NEARSHORE ICE CONDITIONS FROM RADAR DATA, POINT BARROW AREA, ALASKA

by

Lewis H. Shapiro and Ronald C. Metzner
Geophysical Institute, University of Alaska Fairbanks
Fairbanks, Alaska 99775-0800

Supported by

Alaska Sea Grant Program
MMS/NOAA ALASKA OCSEAP PROGRAM

Geophysical Institute
University of Alaska Fairbanks
Fairbanks, Alaska 99775-0800

July 1989

Geophysical Institute Report
UAG-R(312)

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ABSTRACT

From June, 1973 to May, 1979, the University of Alaska maintained a small radar system to monitor near shore ice motion and conditions at the Naval Arctic Research Laboratory near Point Barrow, Alaska. The purpose was to support research projects which required that information. In this report, the data acquired are compiled to describe the annual cycle of the ice year in the area. A short open water season can be defined as extending from late-July to late-September. This is followed by freezeup, which is characterized by a decreasing frequency of occurrence of drifting pack ice in the area between October and January. The winter season extends from January through May and is marked by generally stable or slow-drifting pack ice, or by the absence of pack ice offshore from the edge of the fast ice. The onset of breakup in June is characterized by the increasing occurrence of drifting pack ice again. Comparison of the ice cycle with climatologic data indicates no strong correlations with variables other than (possibly) air temperature. As expected, ice activity is greatest during freezeup and breakup, with rapid changes in the directions and velocity of ice motion. Similar movement patterns occur in winter, but the ice velocities are slower. Data of the type generated by the radar system would be useful for any area in which development of offshore installations is planned. Clearly, a knowledge of the range of possible ice motion patterns and events can provide the basis for improving the design of such installations.

ACKNOWLEDGEMENTS

The radar system used in this study was purchased and operated for the first two years with funds provided by the Alaska Sea Grant Program and the Alaska Oil and Gas Association. For the remainder of the time it was in place, the operation and maintenance of the system, as well as preliminary scanning of the data, were funded by the Minerals Management Survey, Department of Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program. The organization and analysis of the data leading to the results presented here were funded by the Alaska Sea Grant Program and the State of Alaska.

Many individuals contributed to doing the tasks required by the system. Drs. W. Sackinger and J. Rogers were the Principal Investigators on the program through which the radar system was acquired and installed. Dr. T. Hanley operated the system while doing other field work at NARL during the first winter of operation. Various members of the staff of NARL provided assistance by changing the film used to record the data and doing minor maintenance during the times that the Principal Investigators were not at the site. The major task of scanning the data and describing the nature of the ice motion recorded was done primarily by T. McClung.

1.0 INTRODUCTION

From June, 1973 to May, 1979, the University of Alaska operated a radar system along the Chukchi Sea Coast at the Naval Arctic Research Laboratory (NARL) approximately 5 km north of Barrow, Alaska (Figure 1). During most of this time, the radar was intended to be used to support various research projects in the area by monitoring local ice conditions and events. However, efforts were made to operate the system all through the year so that during the period which it was in place, a significant record of local ice conditions and events was obtained. The purpose of this report is to present a synthesis of these observations in the form of a generalized annual ice cycle at Barrow, along with brief descriptions of events and processes to which the radar observations contributed information. Although the data are limited to this particular area, the results may serve as a model for the range of ice conditions which might be encountered elsewhere, particularly along the Chukchi Sea coast of Alaska. In any case, they emphasize the utility of data from monitoring of ice conditions in any area prior to the planning and development of offshore installations. Clearly, a knowledge of the range of possible ice motion patterns and events can provide the basis for improving the design of such installations.

2.0 EQUIPMENT AND METHODS

2.1 RADAR SYSTEM AND DATA RECORDING

The radar system used was a 3 cm X-band standard ships radar of a the type which would normally be installed on a small fishing vessel (Sackinger and Rogers, 1974). It was mounted on a tower on the beach at an elevation of about 12 m, which should give a maximum range of about 15-17 km (8-9 NM, based on the rule-of-thumb that the range of the radar in miles is approximately equal to the square root of twice the height of the antenna in feet). However, the radar was usually operated at a range of 5.6 km (3 NM) (Figure 1) because no man-made reflectors were deployed on the ice, and this distance proved to be nearly the maximum range from which energy was returned from a sufficient number of natural reflectors for the ice motion to be monitored by tracking "blips" on the radar screen. A discussion of the nature of the reflectors is given in Section 2.3 below.

The radar data were displayed on a screen which was photographed (usually at 2.5 minute intervals) as time-lapse motion pictures using a 35 mm camera driven by a timing mechanism. A clock face was included in the picture to give the date and time of the image (Figure 2). For 2.5 minute intervals between pictures, a standard roll of film lasted up to 4 days. Generally, film was developed and examined within 2-3 weeks following exposure so that it was possible (in some cases) to "ground truth" the imagery.

The choice of a 35 mm camera for recording the data was dictated by budget considerations; a 35 mm camera was available and the cost of acquiring similar 16 mm equipment (with the time-lapse capability) was too great for available funds. This was unfortunate because, while the 35 mm camera provided data of excellent quality, there was no commercially available equipment (such as analyzer projectors, which were available in 16 mm) with which to analyze 35 mm film. Accordingly, a viewing system was constructed with which the 35 mm film could be scanned so that ice conditions and motion could be characterized qualitatively. However, the resolution and clarity of the system were poor and the images did not register repeatedly on the viewing screen. This prevented the equipment from being used for detailed work, such as measuring the displacement and velocity vectors of the ice cover (by tracking the positions of identifiable reflectors on successive frames, as described below) or providing details of the sequence of events in development of the ice cover. For these studies, rolls of film in which events or sequences of interest appeared were reproduced on 16 mm film, for which an analyzer projector was

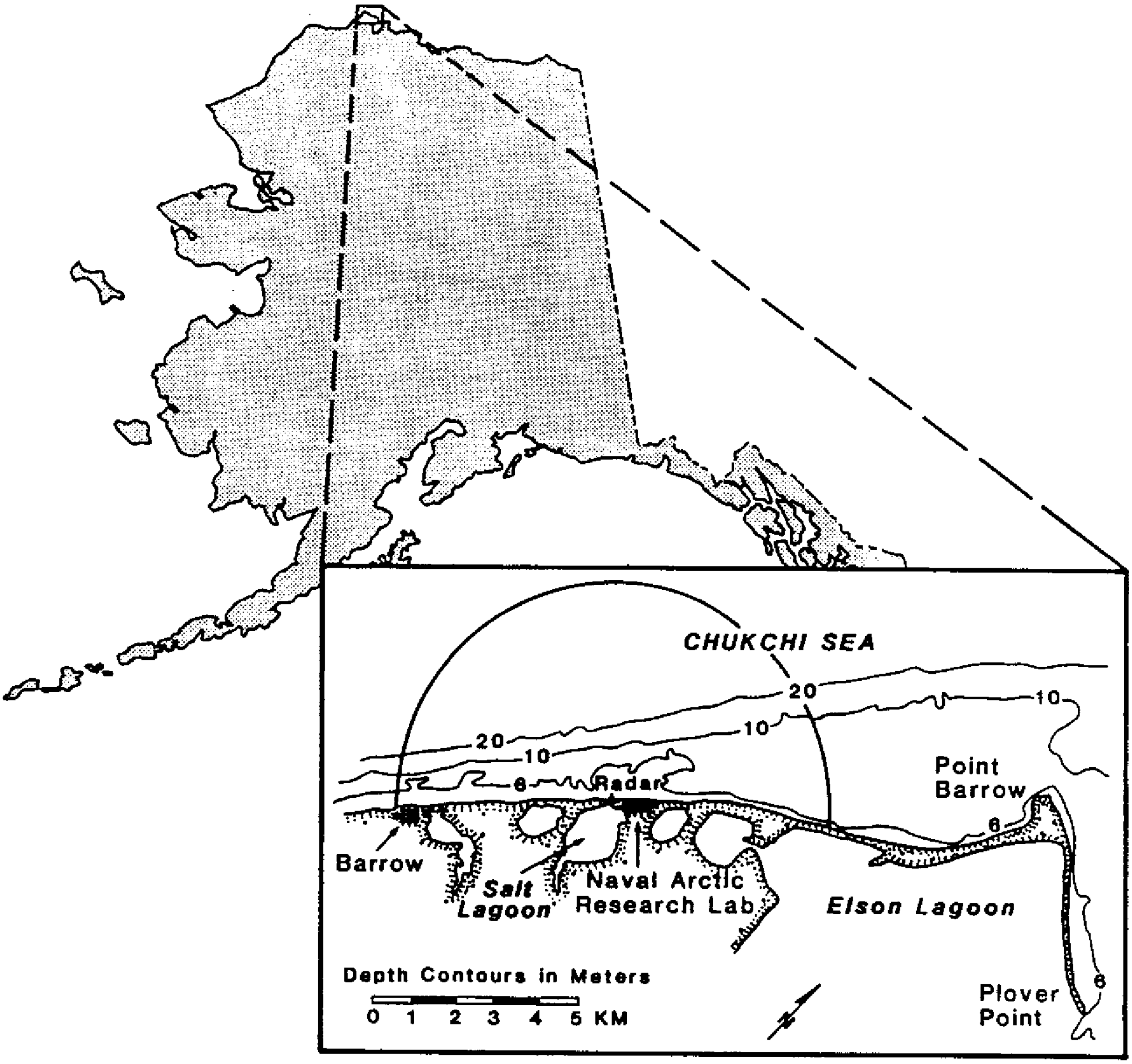

Figure 1. Map of the Point Barrow area showing the location of the radar site.

