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Iceberg Motion in Lancaster Sound and Northwest Baffin Bay, Summer 1978

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ABSTRACT. A radar station on Hope Monument, Devon Island, N.W.T., was operated from 7 July 1978 to 24 September 1978 to track the movement of icebergs in eastern Lancaster Sound and northwestern Baffin Bay. Data were recorded by photographing the radar screen every 20 minutes. Meteorological measurements were also made. The data were processed by computer to provide a statistical picture of the iceberg motions as well as tracks of individual bergs.

The mean circulation pattern of the ice was well defined and variations about the mean did not greatly change the general form of the pattern. The dominant feature of the flow was a stream of icebergs moving with a mean speed of about 40 cm s^{-1} southward along the east coast of Devon Island from north of Philpots Island to Cape Sherard and then westward to Cape Warrender. At Cape Warrender, the bergs turned toward the centre of Lancaster Sound with directions ranging from southwest to southeast and average speeds up to 50 cm s^{-1}. East of the coastal stream in Baffin Bay, the icebergs moved slowly (<25 cm s^{-1}) westward to join the coastal stream, while south of the stream at the entrance to Lancaster Sound two large persistent eddies were observed.

In Baffin Bay, variations in the flow field appeared to be in response to direct meteorological forcing while in Lancaster Sound no evidence of this response was found. The variations in iceberg motion in the sound appeared to be caused by changes in the currents.

Key words: iceberg motion, radar tracking, Baffin Bay, Lancaster Sound

RÉSUME: Une station radar installée sur le "Hope Monument", île de Devon, T.N.O., était en opération du 7 juillet 1978 au 24 septembre 1978 pour suivre le mouvement des icebergs dans les parties est du détroit de Lancaster et nord-ouest de la baie de Baffin. Les données furent enregistrées en photographiant l'écran radar à toutes les vingt minutes. Des jaugeages météorologiques furent également effectués. Les données ont été traitées par ordinateur dans le but de fournir une image statistique du mouvement des icebergs, de même que du tracé individuel des icebergs.

Le modèle de circulation moyen de la glace a été bien défini, et les variations concernant la moyenne n'a pas beaucoup changé la forme générale du modèle. La caracteristique prédominante du courant fut un flot d'icebergs se déplaçant plein sud à une vitesse moyenne d'environ 40 cm s^{-1} le long de la côte est de l'île de Devon à partir du nord de l'île Philpots jusqu'au cap Sherard, par la suite, se dirigeant vers l'ouest en direction du cap Warrender. Au cap Warrender, les icebergs se sont tournées vers le centre du détroit de Lancaster, adoptant des directions s'échelonnant du sud-ouest au sud-est à des vitesses moyennes atteignant 50 cm s^{-1}. A l'est du courant côtier dans la baie de Baffin, les icebergs se déplaçaient lentement vers l'ouest (<25 cm s^{-1}) pour rejoindre le courant côtier, tandis qu'au sud du courant, à l'entrée du détroit de Lancaster, deux larges remous persistants ont été observés.

Dans la baie de Baffin, les variations duchamps d'écoulement semblaient reliées directement aux agents météorologiques tandis qu'au détroit de Lancaster, aucune évidence de ceci ne fut trouvée. Les variations dans le mouvement des icebergs dans le détroit apparurent comme étant causés par des changements de courants.

Traduit par Claude Rocheleau, Arkéos Inc., Montréal.

INTRODUCTION

During the summer of 1978, from July to September, we conducted a field program to study iceberg movements in an area off the southeast coast of Devon Island in the Northwest Territories of Canada. The study formed part of the Eastern Arctic Marine Environmental Studies (EAMES) program started in 1978 in western Baffin Bay and eastern Lancaster Sound. It was designed to provide information for the assessment of the potential problems that icebergs might present to possible future exploratory drilling in the region. We investigated iceberg movements with time scales from several hours to several weeks and spatial scales from one km to tens of km. Earlier work on the motion of sea ice had indicated that radar could be a useful tool for ice motion studies (MacNeill *et al.*, 1978). We used a Lagrangian technique based on a method developed by Buckley (Buckley and Pond, 1976; Buckley, 1977) for tracking surface current drogues.

METHODS

Data Collection

The ice motion data in this study were obtained primarily by using a Decca RM 926 marine radar. Data were recorded on both 70 mm still photographs and super-8 movie film. This technique had been used previously by MacNeill *et al.* (1978).

A camp was set up on Hope Monument (latitude 74° 37.5′ N, longitude 80° 25.5′ W) near Cape Sherard on the southeastern tip of Devon Island (see Fig. 1). Situated at an elevation of 450 m, the site provided a good view of northwestern Baffin Bay and eastern Lancaster Sound. The field camp, consisting of a radar set, a small meteorological station, two accommodation and working shelters and a generator shelter, was established in late June, 1978. The radar antenna and transceiver assembly was situated on the highest point of Hope Monument. The resulting

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field of view was about 225° out to 89 km, the maximum range of the radar. The meteorological instruments were located about 40 m northwest of the camp.

Aside from brief shutdowns, the radar tracking took place continuously from 7 July to 24 September 1978. The radar was operated at the maximum range setting (89 km) and the long pulse (1 μs) mode. Other controls were adjusted for optimum results as conditions changed. Still photographs were taken of the radar display every 20 min with an exposure time of 12 s (about 6 revolutions of the radar antenna). The movie camera ran continuously between film changes with time exposures of about 18 s. In the course of the experiment, approximately 5500 frames of still photographs and 150 rolls of movie film were taken.

Sea clutter could often be picked up at 22 km and occasionally at 30 km while precipitation (snow) clutter could be seen beyond 45 km. A small amount of data was lost when ice targets entered areas of heavy clutter. Interference due to multiple signal paths caused by radar reflections from the terrain within a few hundred metres of the antenna was minimal.

Other data collected included meteorological observations every 3 h, theodolite measurements of iceberg positions, photographs of icebergs and sea ice, and wind velocity and air temperature measurements at Cape Sherard. The automatic weather station at Cape Sherard consisted of an Aanderaa DL-1 data logger with sensors for wind direction, maximum and mean wind speed (during the 10-min sampling interval) and air temperature. The wind sensors were mounted 10 m above ground level (AGL) while the temperature sensor was 3 m AGL.

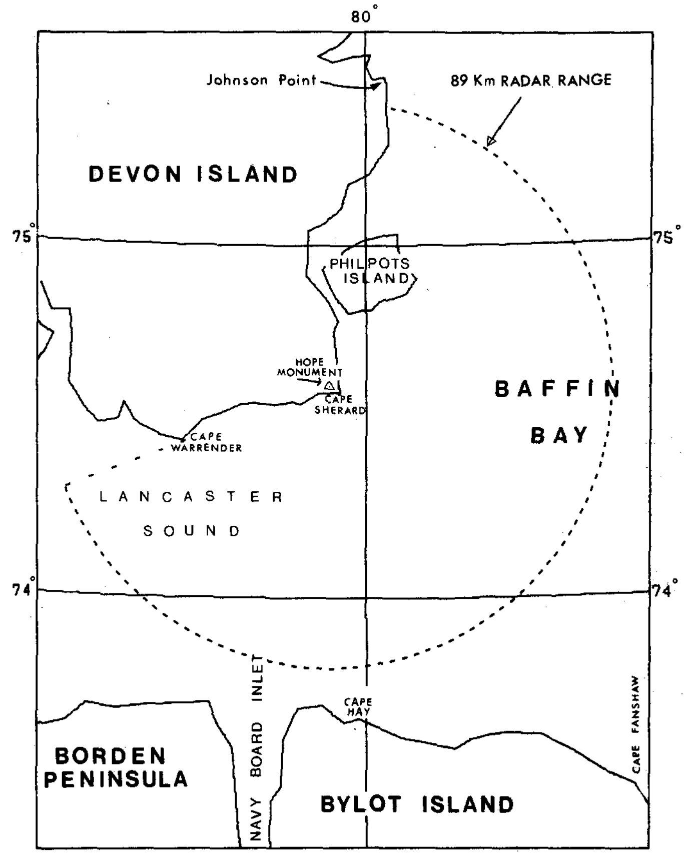

FIG. 1 A map of the study area showing the radar coverage of the region.

Radar Data Processing

The first step in the data processing, referred to as documentation, consisted of examining the still photographs of the radar display to identify individual ice targets and to assign identification and status codes. At this stage a significant amount of poor data was filtered out. The second stage consisted of digitizing the photographs to extract the target positions as well as scaling and orientation information. Data were digitized at 80-min intervals (one out of four photographs). By appropriate transformations and sorting, a set of computer programs produced raw tracks for ice targets. Obvious errors were removed at this stage.

Next a smooth track was fitted to each set of position fixes using a cubic spline interpolation and smoothing routine (Reinsch, 1967). The result was an array of position, velocity and acceleration values equally spaced in time for each target. A 20-min interpolation interval was used to produce values at the same intervals as the radar photographs.

Digitizing introduces some uncertainty aside from gross errors due to mistakes in target identification (usually obvious and easily corrected). As a check on the overall reproducibility of the radar positions after passing through the photographic data logging and digitizing procedures, a few fixed points were digitized a number of times from different photographs. The standard deviations of the point positions were between 130 and 330 m. Because the manufacturer quotes a pulse length of 1 μs (equivalent to 300 m), the radar positioning, data logging and digitizing process apparently do not add significant errors to the positions of objects.

Provided sufficient fixes are obtained for a given target, the track smoothing program tends to remove random errors in the data, as does the averaging of the data at a later stage. Distortion of the radar image due to the curvature of the face of the radar display was removed in the initial stages of the computations.

Many forms of data presentation require that the data set be transformed from a Lagrangian set (where velocities are those of each berg) to an Eulerian set (where velocities are those of all bergs at a particular time and place). Such a transformation cannot, in general, be made exactly, but may be approximated by a process of "square averaging", i.e. averaging all iceberg velocities in a certain area over a certain time interval (Webster and Curtin, 1974). For motion that is both time- and space-dependent, a time average of the Lagrangian velocities underestimates the Eulerian mean while a space average overestimates it. With the method of data collection used here, it is reasonable to expect the calculated averages to underestimate the mean velocity. This error should be small provided the variance of the velocities within each averaging block is kept small relative to the mean. It should be noted that the accelerations calculated by the spline-smoothing technique were Lagrangian or total accelerations (local plus that due to velocity gradient).

Square average plots for all 11 weeks of data are found in Appendix A. (Appendices A to D (75 pages) can be obtained for the cost of duplication from Seakem Oceanography Ltd., 2045 Mills Road, Sidney, B.C., Canada V8L 3S1.) To illustrate features of the flow field, one of the plots is reproduced in the text (Fig. 8). These plots are constructed from all the spline-fitted velocities for any particular week by averaging velocities over that week for a grid of "boxes" covering the study area (as in Fig. 2). The grid spacing is 18.5 km in both the x (east-west) and y (north-south) directions; each "box" is identified by an x and y co-ordinate number with box (1,1) forming the southwest corner of the grid. The coastlines of both Devon and Bylot islands are represented by the 18.5 km block outline most closely following the actual coastline. The average velocities are displayed in each box as arrows pointing towards the direction of average movement with an arrow length proportional to the magnitude of the average velocity of all the points within the box for that week. At the tail of each arrow, the printed number indicates how many data points were used to construct each average velocity vector.

