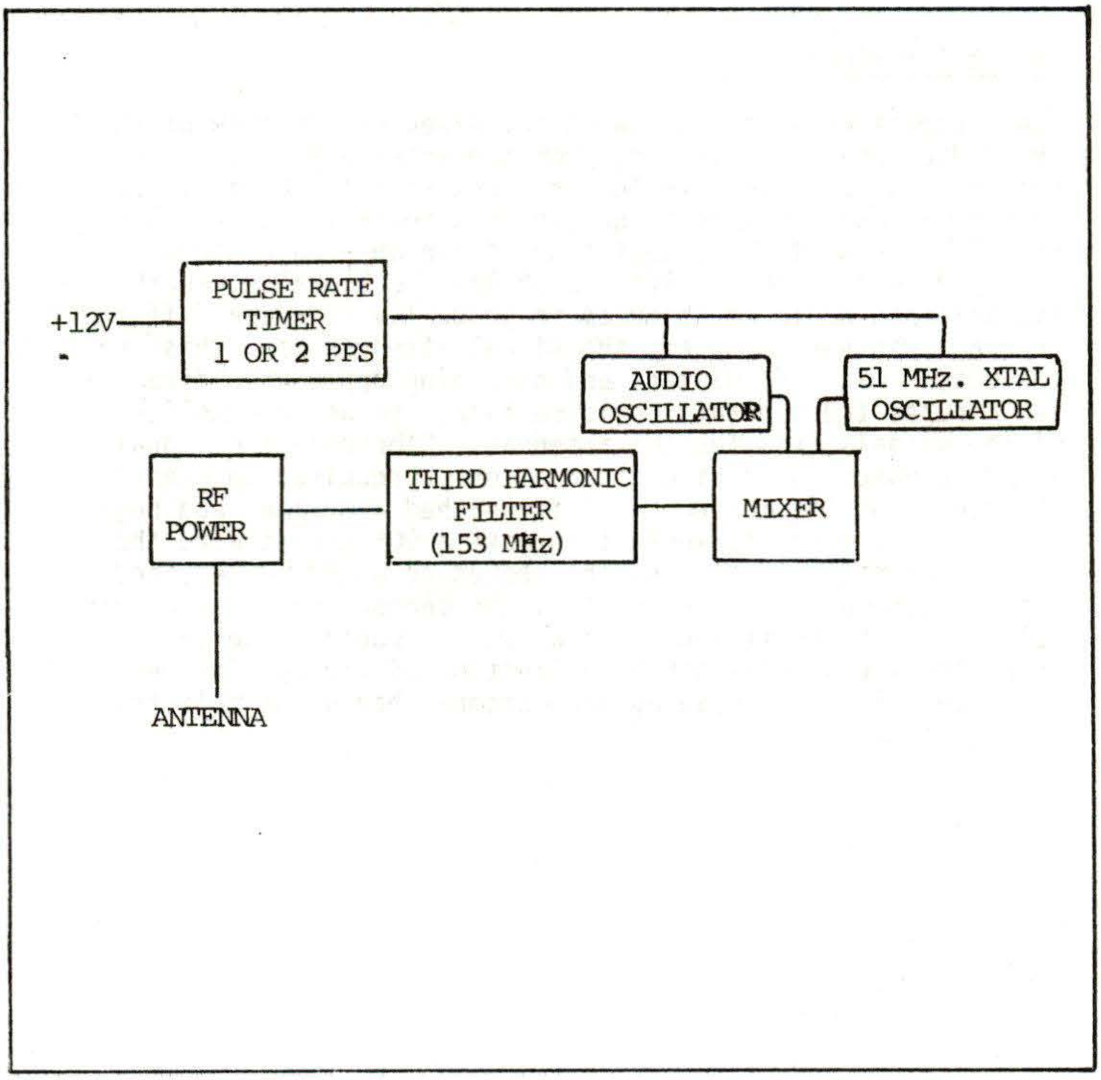


Figure C-1: Block Diagram of Radiobeacon Buoy

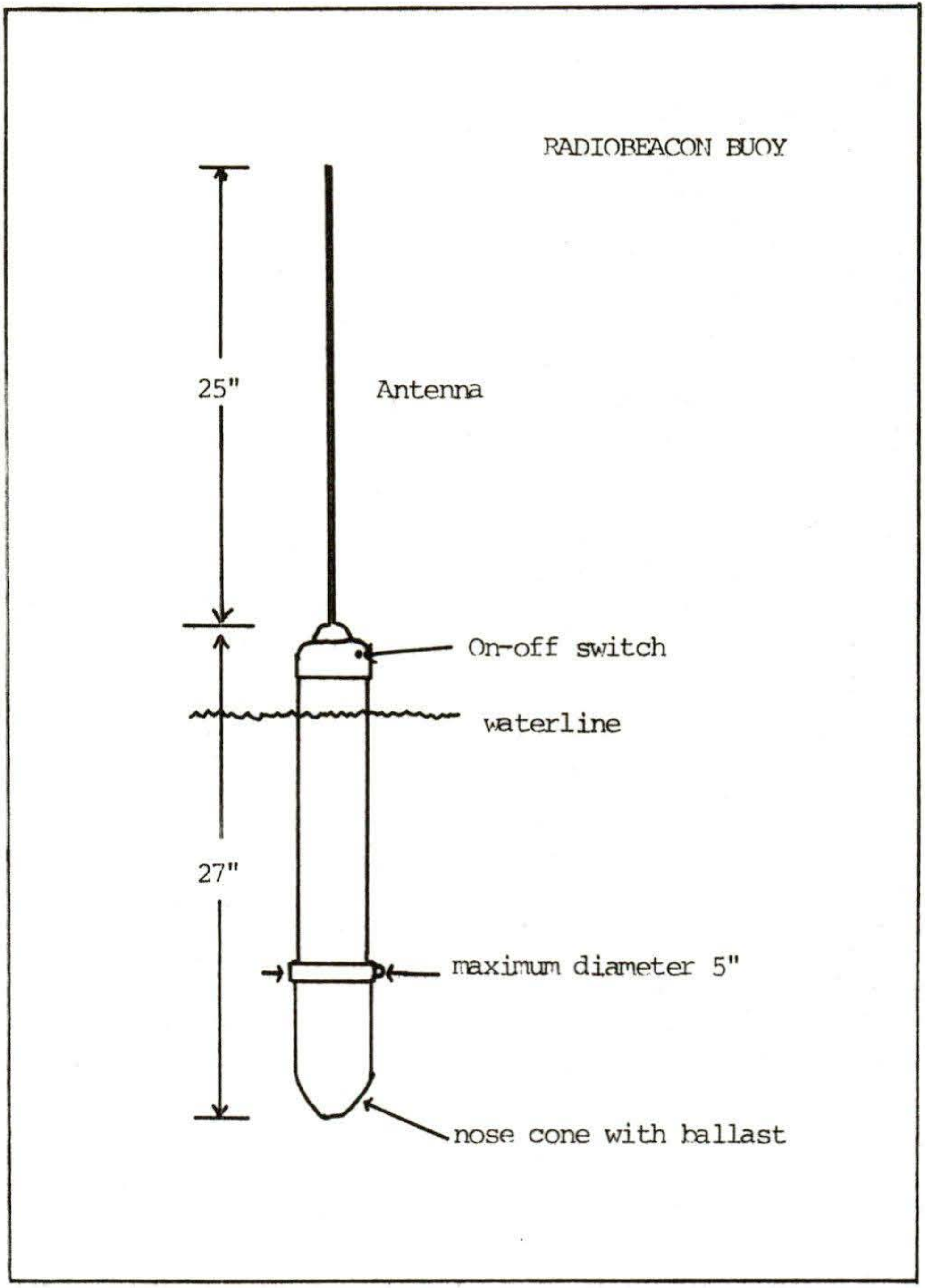


Figure C-2: Radiobeacon Buoy

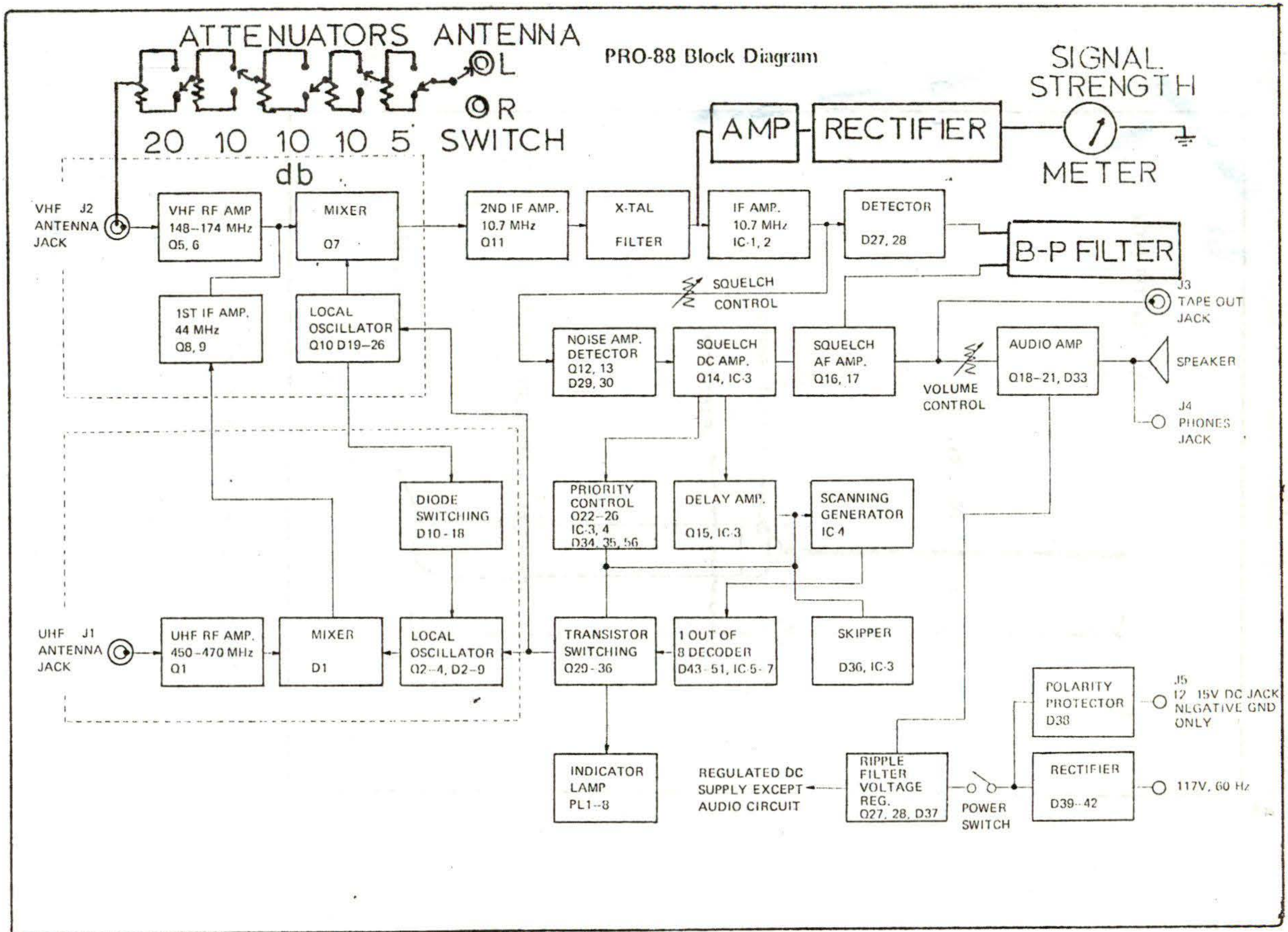


Figure C-3: Receiver Block Diagram

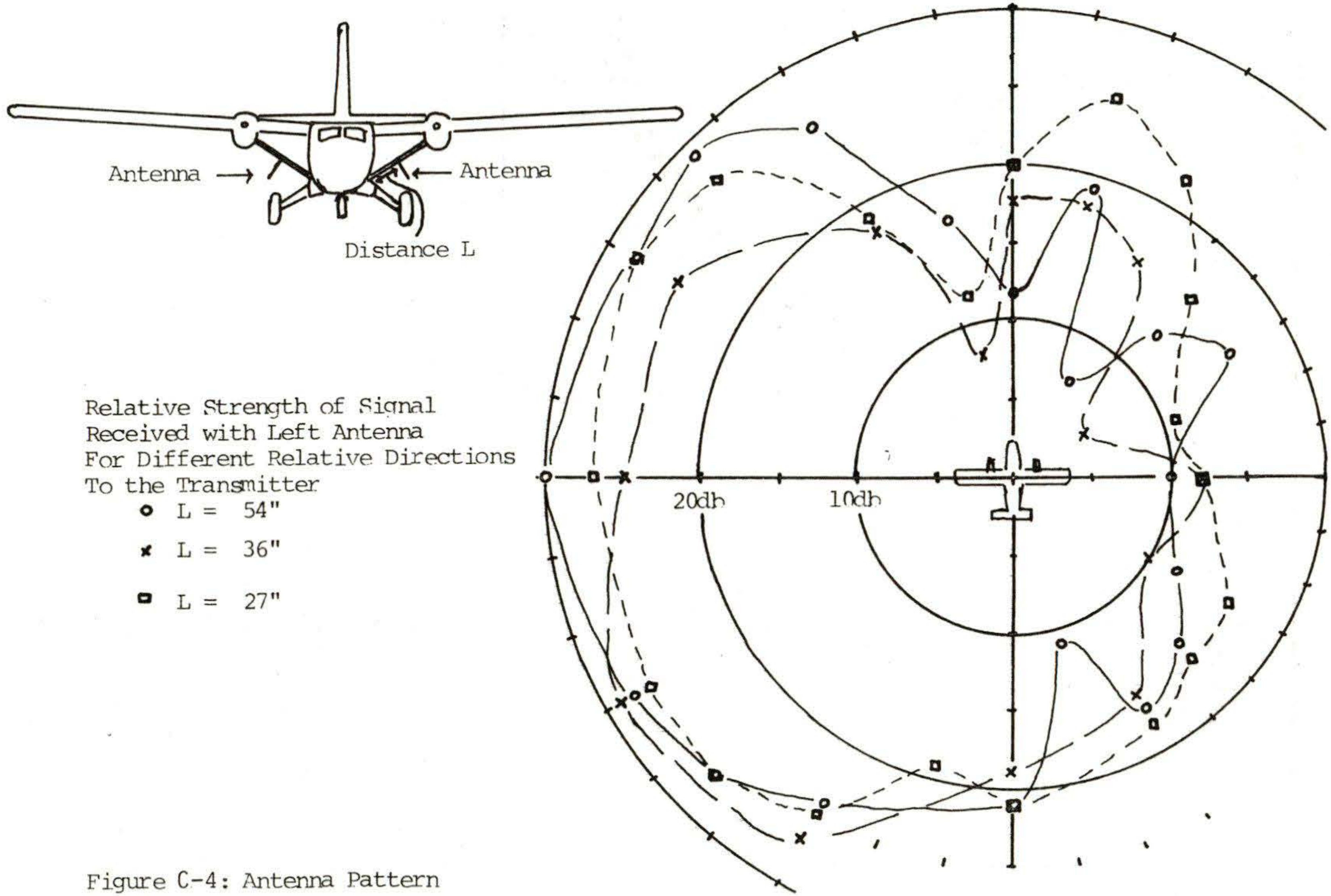


Figure C-4: Antenna Pattern

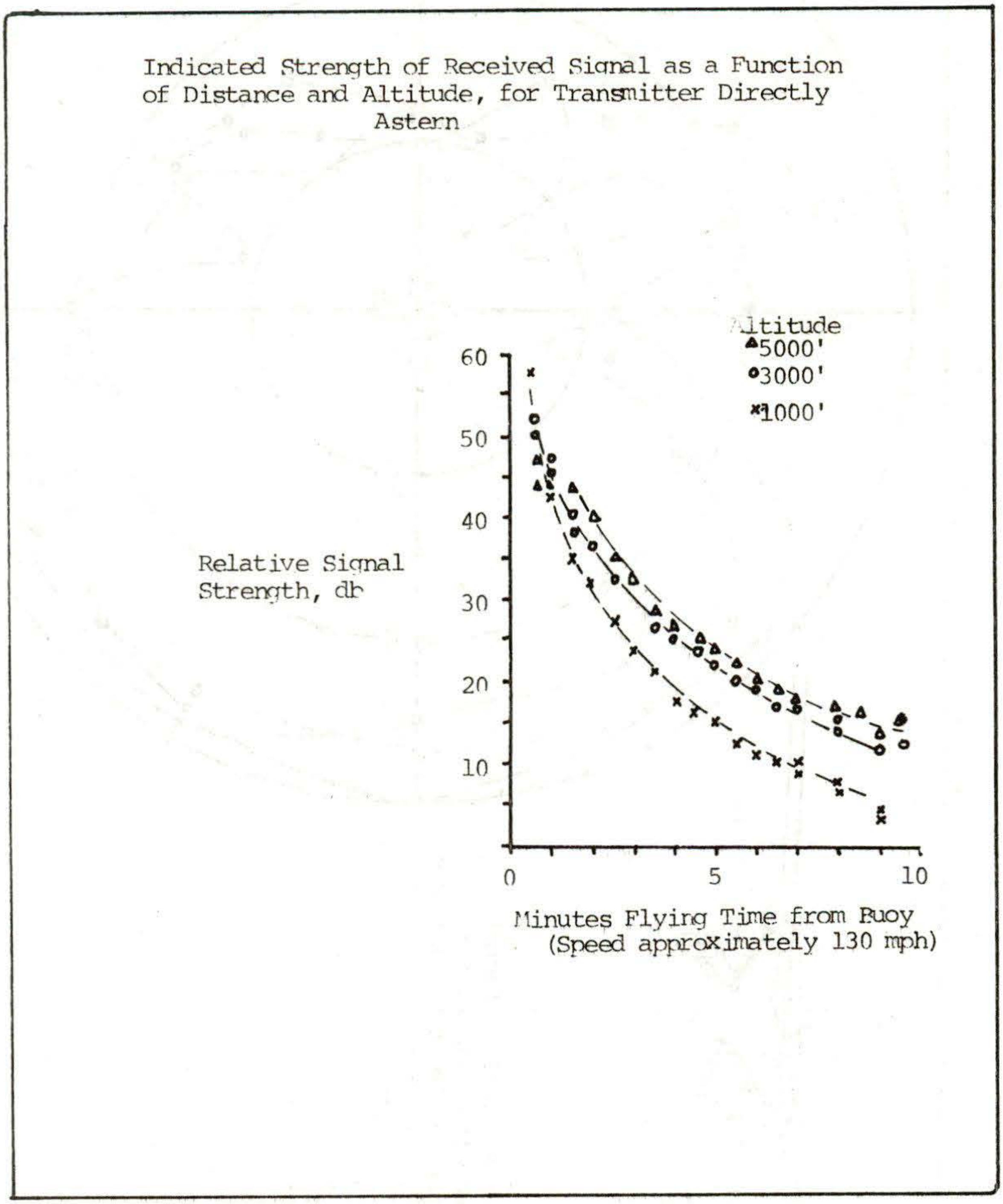


Figure C-5: Signal Strength as a Function of Distance

APPENDIX D

EOTECH OBSERVATIONS

The EOTECH expendable current measuring probe is the production version of a device developed at Nova University and described in Richardson, White and Nemeth (1972), *A Technique for the Direct Measurement of Ocean Currents From Aircraft*, Journal of Marine Research, Vol. 30, No. 2, pp. 259-268.

The principle of operation is as follows: A plastic tube about 3 feet long is dropped from the aircraft attached to a small parachute. Inside the tube