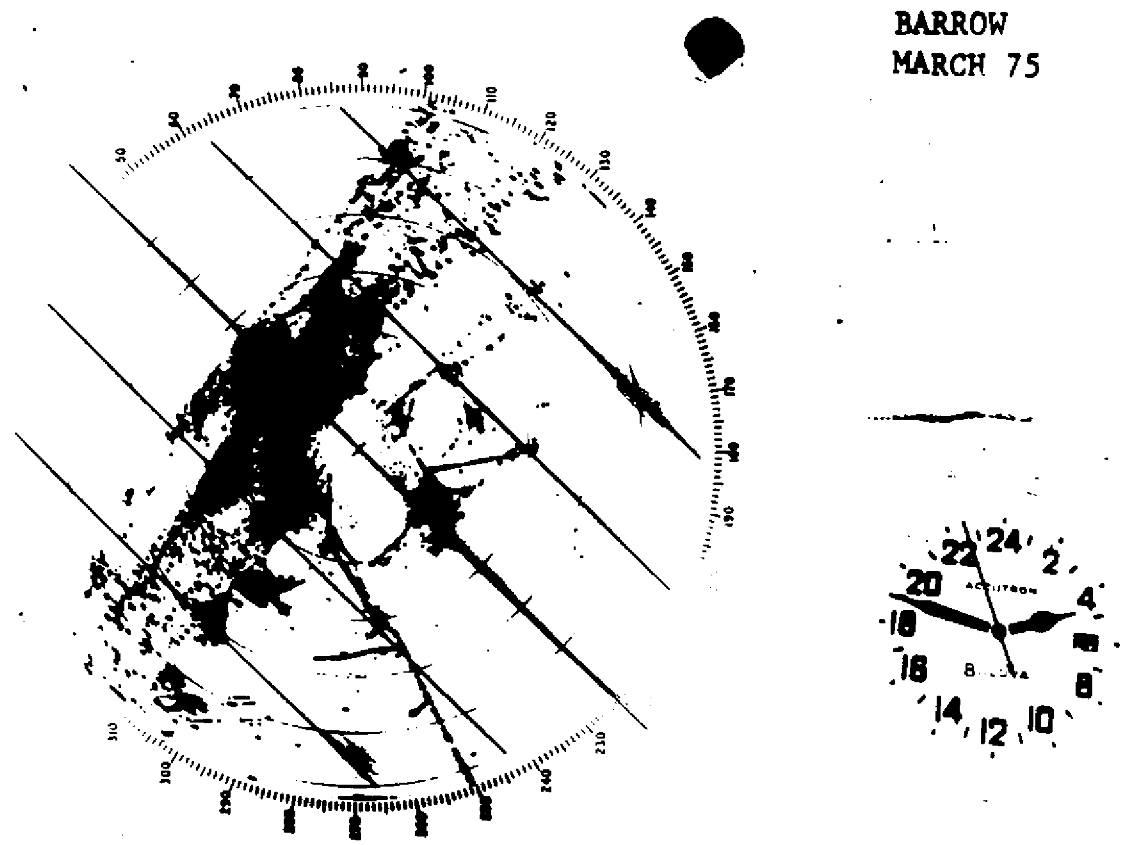

Figure 2. Typical frame of radar data at 5.5 km (3 NM) range.

available. Most of the analysis was done using this equipment. If detailed information was required from a short sequence of frames, the 35 mm data were enlarged to 70 mm and studied on a color additive viewer with which accurate registration could be done. However, the time required to work with the data in this format was prohibitive, and it was not used as often as would have been desirable.

2.2 DATA ANALYSIS

A total of 387 rolls of film were used, representing 1550 days, or 71% of the total days that the radar was in place. Table 1 shows the percentage of possible days of each month for which data were obtained. These range from a low of 38% of all possible days for January to a high of 75% of possible days for May. Unfortunately, the sample is weakest for the late-Summer and Fall, so that relatively little imagery was obtained during the critical freezeup period. Still, the data range over the entire year and provide the basis for a preliminary characterization of the variation in ice conditions in the area through a calendar year, as described below.

The individual film rolls cover periods from 1 to 12 days, although the majority are in the range of 3 to 4 days per roll. Most of the shorter rolls of film were acquired during the first few months of the program when the system was not in continuous operation. At that time, it was run for 1 or 2 days, and then shut down for about the same time interval. The longer rolls of film represent only the last few months of data (Spring, 1979) when only minor movements occurred.

Because of limitations of both time and equipment, the data were characterized by film roll, rather than by time interval. Each film was scanned and ice conditions and the direction of ice motion (if any) were noted. Unusual events, such as pack ice being driven into contact with, or drawing offshore from, the fast ice were also recorded. Simple counts of occurrences of ice motion in various directions, stationary ice, or no ice per film roll are presented in Table 2.

TABLE 1

TOTAL DAYS OF RADAR COVERAGE BY MONTH AND YEAR

Month	1973	1974	1975	1976	1977	1978	1979	days	%
Jan	--	31	0	12	16	9	23	91	49
Feb	--	29	0	24	27	29	6	115	68
Mar	--	31	26	23	26	30	12	150	81
Apr	--	30	22	30	28	30	30	171	95
May	--	31	31	31	31	25	26	175	94
Jun	27	30	24	30	26	12	--	149	83
Jul	31	30	31	28	13	31	--	164	88
Aug	23	30	29	30	0	1	--	113	61
Sep	22	21	30	21	0	0	--	94	52
Oct	0	21	27	31	7	10	--	96	52
Nov	2	10	30	30	22	26	--	120	67
Dec	24	0	28	20	31	2	--	105	56

TABLE 2
ICE DRIFT DIRECTIONS BY MONTH(1)
Drift Direction

Month	Total Films(2)	Northeast	Southwest	In(3)	Out(3)	Reversal	No Drift (4)	No Ice
Jan	25	4	10	4	4	2	13	0
Feb	29	4	4	2	1	0	21	0
Mar	35	5	7	3	4	2	25	0
Apr	43	3	7	4	7	2	35	0
May	42	7	5	3	3	2	32	0
Jun	38	15	2	6	5	1	22	0
Jul	35	18	13	9	11	5	7	2
Aug	24	18	6	5	4	6	1	5
Sep	21	13	5	2	3	4	0	7
Oct	18	7	12	2	4	2	0	1
Nov	30	11	14	8	11	5	10	0
Dec	26	4	6	7	9	0	16	0

(1) Numbers in each category give the number of films on which pack ice displacement occurred in the direction indicated.
(2) Modified number of films; see text for discussion.
(3) Headings "In" and "Out" refer to onshore and offshore (respectively) displacements of pack ice at a high angle to the coast or edge of the fast ice.
(4) Fast ice alone or fast ice and stationary pack ice.

In preparing the data for presentation in the table, rolls of film covering 1 or 2 days (often with a day of no data between them) were combined and counted as a single roll of film. Similarly, rolls of film representing more than 8 days were counted as two rolls of film. The purpose of handling the data in this manner was simply to put the data into a form in which the rolls of film counted in Table 2 are representative of the typical 3 to 4 days that most of the film occur. As a result, the number of films listed in Table 2 is reduced to 362 from the actual number of 387.

In the table, the categories of "no ice" or "no drift" imply that ice was absent, or present but stationary for the duration of the time covered by a film roll. Drift directions are recorded as (to the) northeast or (to the) southwest without connotation as to the duration of the movement. Cases in which the sense of motion reversed on a film are counted as "reversal;" a reversal contributes one count to the ice motion in each direction. Movements "in" or "out" refer to pack ice entering or leaving the field of view of the radar at a relatively high angle to the fast ice edge. These events were also counted as ice movement to the northeast or southwest depending upon the sense in which the ice entered or left the area.

It is clear that the data in Table 2 should be taken as being qualitative, rather than quantitative. However, for the sake of discussion it will be assumed that the data provide a reasonable estimate of the frequency of occurrence of the conditions and events indicated in the table. The distribution of the data in time and the length of time over which the system operated (see Table 1) suggests that the data run may be sufficiently long for the assumption to be valid, although additional work would be required to confirm this.

2.3 REFLECTORS

In general the intensity of the energy return from reflectors on the ice surface decreased with increasing distance from the radar. Thus, low ridges, hummocks or discrete floes of multiyear ice at short ranges gave strong reflections, while similar or larger features at a distance gave weaker returns. Exceptions did occur which were probably due to variations in the orientation of reflecting surfaces on the features.

Attempts to determine the nature of the actual reflecting surfaces and their relationship to the intensity of energy return (as shown by the diameter of the blip produced on the radar screen) were unsuccessful because it was not possible to identify individual reflecting surfaces. However, it was often (but not always) possible to identify a specific floe or ridge as the source of energy for a particular blip shown on the imagery. In this context, it should be noted that the fact that an ice feature was prominent did not ensure that it would return sufficient energy to produce a prominent signature on the radar screen. As an example, in one instance, a large grounded ridge (sail height in excess of 10 m) located 1.5 km offshore from the radar site was invisible to the radar, although a smaller ridge about 100 m to the southwest gave a strong reflection. Apparently, there was no surface on the larger ridge which was suitably oriented to reflect energy back to the radar antenna. In addition, small features were often observed at greater distances from the radar. For example, reflectors defining the outlines of individual floes of thin ice in early-Fall could often be identified at the limit of the field of view of the radar. These reflectors were probably surfaces in low (less than 1 m high) ridges or hummocks formed during impacts between floes. Thus, there is no basis for associating the intensity of a reflector with the size of the feature which produced it.

The number of reflectors visible on the radar screen was always sufficient to permit the distribution and motion of the ice to be determined in the entire field of view when the radar system was operated at a range of 5.6 km (3 NM) or less. In addition, linear alignments of reflectors representing shear ridges within the fast ice were usually easy to identify. Once in place following freezeup, the features of the fast ice remained stationary until breakup. Thus, it was always possible to separate fast ice and pack ice on the imagery, because the distribution of reflectors on the fast ice did not change through the winter.

The smallest blips which could be discriminated on the data [at 5.6 km (3 NM) scan] had diameters of about 40 m at the scale of the imagery. Clearly, the actual sizes of the reflectors on the ice surface were smaller; the enlarged scale of the blips results from the dispersion of the returned radar energy. The effect of the sizes of the blips on the lower limit of the ice displacement which could be detected is discussed in Section 2.4.