An important factor to consider in the square average plots is the grid size. Due to the 18.5 km grid size, smaller scale structure tends to become lost in the averaging process. The loss of detail is especially noticeable in regions of strong shear or areas of convergence and divergence. This occurs because reversals in direction tend to average to zero and large differences in speed tend to be de-emphasized (e.g. peaks are broadened out). Therefore, a discussion of individual berg tracks has been included to help clarify certain areas in the square average plots.

Histograms of ice speed and direction for the grid squares described above were also used for general analysis. The composite histograms which include all 11 weeks of data are found in Appendix B.

As part of the more detailed statistical analysis of two representative areas, histograms of speed and direction, and acceleration and direction within 20 km of the centre were computed for each area. The histograms for Site 1 (Baffin Bay) are presented in Appendix C and those for Site 2 (Lancaster Sound) are presented in Appendix D.

Several individual berg tracks are plotted on maps of eastern Lancaster Sound. On the tracks the 'x' symbols are separated by 24 h and the numbers are iceberg identification numbers. The tracks were selected to illustrate particular features of the circulation pattern. Time series plots of the north-south and east-west velocity components of some of these bergs are presented as well.

Meteorological Data

The magnetic tapes from the weather station data logger at Cape Sherard were processed by computer. The initial step consisted of removing invalid data at the start or end of each data set. A time series plot of the raw data was examined at this stage. The data were found to be of good quality. A tape of calibrated values was then written using the manufacturer's calibration data. The time series plots were made from this tape.

Meteorological observations made at the radar camp were only used to fill the gaps in the anemometer measurements. Wind measurements made at the camp were strictly of qualitative value because they were greatly influenced by local topographic effects.

Unless otherwise noted, all times referred to in this study are GMT. Days that are indicated by number only are days of the year, where 1 January of each year is day 1. For convenience, the data were processed in approximate one-week blocks. Hence, whenever a week is identified by a number (from 1 to 11), the number refers to the week relative to week one (7 July to 13 July 1978).

The usual convention is used when referring to directions; for ice and water motions it is the direction *to* which the matter is going, while for wind measurements it is the direction *from* which the wind is blowing.

RESULTS AND DISCUSSION

Frequency of Occurrence of Iceberg Radar Returns

The processing of the digitized radar pictures yielded 1529 different iceberg tracks fitted on 65 191 data points. Figure 2 shows how these data points are distributed in a grid of 18.5 km square boxes. The expected fall-off in

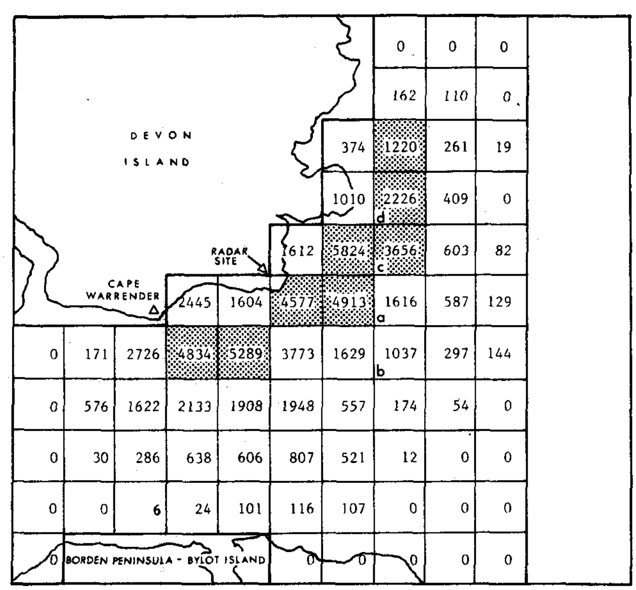

FIG. 2 The square averaging grid with the number of iceberg observations; the shaded area indicates the region with the largest number of observations.

number of points as a function of distance from the radar is present, but it is not symmetrical with azimuth as might be expected. The asymmetry is due to an uneven distribution of bergs in the observation area. Iceberg detectability is a function of berg shape as well as other factors such as size.

On any north-south or east-west line there is a maximum in the number of detected icebergs. The core of largest numbers runs through the shaded squares in Figure 2 or along the core of the Devon Island coastal stream. This stream of relatively high velocity motion follows the coast of Devon Island southwestward from Philpots Island around Cape Sherard and westward towards Cape Warrender. The area in squares a and b, to the southeast of the stream, have less than half the number of observations than in squares c and d, even though they are the same distance from the radar transceiver. This difference implies that there are fewer bergs in the area to the southeast of the stream than in the stream itself. In the area to the south of the radar site, the number of observations per square drops off roughly in the expected fashion, indicating that the number of bergs in this region is approximately constant.

The data were examined for rapid, large variations in the number of observed bergs by looking at the number of bergs tracked in successive six-hour intervals (Fig. 3). The time period up to early August was characterized by a small number of bergs (about 10) and a small random variability. After this time, the number of targets was subject to much greater variability. There were three "pulses" of bergs, during the middle of August. Then after a 10-day period of smaller numbers, the mean berg count increased steadily, but with large variations, to about 2.5 times its original level. Thus, throughout the observation period the total number of bergs increased slowly subject to random variations, but was not, except in three isolated instances, subject to noticeable "pulsing". A comparison of photographed icebergs with radar-tracked icebergs indicated that there was no apparent difference in the types of bergs tracked by radar.

Winds

The anemometer records showed winds from the northeast, southwest and northwest during the field season, with winds from the northeast predominating (Fig. 4). Wind speeds (averaged over 10 min) ranged from 0-15 m s^{-1}, with the largest gust recorded being 18 m s^{-1} from the northeast. Two periods of southwest winds averaging from 7 to 10 m s^{-1} occurred on 2 August (day 214), and from 6 August to 10 August (day 218 to 222), but the stronger storms were generally from the northeast. For example, during a nine-day period of northeast winds from day 195 to 204, the wind speed continuously averaged over 10 m s^{-1} except for one break on day 200 (19 July). Shorter periods of strong northeast winds occurred intermittently throughout the field season. Northwest winds generally averaged less than 5 m s^{-1}.

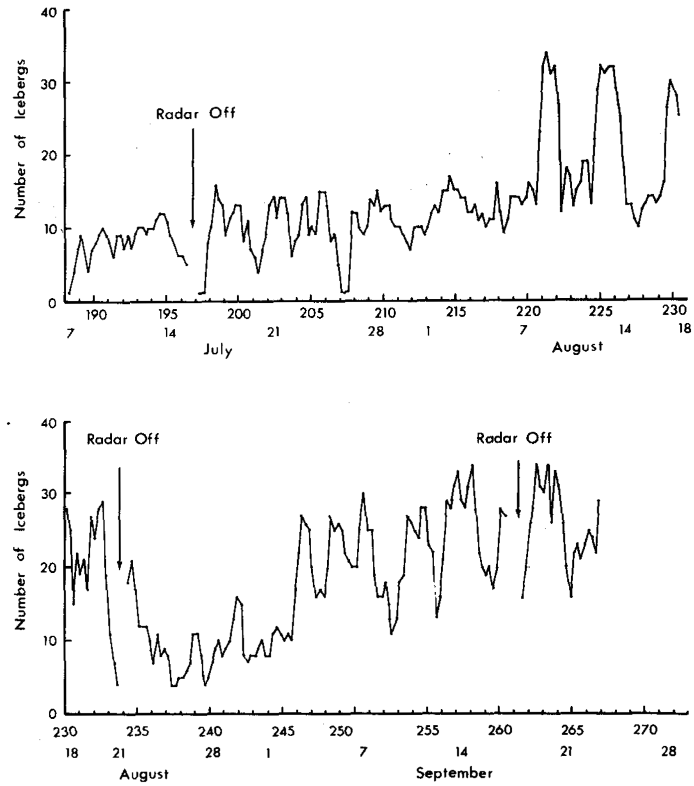

FIG. 3. The number of icebergs tracked in sequential six-hour periods during the study.

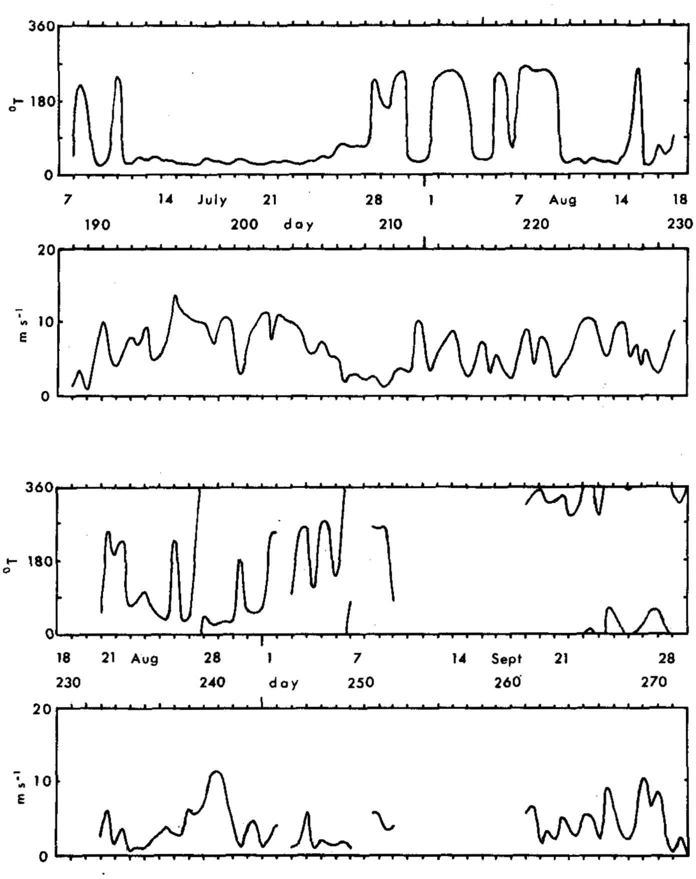

FIG. 4. Wind speed and direction measured at Cape Sherard from 7 July to 27 September 1981.

General Circulation Pattern

Analysis of 11 weeks of data from the Hope Monument radar camp, using histograms, square averaged plots and individual berg tracks has shown that there exists a persistent circulation pattern of icebergs in eastern Lancaster Sound. In order to help visualize the pattern described in the following paragraphs, a qualitative summary of the mean iceberg velocity field observed during the period July to September 1978 is shown in Figure 5.