are three small floats, each containing fluorescein dye, plus a timing device, which is started just before the assembly is dropped from the aircraft. After the device hits the surface, a small piece of water soluble plastic dissolves, freeing the parachute, thus allowing the tubular part to sink rapidly. When it reaches a depth of a few feet, the pressure of the water compresses the foam plastic plug which holds in the first float, allowing this float to come to the surface. The tube, with the timer and remaining two floats, continues to sink to the bottom. After a predetermined interval from the start of the timer (148 seconds in all the probes used in the Beaufort Sea), one of the floats is released from the tube, which should be resting on the bottom by this time. After a second predetermined interval (285 seconds from release of first float) the remaining float is released, and rises to the surface to join the other two. All three floats leave green dye trails, so their separations may be determined from a vertical photograph made from a known altitude with a lens of known focal length. Also the three floats are different colours, so each dye trail may be uniquely related to a float, although in practice this must be done by making a sketch in the aircraft at the time, as it is not possible to distinguish the colours of the floats on most of the photographs. From data on the float characteristics supplied by the manufacturer, knowledge of the water depth (in this experiment obtained from the hydrographic survey chart and the location), together with a few assumptions and the measurements of the vector separations between the floats, it is theoretically possible to determine the surface current and vertically averaged horizontal velocity of the water column. How this is done is shown in Figure E-1.