It would have been desirable to determine the effect of changes in distribution and thickness of the snow cover on the character of the reflectors through the winter. However, this was not possible because of the need to adjust the gain on the radar system periodically which had the effect of changing the intensity of the reflectors.

2.4 DISCRIMINATION AND MEASUREMENT OF ICE MOTION

Ice velocity measurements were made by tracking individual reflectors on sequential frames of the film. The scale of the imagery was provided by the range lines (Figure 2) and the time by the clock (or by simply counting frames of film, since the time interval between exposures was always known). In making velocity measurements it was always possible to track the motion of reflectors over at least 1.5-2 km. At the velocities measured, this took sufficient time that the measurements are believed to be accurate to within 0.1 km/hr, so that velocities reported below are given to this precision.

Ridging events were shown by the formation of lines of reflectors. It was usually possible to identify the exact frame on which a particular reflector on a ridge line appeared, so that the time required for development of a ridge could be determined. An example of the use of this type of data in describing the process of development of the fast ice cover is given in Shapiro (1975a).

It was simple to detect pack ice motion when the data were viewed as time-lapse motion pictures because, even when the movements were slow, the displacements eventually became large enough to be obvious. Smaller displacements of the fast ice were also easy to detect if they occurred rapidly; the apparent "jump" of all of the reflectors in the fast ice was obvious. However, small displacements of the fast ice at low rates were never observed on the radar data although, as described in Section 4.4, at least two examples of such movements did occur during the time the radar system was operating. There is no quantitative basis for defining a lower limit of the magnitude of displacement of the ice which could be detected. However, experience suggests that displacement of a blip by about one-half its diameter (i.e., 20 m for the smallest detectable blip) should be apparent. Thus, this is assumed to be the approximate lower limit of detectable displacement within the fast ice.

As noted above, a color additive viewer was also used in the interpretation of the data. An example of the results of this type of analysis is given in Shapiro and Barnes (in preparation) and is illustrated in Figure 3 which shows the displacement vectors of the fast ice during an ice push event which occurred in July, 1975, superimposed on a map of ice gouges in the sea floor.

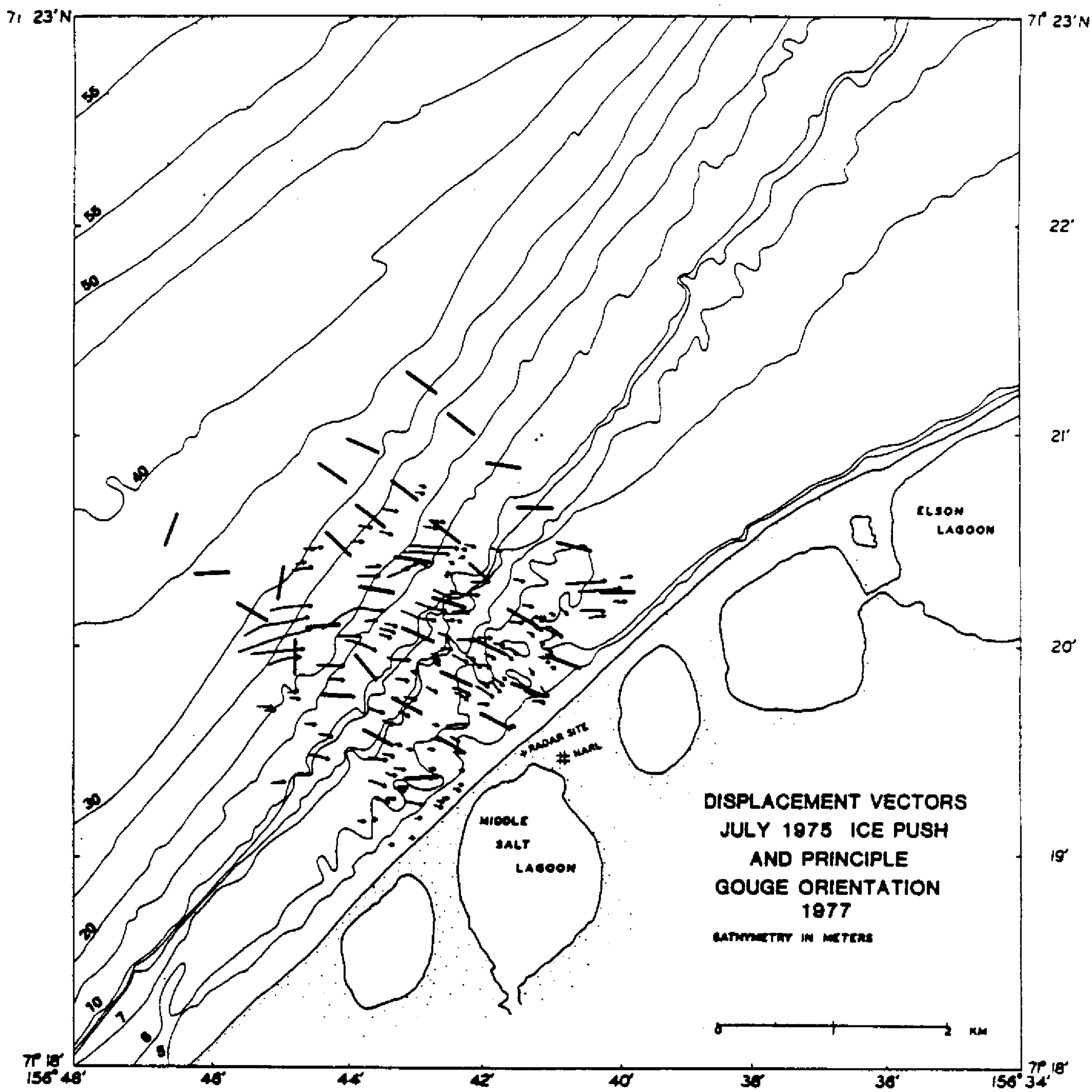

Figure 3. Displacement vectors from an ice push event in July, 1975, superimposed on principal ice gouge orientations mapped by side-scan sonar in August, 1977 (from Shapiro and Barnes, in preparation).

3.0 CHARACTERISTIC ICE MOVEMENT PATTERNS

3.1 INTRODUCTION

No weather or current monitoring equipment was deployed as part of this project at any time during the operation of the radar system. Local weather data were acquired from the NWS station at Barrow and from the NOAA air monitoring station northeast of NARL for use in interpreting the motion during some events which were observed in the field (i.e., ice push events, lead formation, etc.). In addition, satellite imagery of the area and regional weather charts were examined regularly. As a result, various qualitative "rules-of-thumb" were developed for interpreting the local patterns of ice distribution and motion. The rules are based primarily on the assumption that pack ice tends to drift at about 30° to the right of the wind direction under "average" conditions (Whitman and McDowell, 1964). However, the actual movement patterns also reflect the shape of the coastline in the area, the topography of the sea floor (which controls the positions of grounded ice ridges within the fast ice), and the local tides and ocean currents. These factors introduce enough variation and complication into the patterns that it was never feasible to try to develop quantitative models relating ice motion to driving forces.

3.2 GENERALIZED DRIFT PATTERNS

The relationship between the orientation of the coastline and wind and ice drift directions (based on the rule-of-thumb given above) are shown in Figure 4. Details are discussed in Section 4.6. The purpose here is to describe, in general, the basic movement patterns which were observed.

The orientation of the coastline requires that most of the observed ice motion in the area (in terms of the duration of observations) be to the northeast or southwest since these provide the longest path lengths within the radar field of view. Clearly, ice drifting at a high-angle to the coast will be in view for only limited times before it

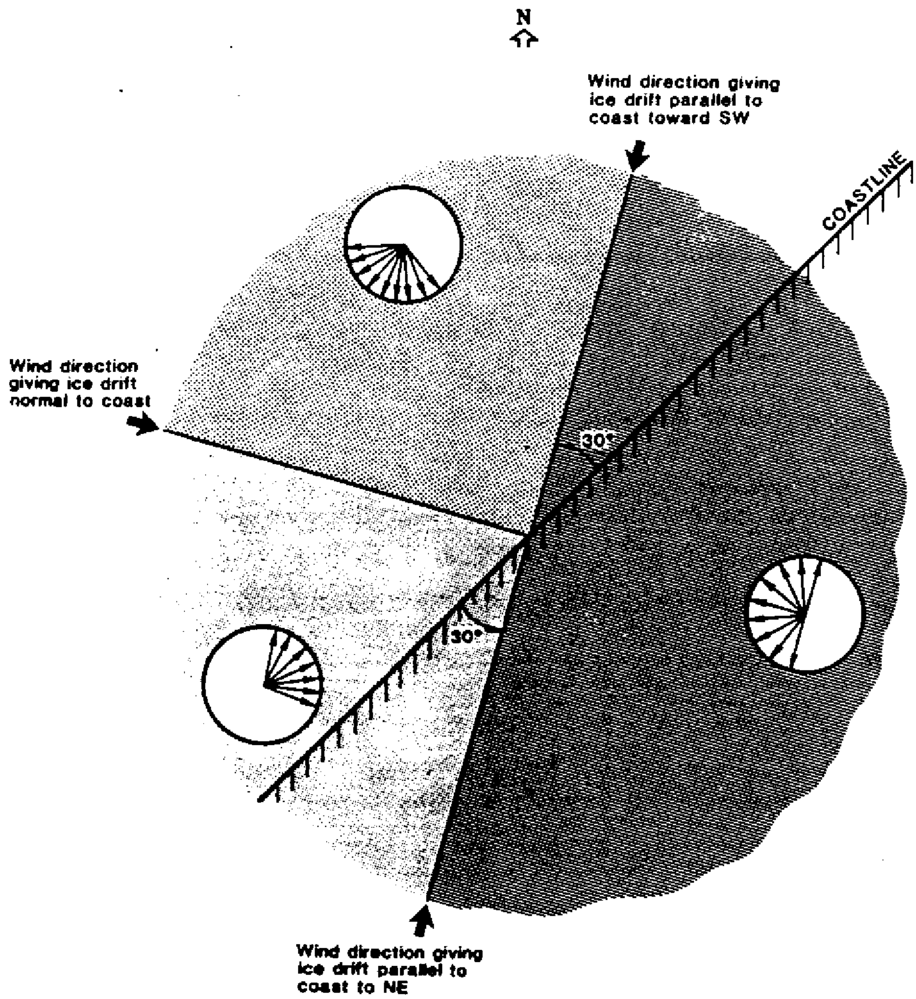

Figure 4. Schematic diagram illustrating the range of possible senses of ice motion within the field of view of the radar for wind from different directions, assuming that the ice drifts at 30° to the right of wind direction. Arrows in circles show the range of possible ice movement directions for winds originating in each patterned sector.

either leaves the field of view of the radar or impacts the edge of the fast ice and stops. However, ice could drift through the area on tracks parallel to the coast for long periods of time. Ice drift along the coast to the northeast is caused by winds from the south to southwest which, in turn, occur when a low pressure system is located over the central Chukchi Sea. With this configuration, the winds tend to drive the pack ice close to shore so that, in general, pack ice drifting to the northeast was close to, or against, the edge of the fast ice. In addition, ice push events observed in the Barrow area always followed the northward movement of a low pressure system through the Chukchi Sea (Shapiro et al., 1984); the winds from such a system tend to compress the pack ice cover against the coast, so that stress can be transmitted to the fast ice.