Cape Sherard area. The dominant feature of the flow was a steady stream of bergs moving southwestward into Lancaster Sound from Baffin Bay through a narrow corridor (typically 18 km wide) just southeast of Cape Sherard (area a in Fig. 5). An example of the narrowing of this stream around Cape Sherard can be seen in the iceberg tracks for week 10 (9-15 September) in Figure 6. The offshore extent of the corridor of southwest berg motion varied from about 15 km to about 25 km. Even when the corridor was wider, the fastest moving bergs tended to pass 3-12 km south of Cape Sherard while the bergs in the southern half of the stream moved more slowly. This phenomenon is illustrated in the berg tracks in Figure 7, where berg speeds were <25 cm s^{-1} for berg 9022, 25-30 cm s^{-1} for berg 9049 and >50 cm s^{-1} for berg 9077. Although in any particular case the velocity gradient between two separated bergs will also be affected by temporal variations in the flow field and/or differences in the size and shape of the two bergs, the results showed that in general, the highest berg velocities occur within 15 km of Cape Sherard. Beyond 15 km, to the south and southeast, the magnitude of the average velocity vectors drops off sharply in most weeks. The corridor of fast-moving bergs was sometimes defined on the radar screen by two areas of convergence of sea ice; one about 4 km south of Cape Sherard and the other about 12-15 km distant. The surface convergence appeared to be associated with a shear zone at the edge of the main stream. It could be seen on the radar photographs, stretching northeast and southwest of Cape Sherard, and was also observed visually from the camp, especially in August and September. During most weeks of the 1978 summer, the average speed of the bergs within 18 km of Hope Monument ranged from 35 to 50 cm s^{-1}, as illustrated in Figure 8. Maximum berg velocities recorded off Cape Sherard often reached 90 to 100 cm s^{-1}.

The winds measured at Cape Sherard were not considered to be completely representative of the wind field over Baffin Bay and Lancaster Sound due to topographic effects. Thus a quantitative correlation of the wind with berg accelerations over the study area was not attempted. Many individual bergs showed significant acceleration independent of the wind velocity as they neared Cape Sherard. For example, on day 250 (7 September), berg 9077 (Figs. 7 and 9) experienced strong westerly acceleration, changing its E/W velocity from 25 to 50 cm s^{-1} as it rounded Cape

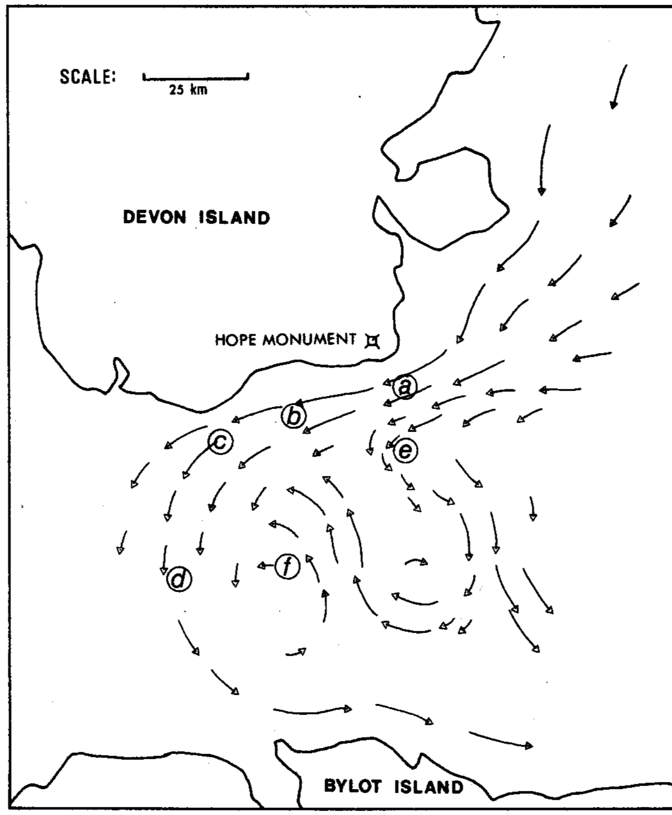

FIG. 5. The general circulation pattern of icebergs as inferred from observations made in July - September 1978. For explanation of letter codes see text.

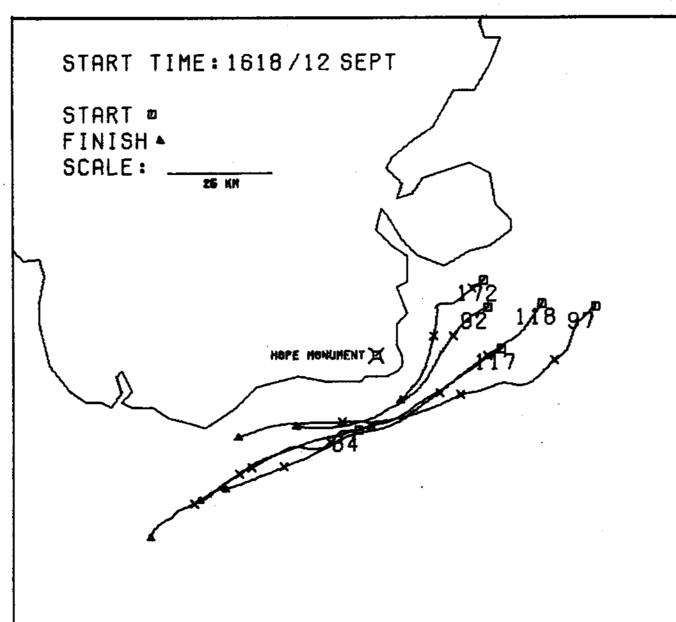

FIG. 6. Selected iceberg tracks from week 10, 9 to 15 September. The "x" marks indicate midnight.

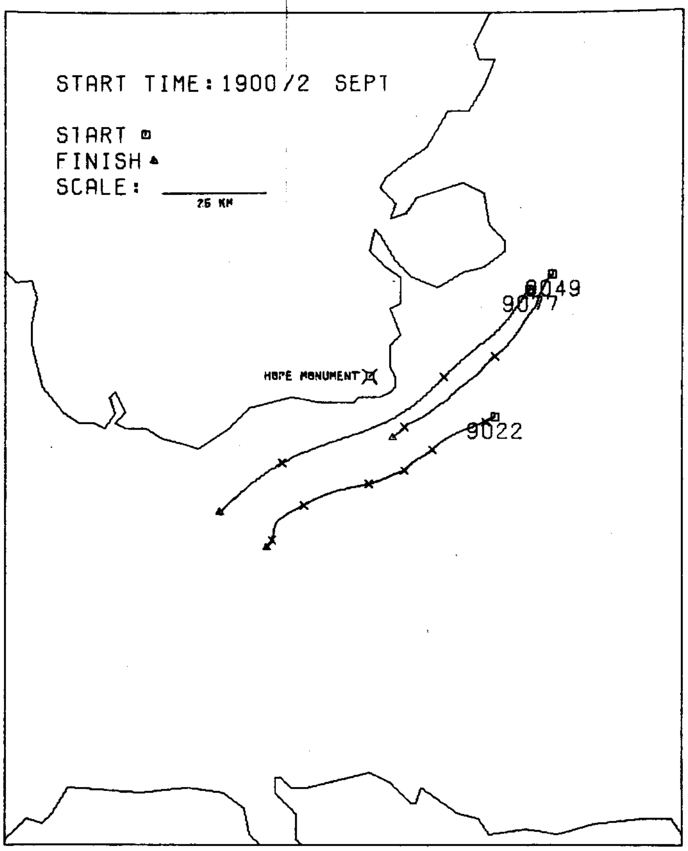

FIG. 7. Selected iceberg tracks from week 9, 2 to 8 September. The "x" marks indicate midnight.

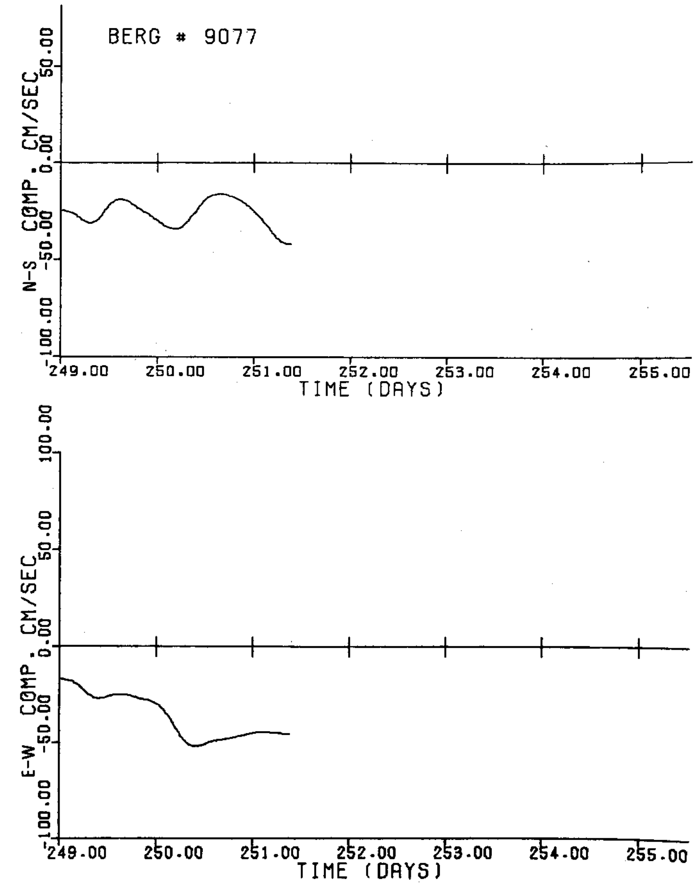

FIG. 9. Time series of the velocity components of iceberg 9077.

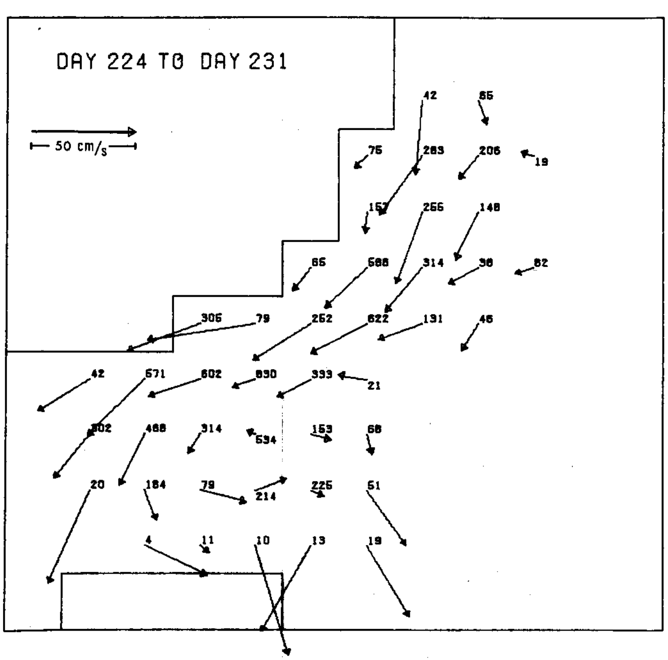

FIG. 8. The average velocities for week 6, 12 to 18 August. The numbers at the arrow tails indicate the number of values used to calculate the average.