During the first part of the field programme we experimented extensively with these devices, finding that it was easy to drop them into large leads in the ice. We quickly discovered that it was impossible to see the dye in places where the water was very silty, and difficult in regions of intermediate turbidity, so we restricted our later efforts to regions of clear blue water. Even then we experienced a rather high failure rate, so we started dropping two devices into each lead, separated by perhaps 200 yards. This would hopefully increase the chances of getting one observation for our investment of aircraft time waiting for floats to surface, and introduced the possibility of getting simultaneous measurements for comparison. Table E-1 lists the drops made, and their results, while Table E-2 gives the relative frequency of success and various kinds of failures.

The most common type of failure was for the timer to not release one or more of the floats. This could be due to cold water causing the timer to be sticky, or to silt from the bottom jamming the timer.

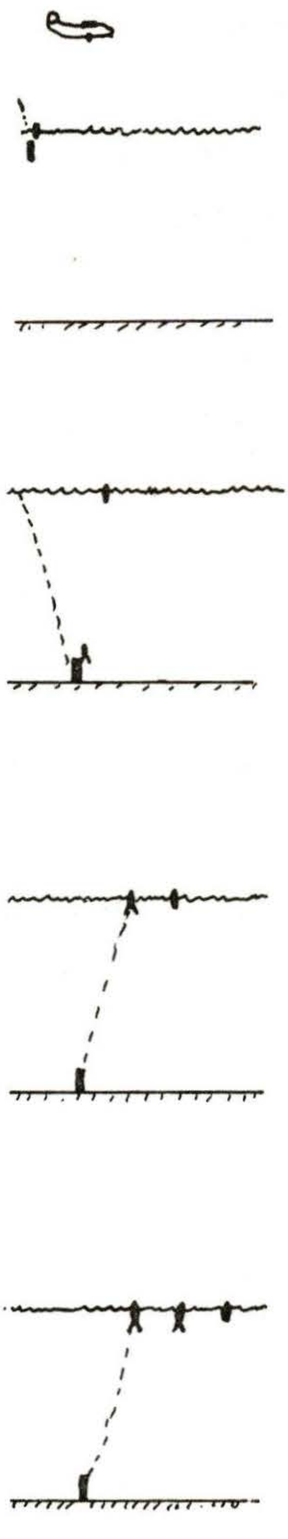
The second most common failure was related to the film processing. We had decided to try to process the film (35 mm High Speed Ektachrome) in the field so as to be able to analyse it more quickly and thus perhaps be able to correct our mistakes. Although the processing arrangements were extremely make-shift, the quality of the first two rolls was very good and seemed to indicate that the film processing should cause no problem. Unfortunately, roll #4 came into contact with a hot pipe while drying in the furnace room, spoiling several frames, while roll #5 was coated with a white deposit, completely spoiling it.