The prevailing winds from the east to northeast (as well as the less common winds from the southeast) tend to move the pack ice offshore opening a wide flaw lead. New ice was usually forming in the lead, but it was always smooth, with relatively few reflectors, so that it was usually invisible to the radar.

Northerly to northwesterly winds would push the ice toward the southwest, along and close to the coast. However, the reach of the coast where the radar was located is in the lee of Point Barrow with respect to ice drift from the north and northeast (see Figure 1) so that ice drifting from these directions would tend to be diverted in an offshore sense. Thus, when pack ice (usually as loose floes) was observed drifting from the northeast to the southwest, it was usually near the limit of the field of view of the radar system. However, floes were occasionally found to be drifting toward the coast to the southeest when the winds were from a northerly gradient. Examination of satellite images suggest that this occurred when pack ice drifted southwestward from the Beaufort Sea and around Point Barrow, and then diverged into the nearshore area (from which pack ice had earlier been driven by the offshore sense of the wind). Southwesterly movement of a continuous ice sheet was observed only when the pack ice sheet separated from the edge of the fast ice and drifted off, opening a lead. Once the ice sheet drifted out of view, it was usually followed by loose floes drifting along a southwesterly track near the limit of the field of view of the radar, as described above.

Drag effects were commonly observed when the pack ice was driven against the edge of the fast ice at a low angle. In these case, forces resulting from the interaction of the pack ice with the edge of the fast ice served to slow the pack ice near the boundary. This produced a velocity gradient so that the pack ice velocity increased with distance from shore. In general, the effect was observable for about 1 km seaward of the fast ice edge. The best example was presented in Shapiro (1975b).

More specific descriptions of patterns of ice motion and distribution through a typical year are given in Section 4.

3.3 FLICKERING OF REFLECTORS

One particularly interesting and important phenomena shown on the radar data is the flickering of reflectors on the pack ice surface prior to motion, when the data are viewed as time-lapse motion pictures. The flickering occurs for periods of up to several hours prior to movement, and is a reliable precursor. Not all movements were preceded by flickering, but flickering episodes were always followed by movement; the pack ice always moved offshore or compressed against the edge of the fast ice following a period of flickering.

The flickering is caused by the repeated disappearance and reappearance of individual reflectors on sequential frames of the data, with no change in their positions. This is interpreted as indicating that the reflectors are vibrating, which rotates the surfaces so that energy is not returned to the radar system continuously. The vibration, in turn, is attributed to the passage of waves through the water which cause the ice sheet to flex to conform to the shape of the water surface. Unfortunately, the nature of the radar data does not permit the period of the waves to be determined.

The observation of flickering was one of the factors which led to the study of ice sheet vibration described in Bates and Shapiro (1980a,b; 1981a, b).

4.0 ANNUAL CYCLE

4.1 INTRODUCTION

Based upon the radar data, the ice year can be subdivided into four phases which grade gradually into each other. These phases do not coincide with the four seasons of the year, so that it is proper to assign names to them. Accordingly, they are referred to as the seasons of open water, freezeup, winter and breakup. In addition, since the timing of the transition between these seasons probably varies along the coast, it should be recognized that the data apply only to the area within, or close to, the field of view of the radar system. However, it is anticipated that similar terminology would apply elsewhere along the coast.

For purposes of the discussion which follows, the data in Table 2 were used to calculate the percentage of films (i.e., 3-4 day intervals) during which the conditions represented in the table occurred. The results are shown in Figure 5.

In the following sections, the changes in the ice cover during each season are described, and examples of particular (not necessarily "typical") events from each season are given. Then, the changes in the ice season are discussed briefly in relation to the climatological data for Barrow as summarized in Brower et al., (1977).

4.2 OPEN WATER SEASON

The term "open water" is defined here as the complete absence of ice within the field of view of the radar. The only months in which this condition was met for any complete roll of film were July, August, September, and October (on 5%, 21%, 33% and 5% of the available data for each of these months, respectively). Note that the

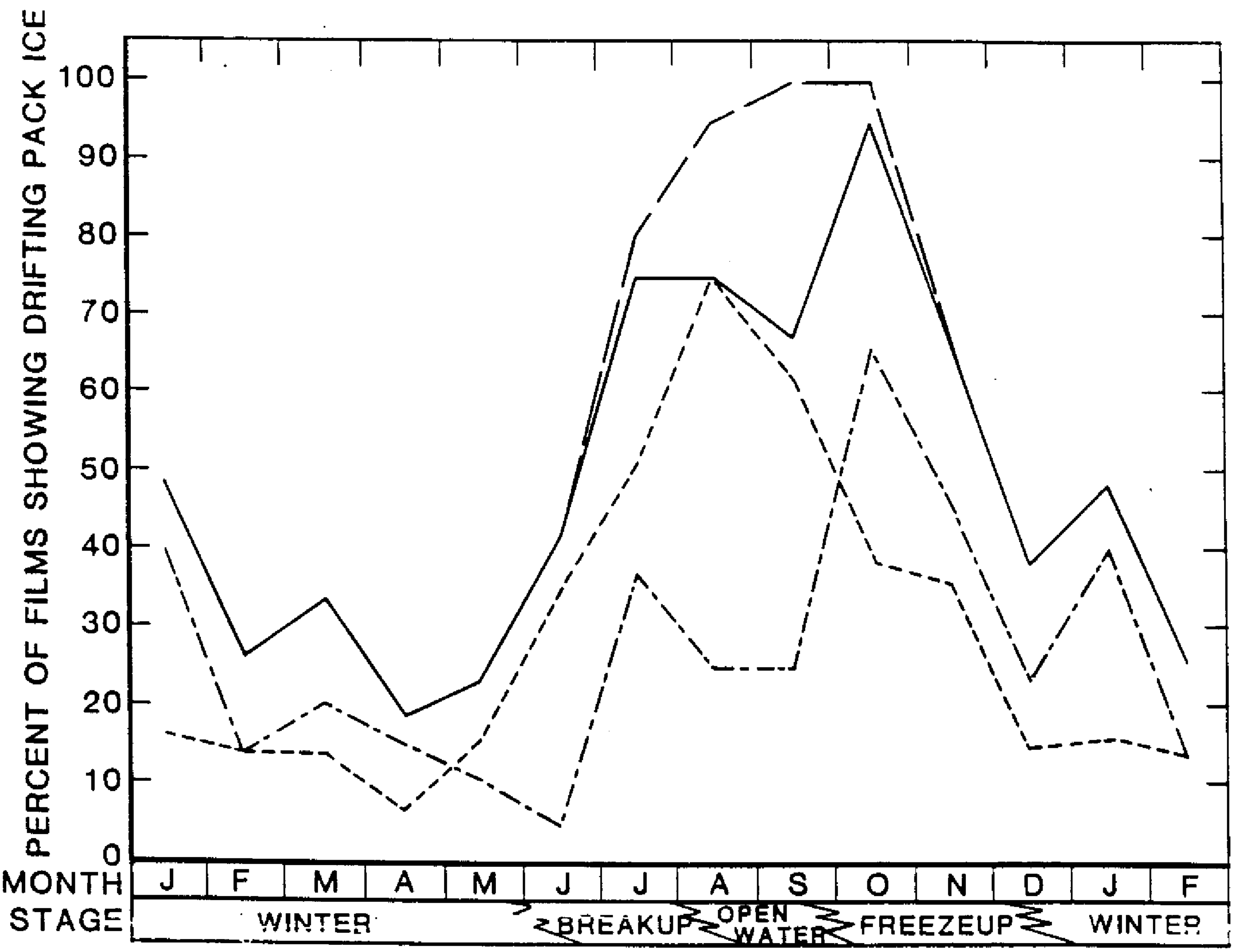

Figure 5. Percent of 4-day films in which pack ice was in motion, plotted by month for the period June, 1973 to July, 1979. The solid line gives the percentage of films with drifting pack ice. The long dashed line is the sum of the catagories of drifting pack ice and open water. Short dashes indicate pack ice drift to the northeast and long-short dashes show drift to the southwest. Note that the latter two catagories sum to a number greater than indicated by the total, because ice motion reversed on some films so that more than one direction of motion was recorded. Stages of the ice year are indicated along the base of the figure.

unusual summer ice conditions of 1975, in which part of the fast ice remained in place all summer so that the condition of no visible ice was never met, were included in the data set. The radar was also operated through the entire summer in that year, so that the data are likely to be biased toward the presence of ice.

The term "open water season" itself is something of a misnomer, because it is not continuous. Ice drifted through the radar field of view in every month, appearing and disappearing throughout the season. If the term is defined more loosely as indicating the time when there may be no fast ice within the field of view of the radar, then the season probably extends from late-July to early-October.