Sherard during a period of light variable winds. On the average, this acceleration was most apparent for bergs approaching Cape Sherard from due east of Hope Monument. Bergs approaching from the north-northeast generally exhibited higher speeds, thus showing little acceleration. Only weeks 4 (29 July to 4 August) and 10 (9-15 September) showed southwestward acceleration for bergs approaching Cape Sherard from the northeast.

Philpots Island area. Up the coast from Philpots Island, the bergs tended to move southward along the coast at speeds up to 40 cm s^{-1} (e.g. Fig. 8). Seaward of the core of the main stream of bergs moving southward along the coast between Johnson Point and Cape Sherard, berg velocities were usually smaller (<25 cm s^{-1}) and directed in a westward or southwestward direction toward the main stream. An exception to this occurred during weeks 3, 4 and 5 (22 July to 11 August) when bergs meandered northwestward in Baffin Bay toward Philpots Island before turning southwestward and moving south of Cape Sherard.

Icebergs fed into the corridor off Sherard from the east and northeast continuously throughout the 1978 summer with the fastest-moving bergs following a path southward within 25 km of Philpots Island before turning into Lancaster Sound. In four out of eight weeks (weeks 2, 4, 8, 9), the southward flow of bergs off Philpots Island was strongest within 6 km of the coast (25 to 50 cm s^{-1} as compared to ~15 cm s^{-1}, 12 to 30 km offshore) while in the remaining weeks (3, 5, 6, 7), average southward flow was stronger between 6 and 24 km east of Philpots than nearer to shore. At least during week 3, this was caused by large-scale eddies (with periods of about 2 or 2½ days) in the vicinity of Philpots Island (Fig. 10).

Cape Warrender area. Once the main stream of bergs passes Cape Sherard it moves westward toward Cape Warrender at an average speed of ~ 40 cm s^{-1} (area b in Fig. 5) before turning southward (c in Fig. 5) towards the centre of Lancaster Sound at average velocities ranging up to 50 cm s^{-1}. During some periods (weeks 5 and 6, 5-18 August and weeks 10 and 11, 9-24 September) there is indication of a divergence of the berg tracks as they turn southward or southwestward, while during other weeks (weeks 3 and 4, 22 July to 4 August and weeks 7, 8 and 9, 19 August to 8 September) the main stream of bergs describes a tight arc southeastward (see Fig. 11). During the period 7-21 July, berg motion south of Cape Warrender was minimal (Fig. 12), probably due to solid pack ice which at that time stretched in a line across Lancaster Sound from just west of Cape Warrender to Navy Board Inlet. Bergs approaching the centre of Lancaster Sound from the Cape Warrender area tend to move toward either the southeast or the southwest. In the region further than 36 km south of Cape Warrender, there are too few data points to determine a reliable average direction of motion, especially since there appears to be weekly variability in the general motions.

Bylot Island area. Within 18 km of the north shore of Bylot Island at the extreme range of the radar, strong (45 cm s^{-1}) easterly motion was observed several times over the 1978 field season but the number of observations was too small to draw any firm conclusions. The icebergs which arc southeastward south of Cape Warrender appear either to continue eastward past Bylot Island to Baffin Bay or to become part of the eddy system in central Lancaster Sound described in succeeding paragraphs. It seems probable that the fastest-moving bergs (35 to 50 cm s^{-1}) in the main stream would continue southeastward back into Baffin Bay. A number of large icebergs tracked using satellite-positioned drifters (Marko *et al.*, 1982), followed this direct path in and out of Lancaster Sound, from the northeast to the southeast.

Central Lancaster Sound. In the central region of eastern Lancaster Sound the iceberg circulation pattern was more complicated and subject to greater temporal variations. Often, the slower bergs moving on the southern edge of the main stream towards Cape Sherard from the east did not follow the main stream of icebergs westward but instead turned southward at a distance of between 18 and 37 km south of Hope Monument (region e in Fig. 5). On the square average plots of the weekly velocity field (Appen-

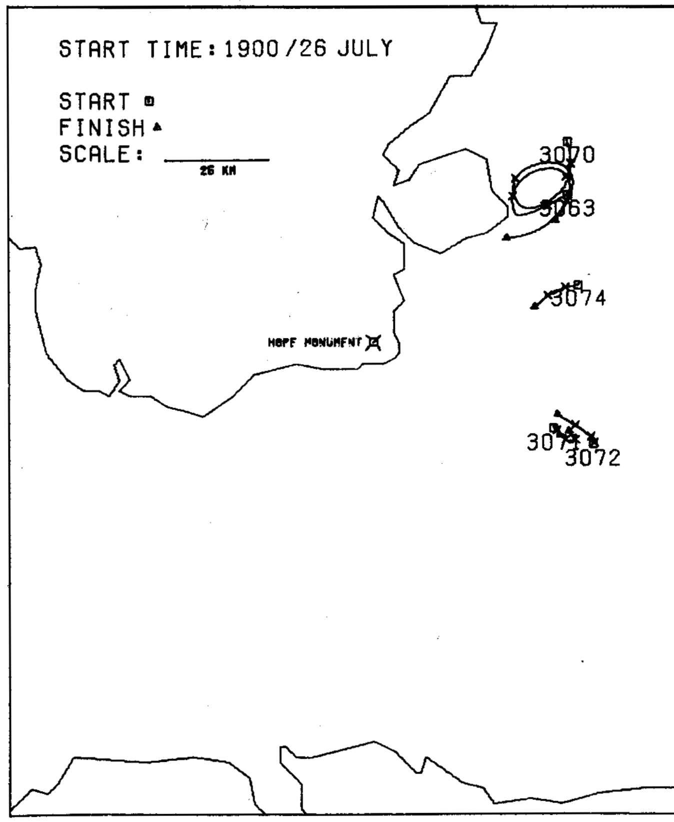

FIG. 10. Iceberg tracks from week 3, 22 to 28 July. The "x" marks indicate midnight.

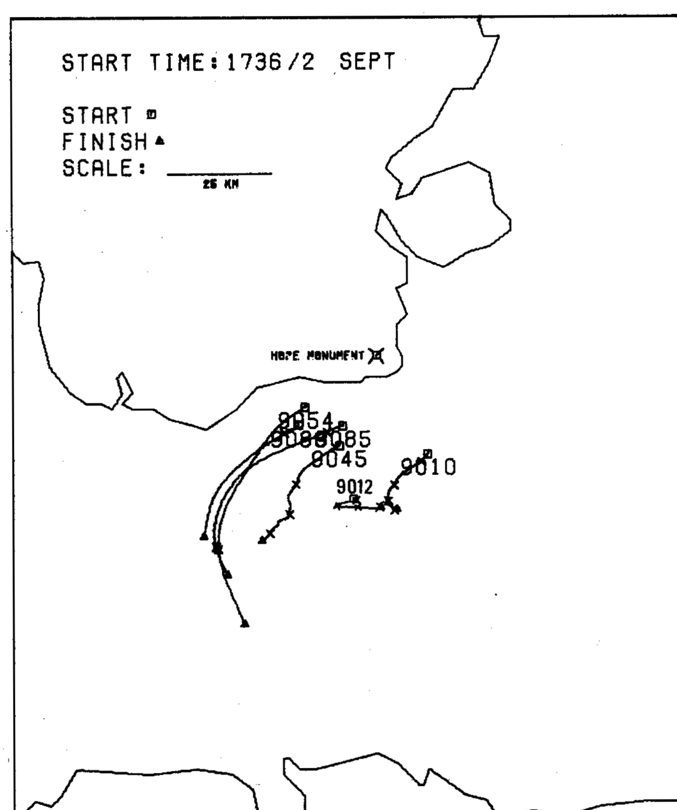

FIG. 11. Further iceberg tracks from week 9, showing the curving paths south of Cape Warrender.

dix A), this area of divergence can be detected during most weeks (except week 10, 9-15 September, which has little data in this area) as either east-west diverging velocity vectors or a very small mean velocity vector. Some of the features can be seen in Figures 11 and 13. South of Cape Sherard, bergs outside the coastal stream either moved to the southeast and out of radar range (as in the case of berg 6011 in Fig. 13) or circled (clockwise) southward and westward back into the system of eddies in central Lancaster Sound. During the first five weeks of the field season (7 July to 13 August), bergs tended to move back into Lancaster Sound in a clockwise motion at speeds of less than 25 cm s^{-1} instead of continuing to the southeast. At times southward-turning bergs moved southeasterly out of the Lancaster Sound with velocities increasing to 35 cm s^{-1} as the bergs moved toward the southeast.

The final feature of the berg circulation was a counterclockwise eddy (f in Fig. 5) of varying size situated west of the clockwise motion described above. This eddy typically was centered about 40 to 50 km southeast of Cape Warrender. Bergs enter this cyclonic gyre from the southeast as shown by berg track 1054 (Fig. 12), from the southwest as shown by berg track 6017 (Fig. 13) and probably from the inner edge of the main stream to the north and northeast of the gyre. Northward speeds in this gyre could average more than 25 cm s^{-1} (weeks 1, 3 and 4) but generally averaged less than 10 cm s^{-1} such as in weeks 6, 8 and 9. There were not enough data available for weeks 2, 7 and 10 to confirm or refute the presence of cyclonic motion during these weeks. The gyre converged with the main stream of bergs about 25 km southeast of Cape Warrender. To the northeast of the gyre was the stagnant area described previously.

Velocity Fluctuations

Short period fluctuations in iceberg velocity are quite noticeable in the time series plots of the velocity components. In the region east of Hope Monument in Baffin Bay these fluctuations tend to be semi-diurnal in the north-south component (Fig. 14), while in Lancaster Sound diurnal east-west fluctuations predominate (Fig. 15). The diurnal fluctuations are likely evidence of tidal currents along Lancaster Sound where the K_1 currents are larger than the M_2 currents (Fissel, 1982). The semi-diurnal components may be either tidal or inertial: neither possibility may be ruled out on the basis of frequency. Current meter data and satellite-tracked surface drifters indicate that at times both tidal currents and inertial oscillations are present in the near surface waters and that the inertial oscillations have typical amplitudes of 10 to 20 cm s^{-1} (Fissel, 1982).