The most significant problem with this technique is revealed by our comparison of the results obtained when two probes were dropped close together nearly simultaneously. As may be seen from Table E-3, the values obtained with one probe can hardly be said to be reproducible, either for surface or water column velocities.

As far as the surface velocities are concerned, it may be that their directions can differ by as much as 200°, or that the drift rates of the second float differ significantly from probe to probe, or that the ascent tracks of the probes are not reproducible, or that the timer speeds vary from probe to probe. We carried out some experiments in Saanich Inlet to test some of these hypotheses. A pair of floats of the type used for the second and third floats were placed on the water surface together: their separation after 15 minutes was only a small percentage of the total distance drifted. Also, a complete Eotech was rigged so that the second and third floats would be released from the bottom at the same time: they reached the surface nearly simultaneously and only about 1 metre apart. Thus, these two mechanisms seem less likely to be the sources of the differences we observed. If the timers were functioning differently, it would be expected that the floats would appear on the surface at different times. This was not noted in the field, although there were often uncertainties of 15 to 30 seconds in detecting the surfacing of floats. It is hard to understand how any of these mechanisms except actual velocity differences or different vertical tracks could result in differences of 200° in direction.

Although differences between the values obtained for the horizontal velocity of the water column are also difficult to explain, there is, in this case, another source of error, which turns out to be very important. It is the difference between the surface drift rate of the first, or surface float and the second and third floats which arises because of their different shape and buoyancy. The first, surface float has only one plastic buoyancy ball and floats vertically, nose upwards, with most of its length submerged. The second and third floats have two buoyancy balls each and float almost horizontally, with much more of their area exposed to the wind. Consequently, the drift rate of the second and third floats due to the action of the wind is much greater. In a test in Saanich Inlet, a pair of the second floats drifted 53 metres in 23 minutes relative to a pair of first or surface floats in a 5-6 mph wind, for a relative speed of 3.8 cm/sec. The effect of this can be seen in the two current values obtained with drop 14-7 from photographs 3 minutes apart.

The conclusion from all this is that the Eotech probes do not seem to be very satisfactory, either in their reliability or in the reproducibility of the data. Since it is an attractive technique, we intend to put some more effort into determining the sources of the problems encountered, but we certainly do not propose to use them operationally until these problems are eliminated.



Timer started, probe dropped.

Time t_1, float A surfaces

$t_1 = \frac{A}{V_F} + t_R$, where A=altitude, V_F = fall rate in air,
t_R = time for parachute to release and float to surface.

$\vec{x}_{A1}$ = position of float A at time t_1, presumed to be impact point.

Time t_2, float B released, determined by timer setting

$\vec{x}_{B2} = \vec{x}_{A1} + \overline{\vec{V}} \cdot H/V_D$, where $\overline{\vec{V}}$ is the average horizontal velocity of the water column, H is the depth, V_D is the fall rate in water

$\vec{x}_{A2} = \vec{x}_{A1} + \vec{V}_{AS} \cdot (t_2 - t_1)$, where V_{AS} is the surface drift rate of float A.

Time t_3, float B surfaces:

$t_3 = t_2 + H/V_{BR}$, where V_{BR} is the rising rate of float B.