Note that these results give little information about trafficability. Minor quantities of ice grounded in shallow water would negate the classification as "open water" and, clearly, vessels can navigate through the area when drifting ice is present. However, the term is useful as an indicator of local conditions in the sense that it indicates the advance of the seasons.

4.3 FREEZEUP

Study of the radar data suggests that the term "freezeup" is a misnomer for the formation of the fast ice near Barrow since it implies that the ice simply freezes in place. However, the data show that a significant percentage of the fast ice consists of floes which drift into the area after forming elsewhere. The percentage of the fast ice cover which formed by freezing was variable from year-to-year, but even where ice did freeze in place, it did so because it was protected by ridges or grounded hummock fields formed from floes which drifted into the area. Observations in other areas suggest that this is a general rule along exposed portions of the coast.

The character of the fast ice varied depending upon the direction from which the ice came, reflecting the nature of the ice itself and the configuration of the coastline (Figure 1). When the ice came from the south, it consisted primarily of thin (less than

0.5 m thick) floes of first-year ice as pans which drifted northeastward along the coast. The typical pattern of movement suggests that the floes were stopped by a barrier to the north, out of the radar field of view, and gradually filled in the nearshore area from north to south. It is likely that the barrier is Point Barrow, and that the process occurs when the bight south of the Point is filled with floes. Subsequently, floes passing through the field of view of the radar gradually slow and stop as they encounter the ice "downstream." Some pressure ridging can occur along the floe boundaries during this process as the ice compacts northward. Simultaneously, the streamlines of the pack ice further offshore are deflected to the north, on a trajectory which carries the ice around Point Barrow. This produces a pattern of ridges (as illustrated in Figure 6) which are aligned along that trajectory. The ridges are dominantly shear ridges and reflect the drag of the drifting pack ice against the ice inshore, which is stationary and continuous with the shore.

The process described above repeats with the addition of new ice, until the fast ice extends out to (approximately) the 20 m depth contour; each ridge in Figure 6 represents an intermediate stage in the process. Stages may last from minutes to days, but for some time, each ridge is at the offshore boundary of the fast ice.

It is not uncommon during freezeup for the entire fast ice sheet, in some stage of development, to detach from the shore and move offshore leaving open water to the beach. The latest time at which this occurred in any year was December 31 (of 1973), during a major storm [the subsequent process of rebuilding the fast ice sheet during the storm was described by Shapiro (1975a,b)] although, in general, these events were more common earlier in the season. Note that when an event of this type occurred during freezeup, the "fast ice" sheet always moved off to the north or northeast. Attempts to associate the start of movement of the ice sheet with local winds showed no apparent relationship, suggesting that ocean currents or tides were responsible.

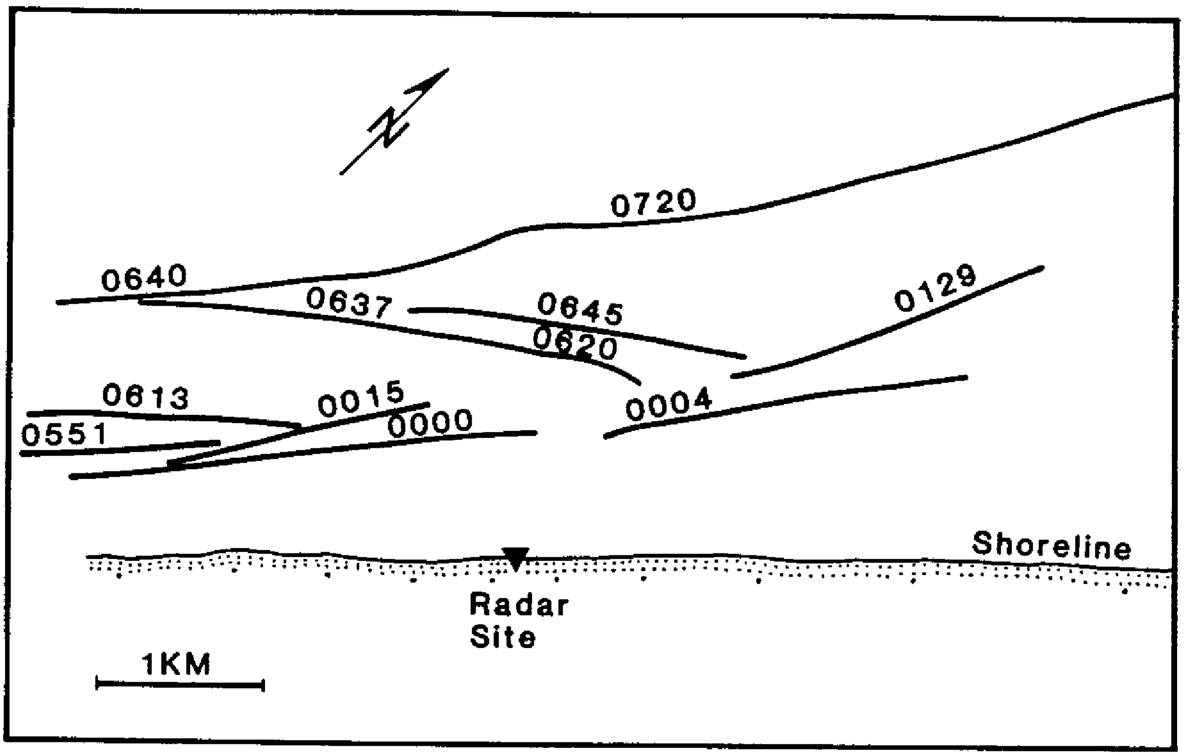

Figure 6. Pattern of shear ridges in fast ice which formed during a storm on January 1, 1974 when ice motion was from the southwest, parallel to the coast. Numbers indicate time (hours:min) when ridge formed, starting from an arbitrary time (00:00). Similar patterns developed over the entire freezeup period of other years when ice motion was primarily from the southwest (from Shapiro, 1975a)

In the 1974-75 winter, the fast ice near Barrow contained an unusually large percentage of multiyear ice floes which dominated the form of the fast ice sheet through that winter. When these floes first entered the field of view of the radar system during freezeup they were moving southeastward from the north-northwest quadrant toward the coast. Many of the floes became grounded (some had sails as high as 3 m in 5 m water depth), although the maximum depth of grounding was not determined. However, multiyear ice floes were common in the fast ice at least to a distance of about 2 km from shore, corresponding to a water depth of 15-20 m. Inshore, the first-year ice of the fast ice was formed by freezing in place between the multiyear ice floes.

The source of the multiyear floes was clearly either the northern Chukchi Sea or the Beaufort Sea, and this was verified by examination of NOAA satellite imagery. The imagery shows that the floes which drifted into the fast ice zone came into the area from the edge of the pack ice north of Point Barrow. The motion could not be tracked in detail from the satellite imagery, but it appears that the floes drifted southwest from north of Point Barrow in diffuse swirls, and then turned back toward the coast along a more southeasterly track as if caught in an eddy.

It is not possible to define the beginning and end of the freezeup season with any precision. The data on the frequency of observation of pack ice motion (Figure 5) indicate a decrease in ice activity through the period from October to April. The earliest that fast ice was recorded by the radar was late-September, which is also about when ice drift to the southwest becomes more frequent than drift to the northeast. This coincidence is taken to provide the basis for defining the start of freezeup as late-September.

The definition of the end of freezeup is more problematic because the drift data do not provide any basis for the definition. In a practical sense, the end of freezeup indicates the start of the period when the fast ice can be anticipated to be relatively stable for the remainder of the ice year. During the time the radar operated, the latest ice event which caused major movement of the fast ice occurred on January 1, suggesting that, conservatively, early-January can be taken as the end of freezeup and the start of the winter season.

4.4 WINTER

The winter season, as shown by the frequency of ice motion (Figure 5) and the pattern of distribution of the ice, extends from January to May. Its start is defined by the end of freezeup and the beginning of the season of relative stability of the fast ice sheet. The end of the season is identified with the marked increase in the occurrence of drifting ice offshore between May and June (Figure 5) and the marked shift to dominance of drift to the northeast during this time. The onset of melting and instability of the fast ice follow in June and July.

The pattern of ice distribution within the field of view of the radar system during winter always included stationary fast ice. Offshore from the fast ice, the most common condition was for the pack ice to be either present but stationary, or absent. By month, between January and May, one of these was the only pattern shown by the-data for (respectively) 52%, 72%, 66%, 81% and 76% of the films (Table 2). During March, April and May of 1976, 1977 and 1978, they were the only patterns recorded; no drifting ice was observed. On the remainder of the films, the pack ice was in motion for at least part of the time covered by the film. When ice drift was parallel to the edge of the fast ice, the direction was more often to the northwest than to the southeast but the difference in frequency is not great (Figure 5). Occasionally the pack ice was driven into the edge of the fast ice at a high angle (such impacts occurred on about 9% of the films for this time of year). A spectacular shear ridge formed in March 1974 from such an event (see description below in this section). However, the effects of the impact events were usually confined to the edge of the fast ice. The single exception which occurred during the time the radar operated had minor effects, as described near the end of this section.

The absence of pack ice offshore from the fast ice indicated that the ice was drifting slowly away from the coast under the influence of the prevailing northeast to east winds, leaving a lead in which new ice was forming. Since the ice in the lead was young and thin with no sizable ridges or hummocks it was invisible to the radar. However, in one event (the 1974 ridging event described below) the radar data show the pack ice to advance directly against the edge of the fast ice after a period of more than one day when it was outside of the field of view of the radar. At that time, new reflectors appeared on the radar screen near the edge of the fast ice while the edge of the pack ice was still about 2 km away and advancing shoreward. This shows that thin ice was present in the lead; the appearance of the reflectors indicates that ridging was occurring as this ice was brought into contact with the edge of the fast ice.