In the region east of Cape Sherard, longer period fluctuations in berg velocity appeared to be related to changes in the wind, especially in the records of the more slowly moving bergs. During week 3 (22-28 July) when periods of light winds followed strong northeast winds, a clockwise

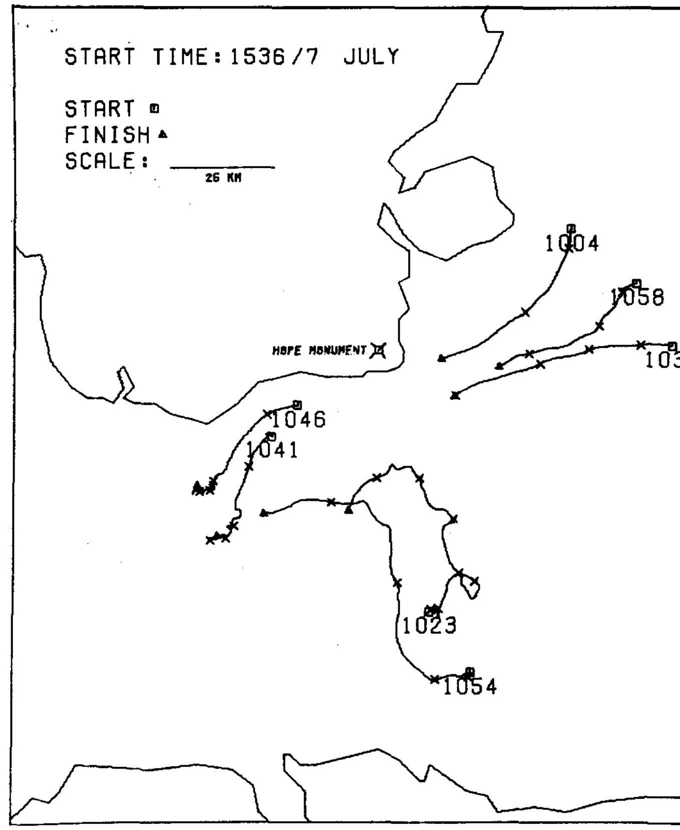

FIG. 12. Iceberg tracks from week 1 (7 to 14 July), showing a portion ot the cyclonic gyre.

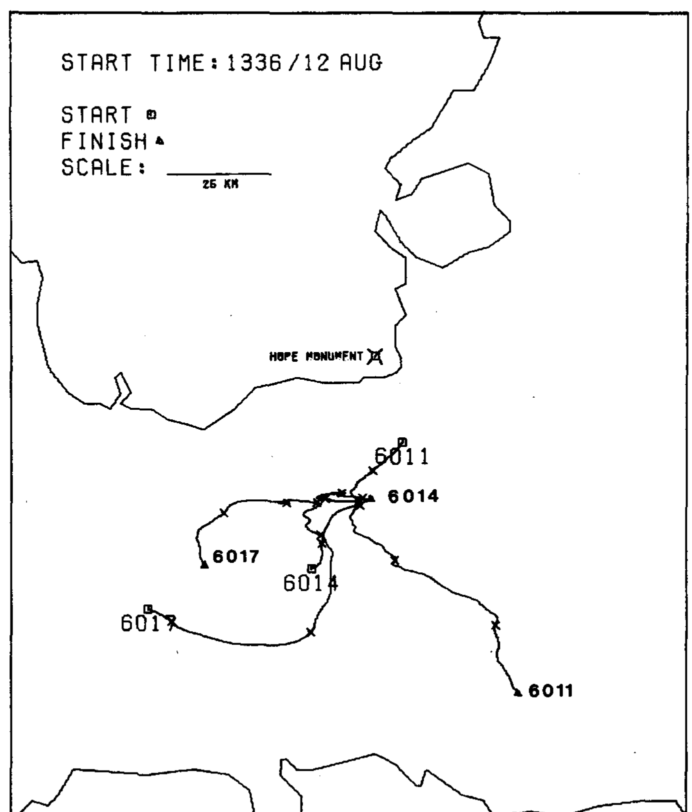

FIG. 13. Iceberg tracks from week 6 (12 to 18 August), illustrating a gyre and the stagnant area.

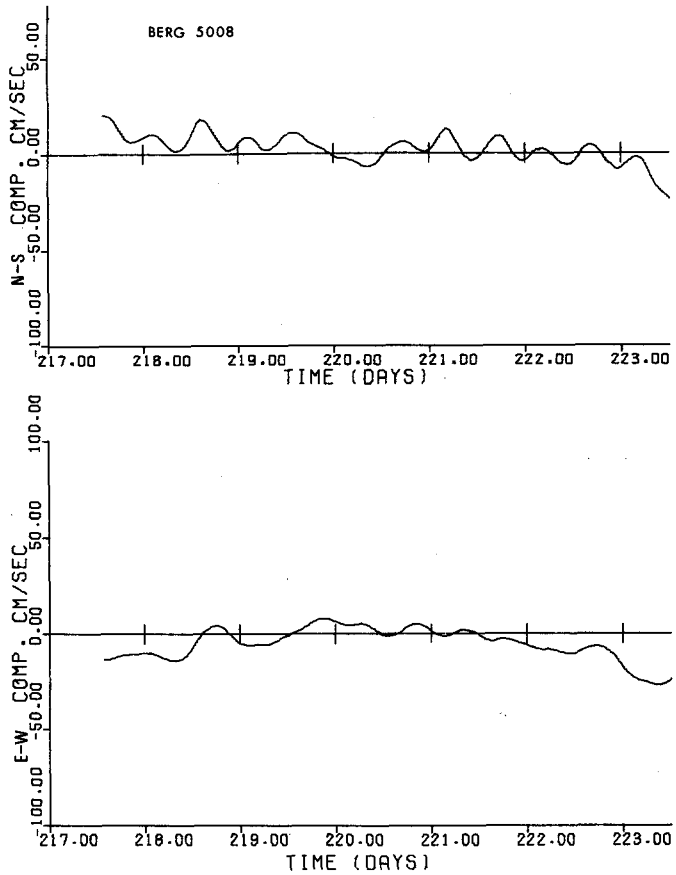

FIG. 14. Time series plot of the velocity components of iceberg 5008 illustrating the semi-diurnal variations in the north-south component.

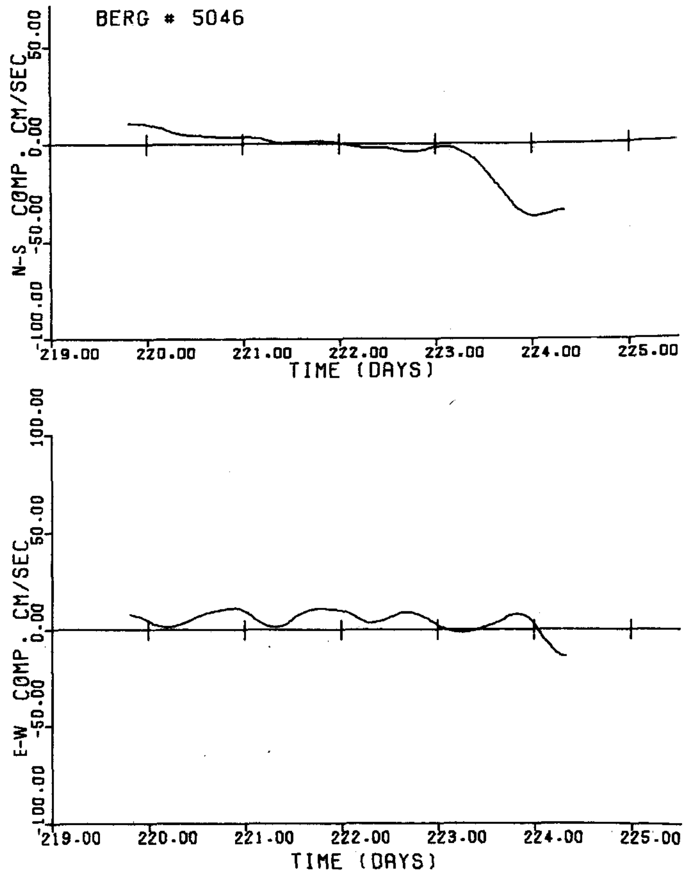

FIG. 15. Time series plot of the velocity components of iceberg 5046 showing the diurnal variation in the east-west component.

gyre motion with a period of 2-3 days was observed in the berg movements off Philpots Island (Fig. 10). At distances greater than 36 km due east of Hope Monument, westerly and southwesterly berg motion was associated with northeast winds whereas northwesterly movement of 5 to 25 cm s^{-1} was coincident with westerlies of lighter wind conditions. Usually, more developed southwest motion and larger berg velocities occurred during strong northeast winds. From week 2 to week 3 northeast winds averaging 10 m s^{-1} at Cape Sherard gave way to light, variable winds (Fig. 4). Concurrently, average iceberg velocities on the east side of Devon Island decreased in magnitude (by as much as 20%) and were more variable in direction. On the other hand, an increase in iceberg velocity from week 5 to week 6 in this region corresponded to a 5-day northeast storm (wind speeds of 8-10 m s^{-1}). Week 8 appeared to be somewhat anomalous in that mean berg velocities south and east of Cape Sherard were small (5-25 cm s^{-1}) despite a two-day period of northeast wind during that week. There may be a bias in the data set here since there are few data points in some areas, most of which may have been recorded before the northeast wind. Perhaps the duration (two days) and speed (about 8 m s^{-1}) of the northeast wind were not sufficient to strongly influence berg motion averaged over the week.

In Lancaster Sound, however, the larger accelerations do not seem to occur in response to the wind but take place as bergs move from one part of the circulation pattern to the other. This behaviour is seen particularly in the acceleration of bergs around Cape Sherard and in the rapid motion in some parts of the gyres in mid-sound (berg 6017 in Fig. 13). Even in periods of strong southwest wind, iceberg velocities in the main stream are greater than 25 cm s^{-1}.

An explanation for the difference in behaviour of the two regions lies in the strength of the kinematic velocity gradients. In Baffin Bay, the water velocity gradients are weak and berg accelerations may be caused mainly by wind stress on the bergs, but in Lancaster Sound, the larger velocity gradients are primarily responsible for the berg accelerations and hence for the fluctuations in the berg velocity field.

Velocity Distributions

Daily average velocity components for 7.5 km square boxes in two lines were calculated, one line running east of Hope Monument along 74° 40′N and one running south of Hope Monument along 80° 25′W. These 25-hour averages make it possible to examine shorter period variations in the velocity distribution than in the weekly averages without the influence of tidal or inertial frequencies. Some of the results of these computations are shown in Figure 16 and Figure 18.

Figure 16 shows the velocity distribution along the east-west line for a period of three days from 10 to 13 September. The horizontal axis shows the distance away from Hope Monument. V_x is the east-west velocity component and V_y is the north-south velocity component. The important features to note here are:

1) velocities are always southwestward within 37 km of Hope Monument;

2) the position of the speed maximum which indicates the location of the core of the coastal stream is located 15 to 23 km east of Hope Monument; and

3) there are daily fluctuations in the distribution, although the sharp change in speed consistently occurs at 20-30 km east of Hope Monument. Some days, the speeds drop off to small values by 37 km; at other times the velocity field contains a broad, non-zero component as in Figure 16c. This increase of southwestward velocities further from shore seems to occur during and immediately following northeast storms.