$\vec{x}_{B3} = \vec{x}_{B2} + \overline{\vec{V}} \cdot H/V_{BR}$

$\vec{x}_{A3} = \vec{x}_{A1} + \vec{V}_{AS} \cdot (t_3 - t_1)$

Time t_4, float C released from x_{B2} determined by timer setting

Time t_5, float C surfaces

$t_5 = t_4 + H/V_{CR}$, where V_{CR} is the rising rate of float C

$\vec{x}_{C5} = \vec{x}_{B2} + \overline{\vec{V}} \cdot H/V_{CR}$

$\vec{x}_{B5} = \vec{x}_{B2} + \overline{\vec{V}} \cdot H/V_{BR} + \vec{V}_{BS}(t_5 - t_3)$, where $\vec{V}_{BS}$ is the surface drift rate of float B

Figure D-1: Operation of Fotech Current Probe (continued on next page)

Time t_6, aircraft photographs locations

$$\vec{x}_{A6} = \vec{x}_{A1} + \vec{V}_{AS} \cdot (t_6 - t_1)$$

$$\vec{x}_{B6} = \vec{x}_{B2} + \bar{\vec{V}} \cdot H/V_{BR} + \vec{V}_{BS} \cdot (t_6 - t_3)$$

$$\vec{x}_{C6} = \vec{x}_{B2} + \bar{\vec{V}} \cdot H/V_{CR} + \vec{V}_{CS} \cdot (t_6 - t_5)$$

The separation between float B and float C is

$$\vec{x}_{C6} - \vec{x}_{B6} = \bar{\vec{V}} \cdot H \cdot \left(\frac{1}{V_{CR}} - \frac{1}{V_{BR}} \right) + (\vec{V}_{CS} - \vec{V}_{BS}) \cdot (t_6 - t_5) - \vec{V}_{BS} \cdot (t_5 - t_3) \ .$$

If we can assume $V_{CR} = V_{BR}$, and $\vec{V}_{CS} = \vec{V}_{BS} = \vec{V}_S$ the surface current, then

$$\vec{x}_{C6} - \vec{x}_{B6} = \vec{V}_S \cdot (t_4 - t_2) \ , \text{ or}$$

$$\vec{V}_S = \frac{\vec{x}_{B6} - \vec{x}_{C6}}{t_4 - t_2}$$

The separation between float A and float B is

$$\vec{x}_{A6} - \vec{x}_{B6} = \vec{V}_{AS} \cdot (t_6 - t_1) - \frac{\bar{\vec{V}} \cdot H}{V_D} - \frac{\bar{\vec{V}} \cdot H}{V_{BR}} - \vec{V}_{BS} \cdot t_6 + \vec{V}_{BS} \cdot \frac{H}{V_{BR}} + \vec{V}_{BS} \cdot t_2 \ .$$

If we can assume $\vec{V}_{AS} = \vec{V}_{BS} = \vec{V}_S$ which has been found from $\vec{x}_{C6} - \vec{x}_{B6}$,

$$\vec{x}_{A6} - \vec{x}_{B6} = \vec{V}_S \cdot \left(t_2 - t_R + \frac{H}{V_{BR}} - \frac{A}{V_F} \right) - \bar{\vec{V}} \cdot H \cdot \left(\frac{1}{V_D} + \frac{1}{V_{BR}} \right) \ .$$

then

$$\bar{\vec{V}} = H \cdot \left(\frac{1}{V_{BR}} + \frac{1}{V_D} \right)^{-1} \cdot \ \vec{V}_S \cdot \left(t_2 - t_R + \frac{H}{V_{BR}} - \frac{A}{V_F} \right) - (\vec{x}_{A6} - \vec{x}_{B6})$$

The manufacturer gives the following values

V_F = 67 ft/sec.

V_D = 3.5 m/sec.

V_{BR}, V_{CR} = 2.0 m/sec.

Figure D-1 : Operation of Eotech Current Probe (concluded)

TABLE D-1 EOTECH USE SUMMARY

DROP #	DATE 1974	LOCATION N Lat.	LOCATION W Long.	SURFACE Speed cm/sec	SURFACE Dir. °T	WATER COLUMN Speed cm/sec	WATER COLUMN Dir. °T	COMMENTS
8-1	July 14	-	-	-	-	-	-	Water too deep - 180 fms.
8-2	July 14	70°20'	136°45'	11	240	9	180	
8-3	July 14	-	-	-	-	-	-	
10-1	July 15	-	-	-	-	-	-	
10-2	July 15	-	-	-	-	-	-	Only one dye appeared
10-3	July 15	70°40'	133°03'	1.4	350	9	290	
11-1	July 15	-	-	-	-	-	-	Water silty, unable to see dye
11-2	July 15	-	-	-	-	-	-	Last 2 floats up at same time
13-1	July 16	70°24'	134°11'	16	295	74	260	Same spot, simultaneously
13-2	July 16	70°24'	134°11'	26	090	93	160	
13-3	July 16	70°32'	134°11'	-	-	-	-	Simultaneous pair, only 1 dye patch for 13-3
13-4	July 16	70°32'	134°11'	8	070	30	030	
13-5	July 16	70°48'	134°04'	13	072	45	050	Simultaneous pair
13-6	July 16	70°48'	134°04'	12	073	12	170	
14-1	July 17	70°30'	133°50'	4	140	14	200	Simultaneous pair
14-2	July 17	70°30'	133°50'	15	087	50	075	
14-3	July 17	-	-	-	-	-	-	Last float didn't surface
14-4	July 17	70°34'	134°14'	14	085	48	080	
14-5	July 17	-	-	-	-	-	-	Only one float up
14-6	July 17	-	-	-	-	-	-	Only two floats up
14-7	July 17	70°29'	133°00'	7	145	32	030	
		70°29'	133°00'	7	130	32	190	From photo 3 min. later