The pattern in which stationary pack ice was located offshore from (but in contact with) the fast ice often indicated the presence of a stable extension to the fast ice (Stringer, 1974) rather than continuous pack ice cover. Stable extensions are probably ungrounded masses of pack ice which attach to the fast ice and extend offshore. They are common features in the local area and, since they often extended beyond the limits of the field of view of the radar, it was not possible to distinguish them from continuous pack ice cover unless they were observed during flights in the area. It is likely that stable extensions of the fast ice originate as part of the pack ice sheet, but are left behind against the fast ice when the pack ice moves offshore.

As noted, a major impact and ridging event occurred in March, 1974, which formed the highest ridge observed in the radar field of view for the entire period that the system was operated; brash ice was piled to an elevation of about 13 m in a water depth of 20 m. The event is described here is some detail as an illustration of the scope of possible movements in the near shore area during the winter season.

The event occurred as part of an (at least) 11-day period of pack ice activity; this was the largest number of days of nearly continuous activity recorded by the radar system during the winter season. The movements were generally slow (ice velocities ranged from about 0.1 km/hr to less than 0.5 km/hr), with interspersed periods of quiesance. However, even when the ice was not in motion, the reflectors on the surface flickered often, indicating that the ice sheet was vibrating and unstable (see discussion in Section 3.3). Figure 7 shows the displacement path of the pack ice in the field of view of the radar during the 11-day period. Each leg of the diagram represents the path of the ice during the time indicated on the figure, as calculated by multiplying the average velocity of the ice over the period of movement by the time over which the movement occurred. Thus, ideally the plot would represent the displacement path of some point on the surface of the ice sheet for the time covered by the diagram.

At the start of the event, the ice sheet had been stable for a period of about one month. The first movement was the slow opening of a lead along the edge of the fast ice. The lead widened from the south end of the radar field of view toward the north, suggesting a clockwise notation of the pack ice, and reached a width of about 0.6 km before the first movement to the northeast (shown in Figure 7) occurred. The first impact of the pack ice with the edge of the fast ice, leading to the formation of the shear ridge, occurred 10 hrs after the movement began, and continued until the ice stopped moving 37 hours later (at 47:00 in Figure 7). The fact that the ridge was developing over this entire time is shown by the nearly continuous appearance of new reflectors along the line of the ridge. In addition, the ridge gradually created a "shadow zone" for the energy from the radar, so that reflectors on the pack ice disappeared as they drifted behind the ridge.

After the movement stopped, the reflectors on the ice surface continued to flicker intermittently until the ice began moving again, but to the southwest, at 63:15 hrs, as shown in Figure 7. Movement in this direction continued for about 36 hrs, after which the pack ice stopped for about 24 hours. It then flickered for about 5 hours, and then moved off to the northwest at about 0.2 km/hr until the ice edge was out of the field of view of the radar, leaving a flaw lead. The pack ice remained out of view for about 28 hours, and then reappeared moving normal to the fast ice edge at about the same velocity at which it departed. During this advance, new reflectors appeared offshore from, but close to, the fast ice boundary, while the pack ice edge was still about 2 km seaward. This is interpreted as showing that the lead was covered by thin ice (as discussed above) which, though less than 24 hours old, was capable of transmitting stress over that distance.

The pack ice advanced until it impacted the fast ice edge. It then continued to compress against the fast ice for several hours, as shown by flickering and slight shoreward motion of reflectors in the pack ice. However, there were no new ridges formed along the edge of the fast ice, and no motion was detected by the radar system within the fast ice during and after the impact. In addition, during the year in which this event occurred, precise surveys were being conducted within the radar field-of-view, in order to monitor slight movements of the fast ice during the winter. The survey data verify that no movement occurred as a result of the impact. However, it should be noted that in the Spring of 1974, numerous grounded ice ridges were distributed throughout the fast ice, so that it might have been more stable than in typical years.

Subsequently, the ice remained stationary for about 18 hours. A lead about 0.1 km wide then opened, separating the pack ice from the fast ice, and the pack ice proceeded to drift to the west-southwest (beginning at 229:30) at about 0.5 km/hr, eventually leaving the field of view. When the sequence of film terminated, other

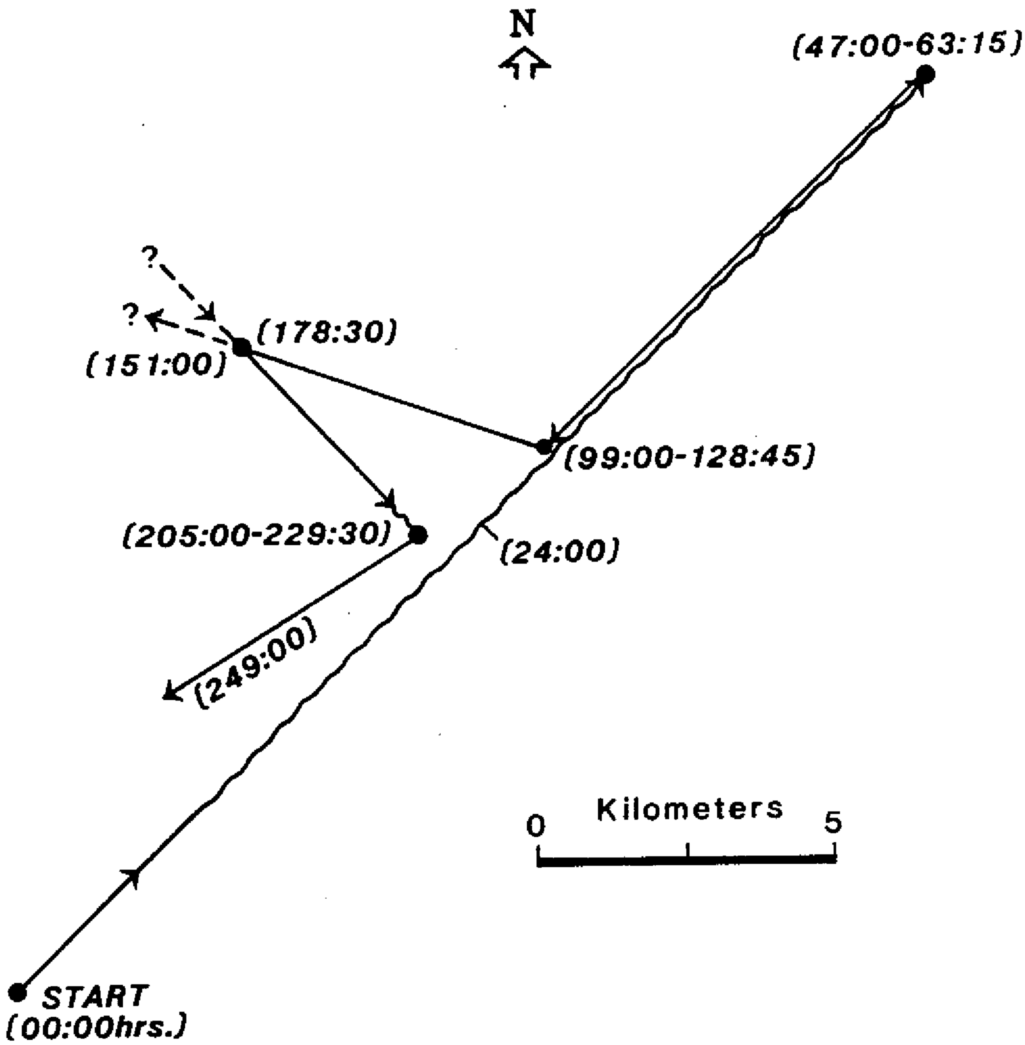

Figure 7. Displacement path of a hypothetical point on the pack ice surface during the movement episode of March, 1974. Distances calculated from ice velocity and time measurements. Arrowheads show the movement direction and numbers in parentheses are cumulative times as hours:minutes. Wavy line segment indicates duration of impact with the fast ice edge. Dashed lines show the path of ice leaving and entering the radar field of view.

floes were drifting at the same velocity to the southwest, parallel to the coast and about 2 km from the edge of the fast ice.

The total displacement of a hypothetical point on the ice surface, as represented by the vector plot in Figure 7, is more than 35 km in the 11 days represented by the data (not including the motion during the 28 hours that the ice was out of view). In addition, the direction of motion changed 4 times during the event. The implications of movements of this type on possible offshore operations are discussed in Section 5 .

Only two episodes of movement of the fast ice during the winter season were observed during the time the radar system was in operation. In neither case were the displacements large enough to be detected by the radar; they were noted only because observers were present in the area at the time of the events. It is reasonable to assume that other events of this type occurred but were simply not observed.

The first event occurred in March, 1976. Strong east to northeast winds forced the pack ice to drift away from the fast ice opening a lead, and also caused tension fractures up to a meter wide to form within the fast ice. This was unexpected, because the width of the fast ice in the Barrow area is too narrow for the wind fetch over the ice to generate stresses high enough to cause fracture. It is possible that the drag effect of ice ridges within the fast ice increased the wind stress sufficiently for tensile fracture to occur.

The second example of fast ice motion during winter occurred in April, 1977 when the pack ice was being compressed against the edge of the fast ice under the influence of southwest winds. Observations were made only near the shoreline, where the effects consisted of audible cracking of the ice and a slight (about 15 cm) rise of the ice sheet where it was driven up along the tide crack.

The fact that no large-scale movements of the fast ice occurred in winter while the radar was operating clearly does not mean that such events cannot happen. In fact, there is anecdotal evidence that major ice push events have occurred during the winter months (Shapiro and Metzner, 1979; J. Kelley, pers. comm., 1986) and an ice push in the area produced shore ice ridges several meters high in February, 1989 (Shapiro, unpub. field notes). However, there is no indication that large motions of the fast ice in an offshore direction have occurred.

4.5 BREAKUP

As might be anticipated, breakup is the time of year when the ice cover is most active. As noted above, the start of the breakup process seems to be indicated by the increased occurrence of drifting ice offshore (Figure 5) and the rapid drop of the frequency of the pattern of no drift in June (Table 2). The frequency of this pattern drops from 76% in May to 58% in June, and then to about 20% in July. The frequency of ice drift from the south also increases in those months, from 17% in May to 40% in June and to 51% in July. Interestingly, the frequency of winds which would tend to give these conditions does not change as much as the drift pattern (see discussion in Section 4.6).