Figure 17 shows the average velocity distribution derived from the histograms along 74° 40′N for the entire field season using a grid size of 18.5 km. The speed peak of 35 cm s^{-1} lies between 18 and 37 km east of Hope Monument. Between 37 and 55 km distance the speed has dropped to half the maximum value; east of 55 km, the north-south (V_y) component drops to less than 5 cm s^{-1} but the east-west (V_x) component remains at about 15 cm s^{-1}, indicating more westerly motion.

Figures 18a, b and c are three velocity distributions on the line running due south of Hope Monunent. The velocities along this line tend to be more complicated and much more variable than those along the east-west line. A strong westerly component always occurs between about 7.5 and 30 km south of Hope Monument. This is the coastal stream of bergs passing around Cape Sherard. The peak westward velocity is usually found between 7.5 and 22 km south of Hope Monument. The westward component falls away sharply to zero at about 30 km. Occasionally, as happened during week 9, the stream broadens to 40 km. South of 30 km the velocity is often eastward as in Figure 18a and b but it can become northwestward if the line crosses part of a counterlockwise gyre as in Figure 18c. In Figure 18c, both V_x and V_y go to zero at 30 km, indicating the presence of a stagnant area south of Hope Monument.

Detailed Analysis of Iceberg Motion At Two Sites

Two locations were chosen as representative areas for more detailed velocity and acceleration analysis. These were site 1 in Baffin Bay, centered on 74° 32′N, 78° 45′W (50 km from the radar site), and site 2 in Lancaster Sound centered on 74° 05′N, 81° 10′W (63 km from the radar site).

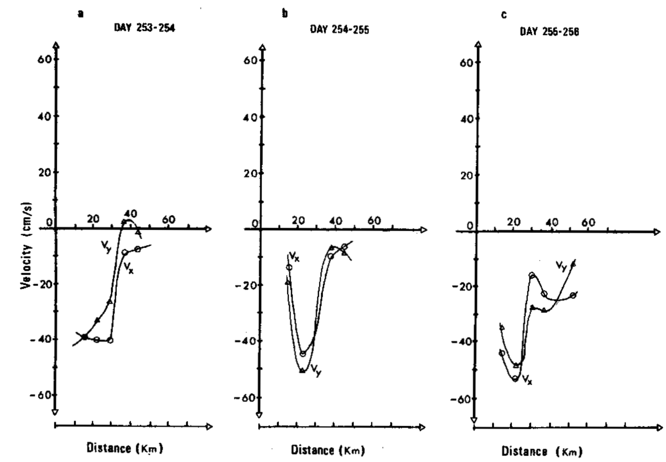

FIG. 16. Three days of average (25 hr) north-south (V_y) and east-west (V_x) velocity components for icebergs along a line extending due east of Hope Monument.

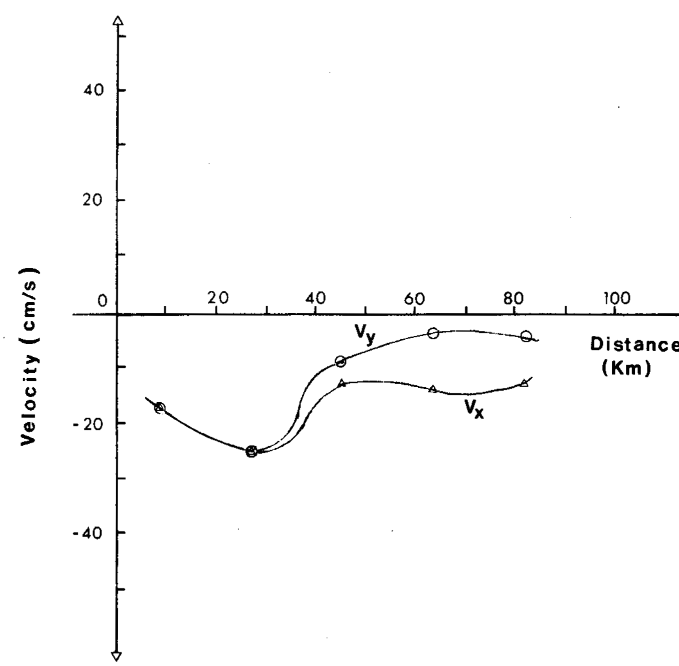

FIG. 17. Mean north-south (V_y) and east-west (V_x) iceberg velocity components along a line extending east of Hope Monument for the entire data set.

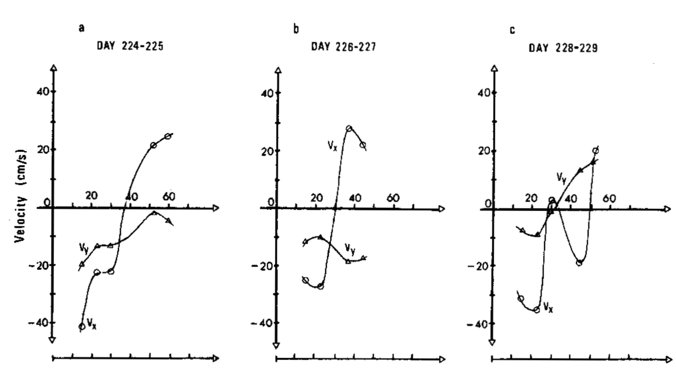

FIG. 18. Three days of average (25 hr) north-south (V_y) and east-west (V_x) iceberg velocity components along a line extending south from Hope Monument.

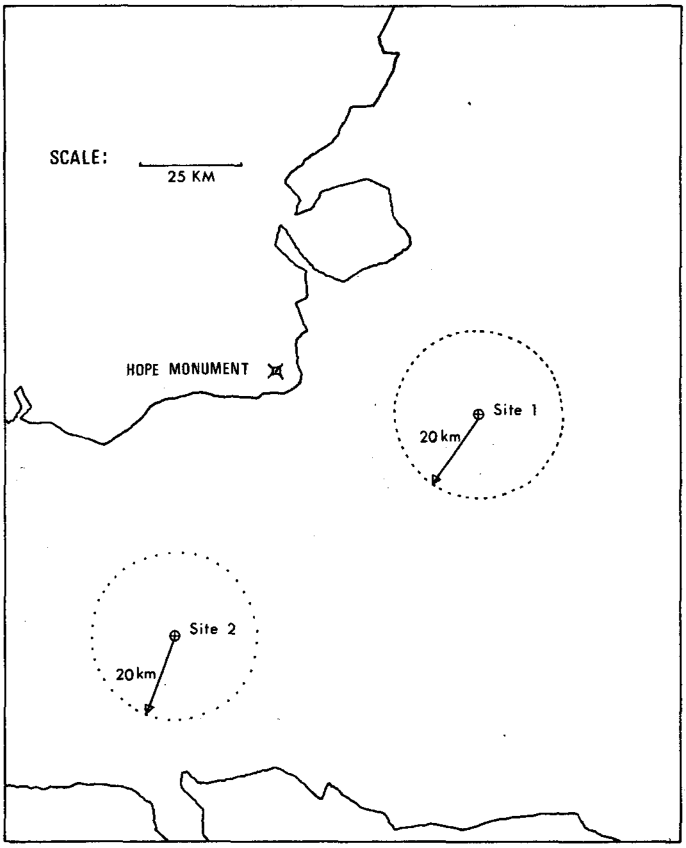

FIG. 19. The location of the two areas chosen for detailed analysis.

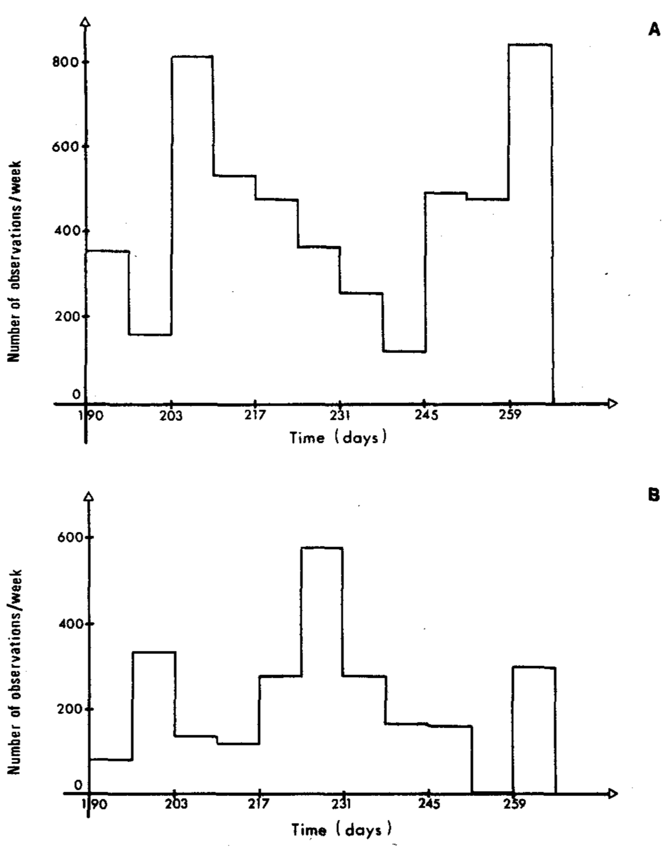

FIG. 20. The number of observations per week at each site; (A) Baffin Bay, site 1 and (B) Lancaster Sound, site 2.

A statistical analysis of the data collected within a 20-km radius of each site was done. These areas are shown in Figure 19.

Basic statistics. To obtain some level of statistical reliability in the analysis, the data were combined into sets of nominally one week in length. The number of individual observations of berg velocity and acceleration in each of the 11 data sets are shown for the Baffin Bay site in Figure 20A and for the Lancaster Sound site in Figure 20B. The average number of observations per week was 456 ± 252 for the Baffin Bay site and 222 ± 157 for the Lancaster Sound site. Because the Lancaster Sound targets were further away from the radar site, they produced weaker echoes. This may account for the differences in the above numbers. Echo strength should decrease as r^{-4} so that, if both areas had the same number and size distribution of bergs, $(63)^4/(50)^4 = 2.5$ times as many returns above minimum detectable strength should be expected at the Baffin Bay site. Although there may be a real difference in the numbers of bergs in the two areas, the observed numbers are not statistically different from the results expected on the basis of the unequal distances. At both sites there is a large variation from week to week in the number of observations. These variations follow no obvious pattern and motions at the two sites seem to be unrelated.

The number of targets seen within each area on any given day was small. A maximum of ten was seen one day at the Baffin Bay site, but the average number was lower (between one and two bergs per day).

Variations within a week. Figure 21 shows the velocity components for the mean berg motion throughout week 11 (16 to 24 September) at the Baffin Bay site. Berg velocity is dominantly to the south and west although there are large variations in both velocity components. These variations appear to have no predominant frequency. The very short period variations in the first third of the record are not due to real variations in target velocity but are an artifact of the data collecting and processing scheme. These artificial variations appear when one or more intermittent targets are present. By averaging the data over one week, any information about events happening within that week is lost but statistical problems such as the one just mentioned are averaged out and hence the result is more reliable.