TABLE D-1 EOTECH USE SUMMARY (continued)

DROP #	DATE 1974	LOCATION N Lat.	LOCATION W Long.	SURFACE Speed cm/sec	SURFACE Dir. °T	WATER COLUMN Speed cm/sec	WATER COLUMN Dir. °T	COMMENTS
14-8	July 17	-	-	-	-	-	-	Only two floats up
15-1	July 17	-	-	-	-	-	-	Only one float up
15-2	July 17	-	-	-	-	-	-	Only one float up
15-3	July 17	-	-	-	-	-	-	Only one float up
31-2	Aug. 2	-	-	-	-	-	-	Only two floats up
31-2	Aug. 2	-	-	-	-	-	-	Only one float up
31-3	Aug. 2	-	-	-	-	-	-	No dye at all
31-4	Aug. 2	-	-	-	-	-	-	Ok - film spoiled during processing
31-5	Aug. 2	-	-	-	-	-	-	Fog rolled in before all up
31-6	Aug. 2	-	-	-	-	-	-	Fog rolled in before all up
31-7	Aug. 2	-	-	-	-	-	-	Appear ok but film spoiled
31-8	Aug. 2	-	-	-	-	-	-	Appear ok but film spoiled
37-1	Aug. 8	-	-	-	-	-	-	Only 2 floats surfaced
37-2	Aug. 8	-	-	-	-	-	-	Film spoiled
37-3	Aug. 8	-	-	-	-	-	-	Only 2 floats surfaced
37-4	Aug. 8	-	-	-	-	-	-	Ok but film spoiled
37-5	Aug. 8	-	-	-	-	-	-	Ok but film spoiled
37-6	Aug. 8	-	-	-	-	-	-	Ok but film spoiled

TABLE D-1 EOTECH USE SUMMARY (continued)

DROP #	DATE 1974	LOCATION		SURFACE		WATER COLUMN		COMMENTS
		N Lat.	W Long.	Speed cm/sec	Dir. °T	Speed cm/sec	Dir. °T	
47-1	Aug. 10	-	-	-	-	-	-	Only 2 floats surfaced
47-2	Aug. 10	-	-	-	-	-	-	Only 2 floats surfaced
47-3	Aug. 10	-	-	-	-	-	-	Only 2 floats surfaced
47-4	Aug. 10	-	-	-	-	-	-	Only 2 floats surfaced
47-5	Aug. 10	70°01'	134°14'	24	264	80	300	Simultaneous pair
47-6	Aug. 10	70°01'	134°14'	24	270	80	300	
56-1	Aug. 21	-	-	-	-	-	-	
56-2	Aug. 21	-	-	-	-	-	-	Thin layer of ice
56-3	Aug. 21	-	-	-	-	-	-	Surface marker lost
56-4	Aug. 21	-	-	-	-	-	-	Only 1 float surfaced
56-5	Aug. 21	-	-	-	-	-	-	Under ice
56-6	Aug. 21	-	-	-	-	-	-	Last float under ice

TABLE D-2 FUNCTION

Total number tried	51	(100%)
Number giving data	13	(25%)
Eotech Malfunctions:		
a) No floats released	1	
b) Only one float released	8	
c) Two floats appear simultaneously	10	
d) two floats appear simultaneously	1	
Total Eotech malfunctions:	20	(39%)
Operator Errors:		
Water too deep - floats presumably crushed	1	
Film spoiled during processing	7	
Unexplained	3	
Total operator errors:	11	(22%)
Bad Luck:		
Fog covering drop site before photos	2	
Floats under thin surface ice	4	
Water too silty to see dye	1	
Total bad luck:	7	(14%)

TABLE D-3 EOTECH PAIRS

PROBE #		SURFACE Speed cm/sec	SURFACE Direction °T	WATER COLUMN Speed cm/sec	WATER COLUMN Direction °T
13-1		16	295	74	260
13-2		26	090	93	160
	Difference	10	205	19	100
13-5		13	072	45	050
13-6		12	073	12	170
	Difference	1	001	33	120
14-1		4	140	14	200
14-2		15	087	50	075
	Difference	11	053	36	125
47-5		24	264	80	300
47-6		24	270	80	300
	Difference	0	006	0	0