The fast ice never moved out as a unit during breakup. Instead, by a combination of melting and fracture during movements it was simply reduced to small, individual floes which drifted off in streams. In general, the reflectors representing lines of grounded ice ridges were the last features to disappear; apparently they remain in place until they lose sufficient mass through melting to float up and drift offshore.

The effects of the impact of the pack ice on the edge of the fast ice were more apparent during breakup than at other times of year and generally took the form of a pervasive tightening shoreward through both the pack ice and fast ice following an impact. In addition, ice push events, in which the fast ice was pushed up the beach, occurred only early in breakup while the fast ice sheet was continuous, and never after the fast ice had begun to disaggregate. This may reflect the development of zones of weakness looseness of the ice within the fast ice zone, which might enhance the possibility for piling along the ridge lines, rather than transmission of stress through a continuous ice sheet to the ice along the beach. However, there are no field observations of the process to verify this.

Patterns of ice motion within the radar field of view during breakup were variable, particularly when the pack ice had been reduced to discrete floes. As a result, the patterns are difficult to describe in general. The following discussion and examples illustrate the point.

It was not uncommon for floes inshore from a line of remnants of ice ridges to be moving parallel to the coast, but in the opposite direction from that of the floes offshore from the ridge line. Examples of such patterns were observed in which the motion was in both senses (i.e., inshore floes drifting northeast and offshore floes drifting southwest, and vice-versa). This may reflect the influence of near-shore currents carrying the ice on one side of the ridge in one direction, while the wind pushed the ice on the other side in the opposite direction.

Rapid reversals of the direction of the ice motion (say, from southwest to northeast) were also common when the pack ice was composed of discrete floes. In some cases, the reversals occurred as part of a continuous movement, in contrast to reversals during winter, in which the pack ice always came to a halt before changing its direction of motion. When the movements were continuous, they occurred over periods of a few hours. In addition, the floes were often observed to move in patterns of whirls or eddies during these events.

The motion of a continuous pack ice sheet, and its interaction with the fast ice over a 6-day period in late-June, 1974 are illustrated in the displacement vector diagram in Figure 8. This figure was prepared using the same procedures as Figure 7. The sequence of movements began with the pack ice moving northeast along the coast at a velocity of 2.2 km/hr for about 4.5 hours. It then stopped for about 8 hours,

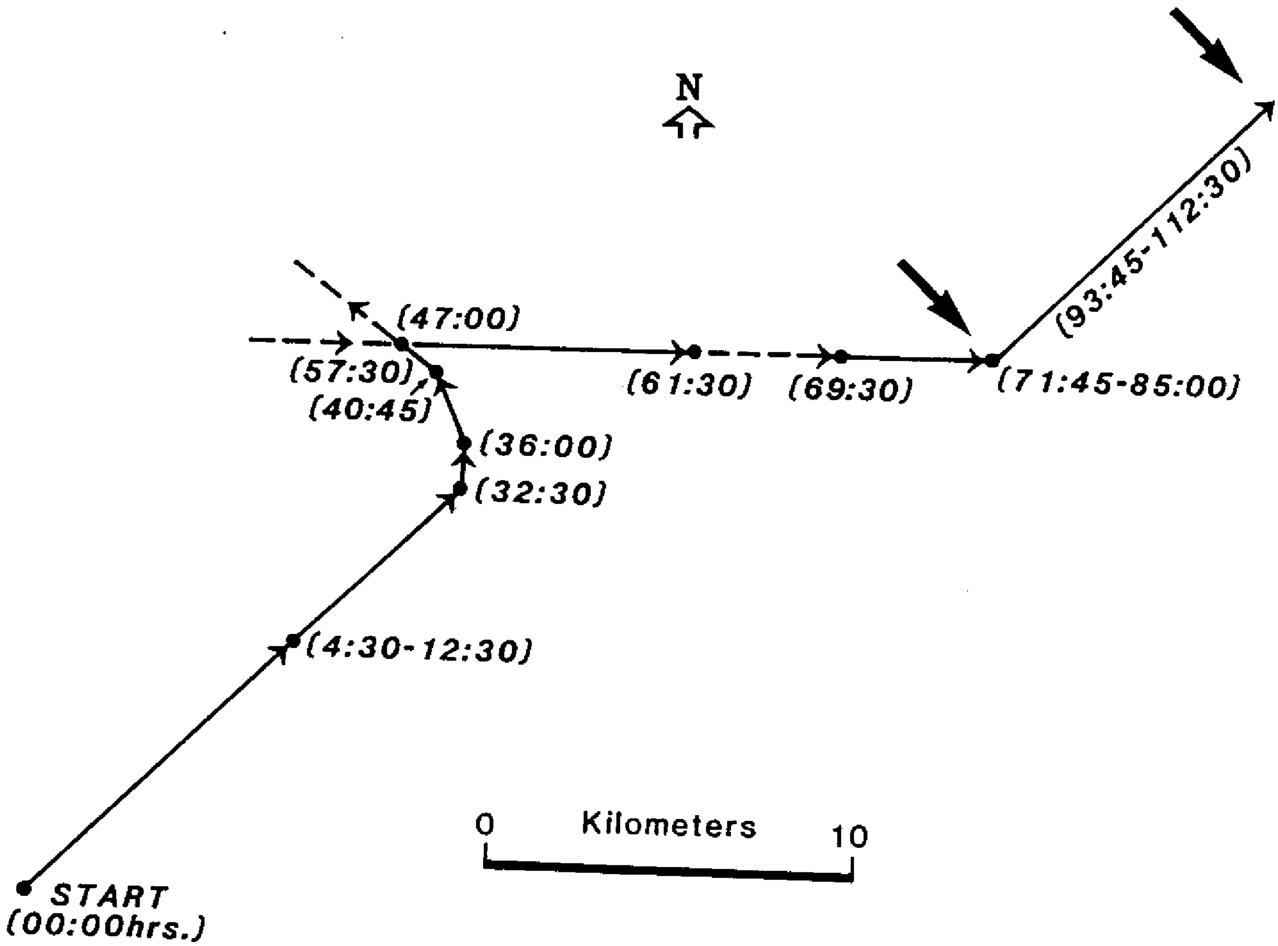

Figure 8. Displacement path of a hypothetical point on the pack ice surface during the movement episode of June, 1974. Distances calculated from ice velocity and time measurements. Arrowheads show the movement direction and numbers in parentheses are cumulative times as hour:minutes. Dashed lines show the path leaving and entering the radar field of view. Bold arrows indicate impact with the fast ice edge followed by compressive pulses or flickering during the time indicates.

and then moved northeast, but dragging along the edge of the fast ice as indicated by a velocity gradient in the ice which varied from 0.6 km/hr at the edge of the fast ice to 1.2 km/hr about 1 km further offshore. Drift in this direction continued for about 16 hours. Then, over the next 16 hours, the drift direction turned from northeast to north, then to north-northwest, and finally to the northwest. During this time the ice velocity slowed gradually to 0.2 km/hr, and the ice drifted out of the field of view of the radar to the northwest. It remained out of view for almost 24 hours, with the exception of a 4-hour period (from 57:30 to 61:30, about midway through the 24 hour period) when floes were visible drifting northeast at 0.5 km/hr at the limit of the field of view. When the pack ice next appeared on the radar screen it was drifting eastward at 2 km/hr on a path which led to impact with the edge of the fast ice (at 71:45). For 12 hours following the impact the pack ice continued to tighten against the edge of the fast ice. Numerous compressive pulses occurred, each of which resulted in a slight shoreward displacement of the reflectors in the pack ice. Subsequently, no movement occurred for about 4 hours, when the reflectors on the pack ice began to flicker again. The flickering continued for about 3 hours, after which the pack ice began to move northeastward, parallel to the coast at a velocity of 1.2 km/hr. The movement continued for about 9 hours, when the pack ice stopped and compressed against the coast again. It then remained in place for about 18 hours with no further movement when the film sequence was terminated.

The most unusual movement pattern observed during the breakup season is illustrated schematically in Figure 9. The figure shows three different velocities and two different directions of ice motion occurring in the small area of the field of view of the radar at the same time. Inshore of a line of ice grounded ridges, small, loose floes were drifting northeast along the coast at a velocity of 0.8 km/hr. Offshore from the ridge line, larger floes were drifting northeast at 4.1 km/hr. Then, the edge of the