To show the nature of the distribution of velocity values about their mean, a histogram of berg speeds is shown in Figure 22. These speeds come from the same data set as was used in Figure 21. The histogram is roughly symmetrical and appears to have a Gaussian shape. A Gaussian curve with the same mean and standard deviation as the histogram is also plotted on the figure for comparison. A Chi-squared goodness-of-fit test with 22 degrees of freedom indicates that the histogram is indeed normally distributed at the .995 level of significance. This goodness of fit indicates that it is statistically meaningful to use the mean and standard deviation as descriptors of the data sets.

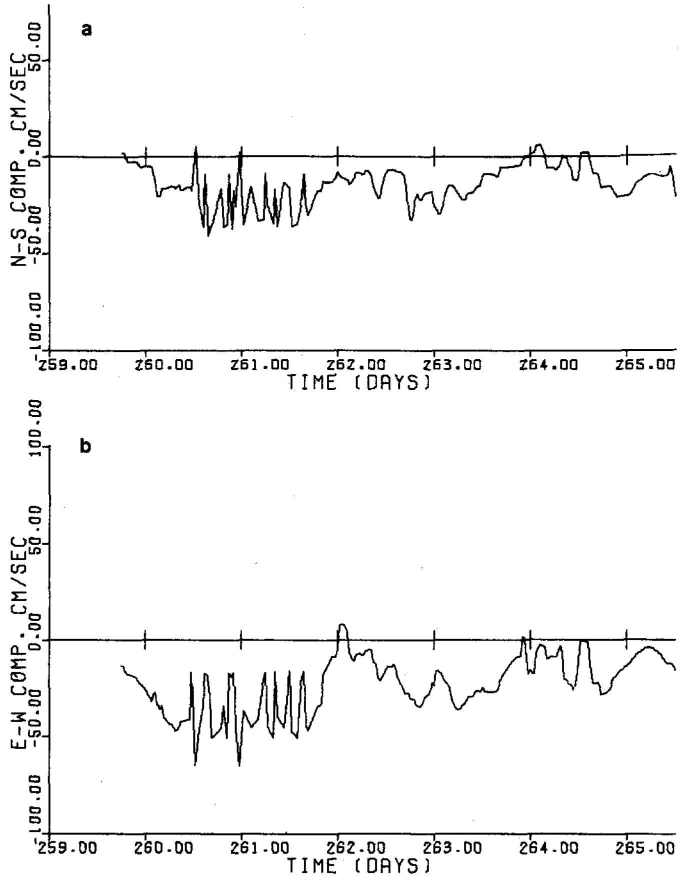

FIG. 21. Time series plot of the mean iceberg velocity components for week 11 (16 to 24 September), at the Baffin Bay site.

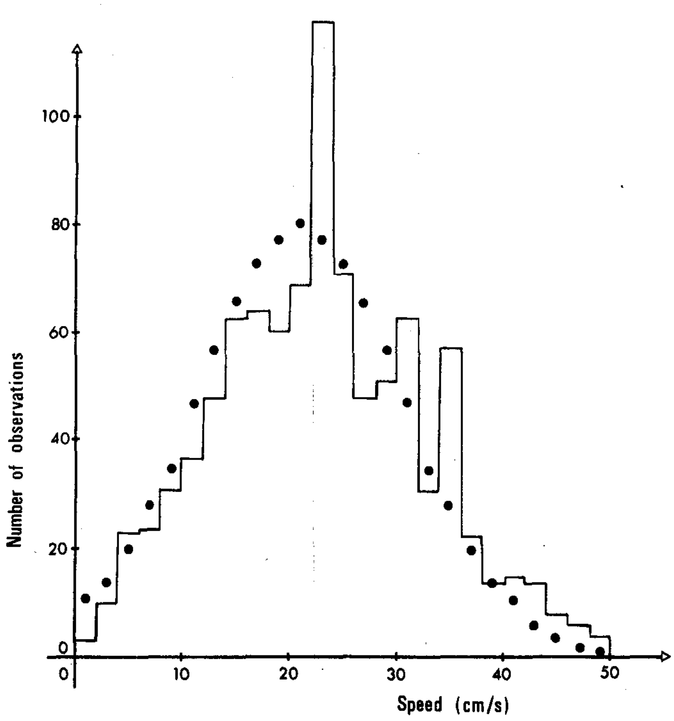

FIG. 22. Speed histogram for the Baffin Bay site for week 11 (16 to 24 September). The dots outline the fitted Gaussian curve.

Weekly analysis at the Baffin Bay site. The statistical results from the weekly analysis at the Baffin Bay site are summarized in Table 1. The first two columns show the magnitude and direction of the mean velocity vector for the week. These numbers indicate the mean iceberg displacement per second and the direction of that displacement in the week. The next column gives the mean target speed. This number, which is always equal to or greater than the magnitude of the mean velocity is proportional to the mean berg momentum for the week. The error (± one S.D.) gives some indication of the variability of the strength of the motion. The mean direction of berg motion for the week is not mathematically the same as the direction of the mean velocity, but in practice the two have essentially the same value. To put the size of the angular standard deviation in the proper perspective it should be noted that the standard deviation of a uniform distribution of angles is 104°. Therefore any deviations of approximately this size or greater must be taken to indicate that no angular information may be obtained from the data.

Table 1 also includes information on the mean berg acceleration magnitude and direction. The acceleration is a measure of the influence of external forces on the berg and in this study indicates the effects of wind or changing water currents. Because the exact shapes of the bergs are not known, the acceleration cannot be related directly to the forcing, but the general tendencies of the acceleration sometimes yield useful information.

Velocity and speed information is also presented graphically in Figure 23. Detailed histograms of velocity and acceleration are given for each week in Appendix C.

The mean direction of the velocity was fairly consistently to the west throughout the observation period, but there were large variations in the magnitude of the velocity. The mean speed and velocity peaked in weeks 2, 6 and 11. During these weeks the average direction tended to be more southerly than in the weeks of lesser mean speed. At Cape Sherard, weeks 2 and 6 contained extended periods of strong northeasterly winds. Wind data are not available from Cape Sherard for week 10 and the first part of week

TABLE 1. Baffin Bay site weekly average iceberg statistics

	Velocity				Acceleration	
Week	Magnitude cm s^{-1}	Direction °T	Speed cm s^{-1}	Direction °T	Magnitude 10^{-3}cm s^{-2}	Direction °T
1	14.0	253	16.1 ± 9.1	248 ± 34	0.70 ± 0.45	230 ± 102
2	20.2	261	21.3 ± 6.2	261 ± 18	0.58 ± 0.31	195 ± 104
3	5.9	272	9.2 ± 6.5	287 ± 77	0.54 ± 0.20	281 ± 93
4	9.9	293	12.2 ± 5.8	294 ± 43	0.70 ± 0.43	204 ± 102
5	3.0	340	9.2 ± 6.7	034 ± 103	0.57 ± 0.29	141 ± 104
6	20.7	247	23.1 ± 6.0	247 ± 27	0.90 ± 0.78	279 ± 86
7	9.4	254	13.9 ± 7.9	254 ± 47	0.99 ± 0.90	003 ± 86
8	13.0	266	14.6 ± 11.0	269 ± 32	0.80 ± 0.85	021 ± 99
9	8.5	269	10.8 ± 5.4	265 ± 56	0.60 ± 0.29	182 ± 100
10	8.5	246	13.7 ± 9.1	257 ± 61	0.98 ± 0.61	030 ± 101
11	22.2	217	24.2 ± 9.4	215 ± 29	0.96 ± 0.69	089 ± 112

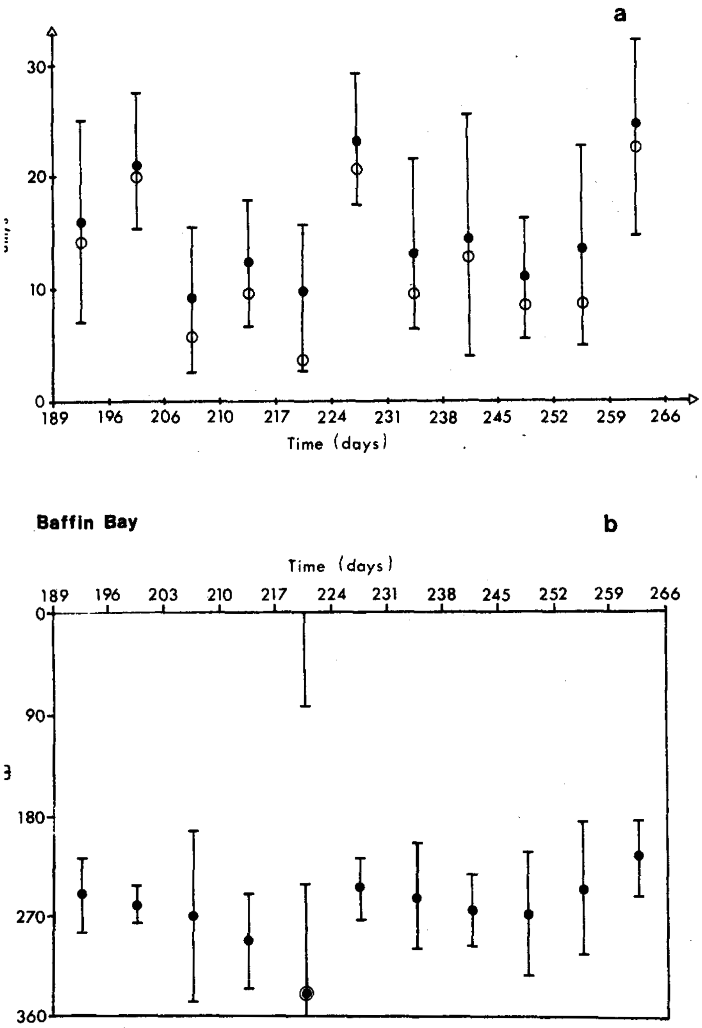

FIG. 23. Weekly mean iceberg speed and direction for the Baffin Bay site. (a) Solid circles are the mean speed, open circles are the mean velocity magnitude and the error bars are ± one standard deviation about the mean speed. (b) mean direction, error bars are ± one standard deviation about the mean direction and a circle about the mean indicates it to be statistically indeterminate.