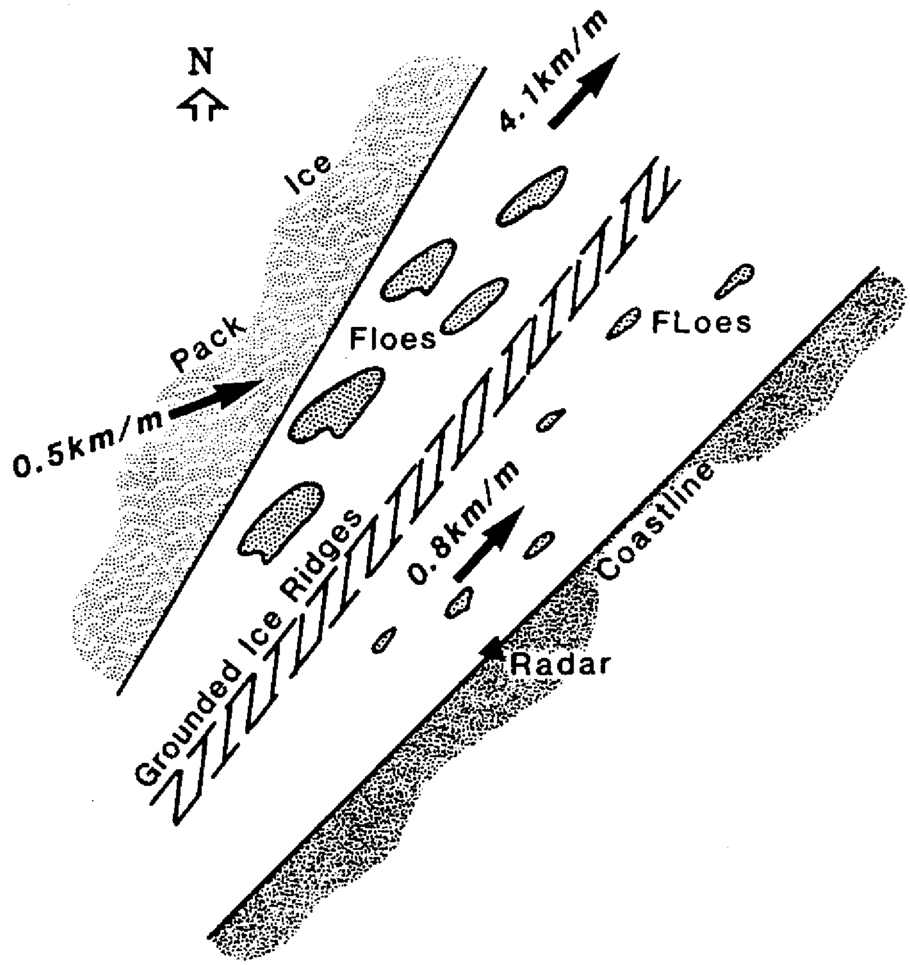

Figure 9. Schematic diagram of an unusual ice movement pattern during breakup. Pack ice moving eastward at 0.5 km/hr as large floes offshore from the line of grounded ice ridges (about 1 km from shore) are moving at about 4.1 km/hr. The velocity of the small floes inshore from the ridges is about 0.8 km/hr. The pack ice ultimately impacted the line of grounded ridges and compressed against it.

pack ice entered the field of view of the radar moving almost due east toward the coast at 0.5 km/hr, crossing the path of the drifting floes. Ultimately the pack ice impacted the line of grounded ridges and compressed against it.

The examples above illustrate the difficulty of characterizing "typical" ice movements or conditions during the breakup season. It is sufficient to conclude that breakup is a time of almost continuous ice activity leading to the disintigration of fast ice.

4.6 COMPARISON TO CLIMATIC DATA

The weather data for the Barrow area, summarized by Brower et al. (1977), were examined for correlation with the seasons of the ice year defined above. As noted earlier, the data sets for the weather and the radar system do not overlap in time. Brower et al. used climatic data for the period from January, 1966 to December 1974 in their compilation, while the radar system was operated from June, 1973 to May, 1979. It is assumed here that both data sets cover sufficient time to be considered as representative. However, the correlations between the climate data and the ice seasons are weak at best; they are discussed here only for the sake of completeness.

Variations in wind direction, storm tracks in the Chukchi Sea and air temperature were considered most likely to be associated with changes in the ice season. The relationship to wind direction is clear from the discussion above regarding the variation of ice drift direction parallel to the coast with the seasons. Storm tracks through the Chukchi Sea generate southerly winds which drive the ice northward and, in addition, they trigger ice push events. Temperature is simply the most reliable indicator of seasonal change.

All the northerly moving storm tracks in the central Chukchi Sea, recorded in Brower et al. (1977) are listed in Table 3 as the number of storms per month. There

TABLE 3

CLIMATE DATA BY MONTH (1966-1974) FROM BROWER ET AL. (1977)

	TOTAL NUMBER OF NORTHERLY STORMS	MEAN AIR TEMPERATURE (C)	WIND DIRECTION (%) (*) NE-E-SE	S-SW	W	N-NW
JAN	6	-26	52	20	12	18
FEB	1	-29	53	15	13	18
MAR	2	-27	58	15	10	17
APR	0	-19	62	15	6	15
MAY	6	-7	67	15	6	12
JUN	2	0	60	12	10	17
JUL	5	+3	48	18	15	17
AUG	4	+3	54	15	12	18
SEP	2	-1	S8	15	8	17
OCT	5	-9	62	20	5	12
NOV	4	-25	64	16	7	12
DEC	3	-25	56	18	11	12

(*) NOTE: Percent of time that wind was calm brings the total of these four columns to 100%.

are too few events to justify a statistical analysis of the data. However, it appears that storms are least common in the winter months (February, March and April), but are not noticeably more likely to occur consistently at other times of year. Clearly, there are no major "spikes" in the data which coincide with the changes in season of the ice year.

The data on wind directions listed in Table 3 show the percentage of time that the wind was from the quadrants indicated in Figure 3, corresponding to the directions of pack ice motion indicated in that figure. The only suggestive points in the data are for the month of July, in which the frequency of winds from the northeast, east and southeast decreases in favor of winds from the south, southwest and west. This appears to coincide with the increased frequency of ice motion from the southwest noted above. However, it should be noted that a similar relationship occurs in January and February, so that it is difficult to draw conclusions from the data.

The monthly mean temperatures at Barrow (Table 3) indicate some correlation with the ice seasons, in that two of the ice seasons (winter and breakup) begin about 1 month following a sharp change in the mean temperature. In addition, as might be anticipated, the open water season occurs during the two warmest months and the month which follows them.

It would be possible to extend the study to attempt to interpret the changes of the ice seasons in terms of the extent and nature of the ice cover (i.e., continuous pack ice cover vs. discrete, drifting floes) which clearly reflect the air temperature. However, that would require extensive examination of satellite imagery, which was beyond the scope of this project.

5.0 SUMMARY AND DISCUSSION

The descriptions above can be summarized into the following generalizations regarding the seasons of the ice year:

1. The open water season, defined as those months in which no ice was visible in the field of view of the radar system for the time represented by at least one roll of film, may range from late July to early October. However, drifting pack ice or remnants of the fast ice were often visible during these months, so that the radar field of view was never totally free of ice for more than a few weeks.

2. The process of freezeup (in particular, the formation of the fast ice) can begin in late-September and can extend to about early January. The definition of the duration of the season is based upon (1) the observation of the earliest occurrence of fast ice in the area (neglecting the single year when the fast ice remained in place through the entire summer) and (2) the last observed offshore movement of fast ice and the frequency of observation of drifting pack ice in the field of view of the radar.

In the Barrow area, a significant portion of the fast ice is compose of floes which drift into the area. First-year ice which freezes within the fast ice zone forms primarily in sheltered areas between floes or inshore from grounded ice ridges. In three of the years in which our observations were made, the pack ice came from the southwest in the form of floes of first-year ice up to 0.5 m thick. In one year, it originated in the Beaufort Sea and included floes of multiyear ice; the fast ice remained in place through the following summer, so that no new floes were introduced during the subsequent freezeup.

When the fast ice formed from floes drifting into the area from the southwest, it commonly developed in segments which became attached to the offshore boundary of ice already in place. Segments frequently broke loose and drifted off, to be replaced by other floes until the fast ice was built seaward to (approximately) the 20 m depth contour. The offshore edge of each segment was usually marked by a shear ridge which, at some stage, had represented the fast ice-pack ice boundary.

The highest ice velocity measured during the years the radar system operated was 8 km/hr, which occurred during a storm late in the freezeup season.

3. The winter season extends from early January through May. During this time, the pack ice is most commonly either out of the field of view of the radar system (i.e., greater than about 5.5 km from shore) or adjacent to the fast ice but stationary. Note that the latter condition may be due to the presence of a local floating extension of the fast ice which could not be distinguished from pack ice without independent observations.

Incursions of pack ice against the fast ice are not uncommon during the winter season and can lead to the formation of ice ridges along the edge of the fast ice. During the course of the project there were no cases of large-scale motion of the fast ice as a result of impacts. However, such movements, in the form of ice-push events, have occurred in the past, but there are no reports of the fast ice sheet floating offshore during the winter season.

There was no preferred direction for pack ice motion observed by the radar during the winter, and ice velocities were generally low.

4. The start of the breakup season is indicated by the increase in the occurrence of drifting ice in the field of view of the radar in June. Ice motion is dominantly to the north during this season and, as the fast ice deteriorates (primarily through melting) it tends to break into small floes which drift off in that direction. However, examples of a wide range of movement patterns and directions were observed during the course of the project. In addition, in 1975, the fast ice remained in place through the entire summer. In that year, pack ice drift from the north was common through July, August and September. This does not presuppose a cause and effect relationship between the pattern of ice drift from the north and the absence of a true breakup that

year. Rather, it suggests that both resulted from an unsual distribution pattern of weather systems during the summer of 1975.

The changes in the ice cover with the seasons, as defined above, may be related to variations in air temperature through the year. However, they cannot be correlated to changes in prevailing wind directions or the passage of storm systems, the only other climate variables examined.

The patterns of ice distribution and motion in the field of view of the radar can be interpreted as being driven primarily by the regional wind field, but strongly influenced by the local regime of tide and currents, sea floor topography and the configuration of the coastline. It seems probable that similar influences would operate elsewhere along the coast, reflecting local conditions. Quantitative modeling of ice motion under these conditions would be difficult, because of the number of variables and the range of possible interactions between them. Thus, rules-of-thumb developed from repeated observations may be necessary if local ice conditions are to be predicted. This, in turn, requires a period of monitoring of local patterns of ice movement and distributions, such as was done for the Barrow area on this project.

Many of the problems of operating a program such as this have been negated by technological advances in recent years. Smaller, portable radar systems are available, and the availability of low-light video equipment for recording images of the radar screen would eliminate many of the difficulties encountered in interpreting the data. In addition, it would make the data available quickly and facilitate ground truth studies.

The range of changes in ice movement direction described in the winter and breakup movement episodes (Figures 7 and 8) indicates some of the problems which might be encountered in developing offshore installations in exposed coastal areas. An example is provided by suggestions for the design of a tanker terminal for the Chukchi Sea coast of Alaska, using a single-point mooring system mounted on a monopod. The idea is that a ship at the terminal could be positioned so that it was always on the lee side of the structure with respect to moving pack ice. However, the data raise the question of whether a vessel could maneuver near the monopod, given the rate of ice motion and associated problems of clearing ice from around the structure. This is not to suggest that the design is not feasible; instead, it emphasizes the point that knowledge of the pattern of ice motion in the area should be available for consideration during the design stage.

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