TABLE 2. Lancaster Sound site weekly average iceberg statistics

	Velocity				Acceleration	
Week	Magnitude cm s^{-1}	Direction °T	Speed cm s^{-1}	Direction °T	Magnitude 10^{-3}cm s^{-2}	Direction °T
1	16.1	251	17.5 ± 7.4	243 ± 26	0.91 ± 0.70	111 ± 128
2	8.1	179	13.6 ± 8.8	190 ± 73	0.71 ± 0.49	068 ± 110
3	9.4	333	14.0 ± 5.3	334 ± 55	1.16 ± 0.95	248 ± 97
4	11.3	258	15.7 ± 12.2	268 ± 45	0.66 ± 0.37	335 ± 71
5	7.8	91	14.4 ± 13.3	094 ± 111	0.99 ± 0.92	047 ± 95
6	9.8	120	27.0 ± 12.1	139 ± 120	1.75 ± 1.45	297 ± 95
7	1.7	114	12.5 ± 9.7	129 ± 114	1.33 ± 1.59	070 ± 113
8	6.5	345	20.1 ± 10.9	340 ± 73	3.32 ± 1.66	103 ± 112
9	38.2	168	45.4 ± 17.5	174 ± 59	0.73 ± 0.47	012 ± 68
10	—	—	—	—	—	—
11	6.3	141	20.9 ± 12.5	181 ± 109	1.44 ± 1.16	303 ± 87

11, but data from Hope Monument indicated strong winds in the latter part of that period and records from the M/V *Theron* indicate that the wind was from the northwest, although the wind directions may be distorted by topography. Strong winds from that direction may have had an effect on the bergs in the central site region similar to that of the northeasterlies of weeks 2 and 6. Thus it appears that strong winds from the northern quadrant increase berg speed and deflect their paths slightly to the south of the mean flow of bergs.

The only extended period of westerlies was in week 5. These winds should be expected to counteract the westward currents and decrease berg velocities. The data show that the week 5 mean target velocity and speed are the smallest and that the standard deviation of the direction is over 100°, indicating that the direction is indeterminate.

The acceleration statistics show no variations in magnitude related to the changes in wind forcing and the directions are essentially random. Examination of the acceleration histograms (in Appendix C) reveals, however, that in weeks 2 and 6 the strongest accelerations are in the westerly direction, indicative of forcing from the eastern quadrant. This is consistent with the northeasterly winds of those weeks.

Winds in weeks 7 and 9 were very weak. Berg velocities in both weeks were similar in magnitude, direction and direction spread. This velocity is likely representative of the mean iceberg field in the vicinity of the Baffin Bay site, under conditions of either no wind or light winds.

Weekly analysis at the Lancaster Sound site. An identical statistical analysis was carried out on the data collected within 20 km of the Lancaster Sound site. The results are summarized in Table 2 and the velocity results are plotted in Figure 24. Appendix D contains the detailed histograms for this site. No targets were recorded passing through this area during week 10 (days 252-259).

The general picture these data present is one of much greater directional variability than at the Baffin Bay site. The direction, in the six weeks that it may be considered non-random, ranges from south to northwest in no discernible pattern.

Direct wind influence on the mean berg motions at this site is not obvious. There is a peak in speed in week 6 as there was at the Baffin Bay site, which may be related to the strong northeasterly winds, but the major peak, in week 9, occurred under weak wind conditions similar to those of week 7, when the mean speed was much smaller. There are several possible reasons for this behaviour. The most likely cause of the high variability is that the site is in a region of rather complex and variable currents as discussed earlier. Another is that the winds in Lancaster Sound may bear little resemblance to those measured at Cape Sherard. This hypothesis seems unlikely because the scale of weather systems is much greater than the separation between the locations, both of which are rela-

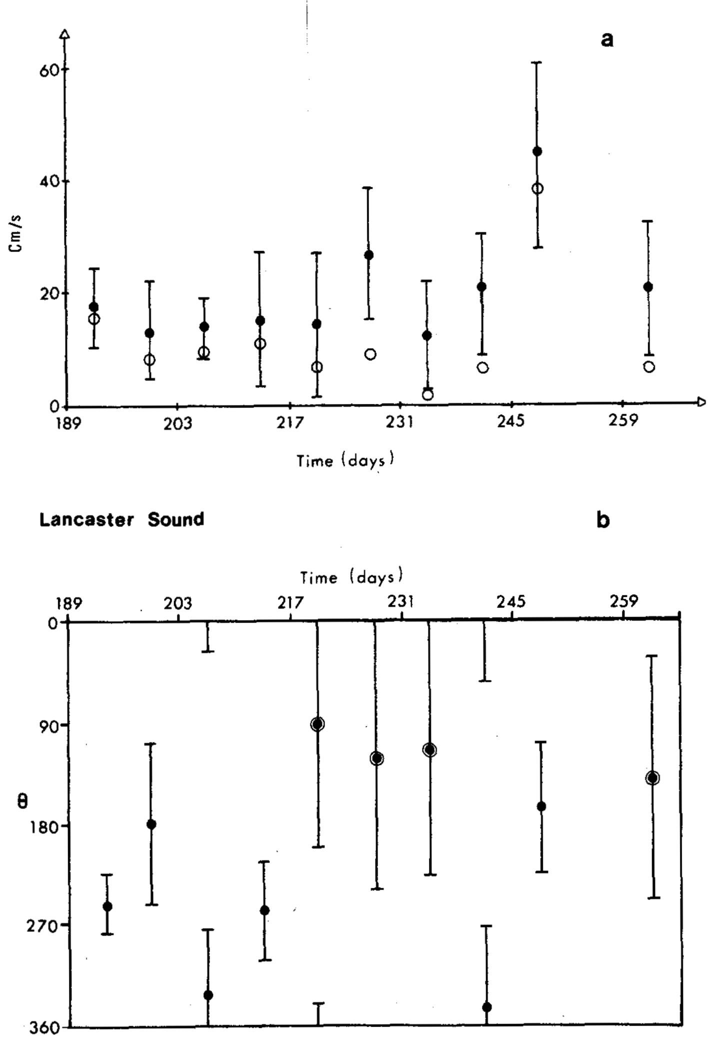

FIG. 24. Weekly mean iceberg speed (a) and direction (b) for the Lancaster Sound site; plotted as in the previous figure.

tively unshielded. A further hypothesis is that the number of targets tracked was so small that the sample size was statistically inadequate. However, the number of data points was generally more than 100 per week, although the Lancaster Sound site had about half the number of data points observed in Baffin Bay. This difference in numbers does not appear to be great enough to account for the apparent difference in wind effects.

The acceleration results calculated from the data do not represent only the time rate of change of velocity $\partial \mathbf{v}/\partial t$ but the total derivative $D\mathbf{v}/Dt = \partial \mathbf{v}/\partial t + \mathbf{v}\cdot(\partial \mathbf{v}/\partial \mathbf{x})$. Hence the passage of a berg through a region of velocity gradient will be marked by an increase in the magnitude of the acceleration of the berg. That the current gradients are stronger near the Lancaster Sound site than near the Baffin Bay site is implied by the fact that the magnitude of the mean acceleration at the Lancaster Sound site is about twice that at the Baffin Bay site. The magnitude of the accelerations at the Baffin Bay site appears to be less variable than at the Lancaster Sound site. This observation indicates that the features driving the ice motions are more constant, at least on the time scale of a week. Hence wind effects are more likely to be masked at the Lancaster Sound site. The directions of the mean accelerations at this site have an approximate mean of north, showing that the bergs should, in general, slow down as they move south. Such a slowing down is not obvious in the square average plots, but can be seen upon closer examination.

SUMMARY

Analysis of 11 weeks of data has shown that there is a well-defined mean circulation of icebergs in northwestern Baffin Bay and eastern Lancaster Sound within about 74 km of Cape Sherard. The dominant feature of this circulation is a strong stream of bergs moving south at about 40 cm s^{-1} from Philpots Island along the shore of Devon Island to Cape Sherard. At Cape Sherard the stream accelerates slightly and turns westward to Cape Warrender. Near Cape Warrender the stream turns south and moves either southwestward or southeastward into an eastward current along the southern half of Lancaster Sound. Outside this stream in Baffin Bay, the flow of bergs is slower and westward into the main stream. In Lancaster Sound, the flow is dominated by two persistent eddies: one, counterclockwise between Cape Sherard and Cape Warrender; and one, clockwise in the mouth of the sound. Between the two eddies is a weak current northward towards Cape Sherard.

Both diurnal and semi-diurnal oscillations were seen in the velocity components of the bergs. These oscillations are likely to be both tidal and inertial in nature. Longer term oscillations were also observed. In Baffin Bay, these oscillations appear to be related to changes in the wind, but in Lancaster Sound, no such relationship was seen. The difference in behaviour is due to the difference in strength of velocity gradients in the two areas. Changes in wind cause changes in berg velocity in both areas, but in Lancaster Sound these velocity changes are overwhelmed by the changes due to the strong spatial velocity gradients. These velocity gradients can be attributed, in part, to the presence of large-scale eddies or gyres in the region.

The greatest iceberg concentrations were found in the Devon Island coastal stream, i.e. in a region about 30 km wide between Philpots Island to Cape Warrender. East of this area in Baffin Bay there were significantly fewer bergs. Because numerous bergs which enter Lancaster Sound in the coastal stream seem to return to Baffin Bay via the southern half of Lancaster Sound, the number of bergs was relatively high in this region as well. Due to the eddy-like structure of the flow field in Lancaster Sound the relative proportion of bergs at any location cannot be predicted. During the course of the field season the number of icebergs increased slowly. Only three definite pulses of increased iceberg counts were observed.

Detailed analyses were made of data collected within a 20-km-radius circle of two selected sites. Ice motions at both of the sites had a Gaussian distribution when averaged over a one-week period. At the Baffin Bay site the mean ice velocity was about 12 cm s^{-1} to the west. The mean speed was increased by northeasterly winds and decreased by westerlies. Northeasterly winds also shifted the direction of motion slightly toward the south. Although there was some spread in the magnitude of velocity about the mean, the direction was relatively stable. Values of acceleration were small and indeterminate in direction. This site lies in a region of Baffin Bay outside the main stream along the Devon Island coast, hence not as many bergs pass through it as through regions to the north and west of the site. On any given day, between zero and 10 targets were recorded, but the average number was only two, about one-third of the total in similar regions to the north and west.

The Lancaster Sound site presents an altogether different picture. The mean berg speeds were higher (about 20 cm s^{-1}) and were unpredictable in direction. No significant correlation between berg velocity and wind was found. The acceleration results indicated a decrease in the southward component of berg movement. This site is in the general region of southward flow from Cape Warrender towards Navy Board Inlet. The exact location of this southward flow, however, varies greatly, and often the site is out of the flow. The region to the east of this flow contains very large, energetic eddy motions. The Lancaster Sound site is sometimes in this region. Thus the variability in berg velocity at the site is governed mainly by the variability of the current field in eastern Lancaster Sound, and hence is not easily predictable. The number of bergs passing this site will likely be greater than at the Baffin Bay site because the region of southward flow between Cape Warrender and Navy Board Inlet contains virtually all of the ice that enters Lancaster Sound in the Devon Island coastal stream. The smaller number of targets recorded in this area as compared to the Baffin Bay area is due to the fall-off with distance of the strength of radar echoes, not a smaller actual number of targets.

ACKNOWLEDGEMENTS

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