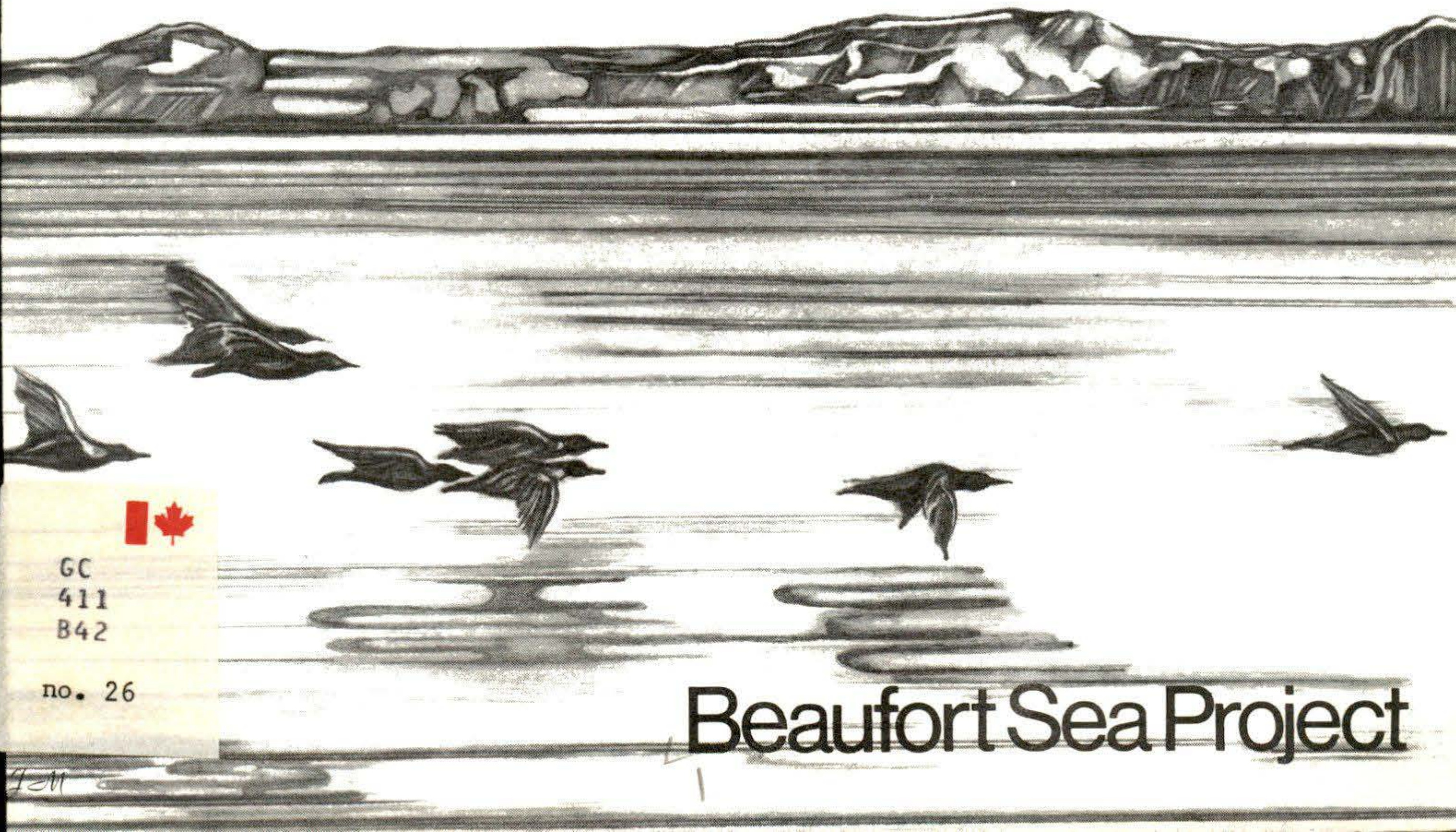
Ice Climatology of the Beaufort Sea

W.E. MARKHAM

Technical Report No. 26



Beaufort Sea Project

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1. SUMMARY

This report consists of four separate studies concerned mainly with ice climatology in the southern Beaufort Sea. The first, based on a study of twenty years' of historical ice charts, describes the variation of ice concentration with the time of year for six regions with different ice regimes. The second describes the motion of individual ice floes relative to the wind. The third describes a reasonably accurate method for predicting the gross features of the northward retreat of the polar pack ice in the Beaufort Sea and the fourth is an examination of the size of ice floes within various ice concentration ranges near the edge of the polar pack.

2. INTRODUCTION

The Atmospheric Environment Service of the Department of the Environment has flown ice reconnaissance surveys in support of shipping in the Beaufort Sea since 1958. Weekly summary ice charts were produced from these surveys. Other ice reconnaissance data (which was collected prior to and during the construction of the DEW Line) is available from U.S. Navy observers. In order to make this data more useful in planning offshore activities, an analysis has reduced these observations into graphs of the frequency of occurrence of various ice concentrations vs time of year for six representative offshore regions in the southern Beaufort Sea. The resulting graphs should be useful for determining expected duration of the operating season for drill ships at specific offshore sites. Results are described in Section 5.1.

Offshore industrial activity would usually have to be protected by an ice reconnaissance and weather forecasting service with an ability to predict the movement of ice floes. It is therefore important to know the actual motions of individual floes and how these motions relate to winds. The analysis described in Section 5.2 is based on the movement of floes which were tracked in satellite imagery and on observations made by Garrett and MacNeill (1976), of the drift of ice floes tagged with radio beacons.

It would be useful to have a means of predicting whether the ice conditions would be good, fair or bad in the ensuing summer. Although weather prediction on a seasonal basis is not yet possible, some useful results were obtained based on the conservative nature of the ice in the Arctic Basin. The prediction method is described in Section 5.3.

Existing climatological records for the southern Beaufort Sea do not contain much information concerning floe sizes which would be useful in designing offshore vessels or structures. The mass and strength of ice floes in the area are important for the safety of marine systems. A 50% cover of 10 cm thick ice is of small importance to ice-strengthened offshore structures regardless of the lateral dimensions of the floes. On the other hand, a single floe 150 cm thick and 100 m in diameter would weigh 12,000 tonnes and could present a problem if it approached a platform. In the summer, floes are generally thick and hence their size is important. A special photographic mission was flown in August 1974 to obtain more data and the analysis of the results are described in section 5.4.

3. STUDY AREA

The ice climate study area is shown in Figure 1 and includes not only the area off the Mackenzie Delta but also covers the continental shelf west of Banks Island. This area is roughly inshore of the 400 m isobath bounded by the coordinates 70° 30'N 141°W, 71° 30'N 131°W and 74° 15'N 128°W and extend eastward to 125°W.

The study on the prediction of the summer ice retreat of necessity included the Arctic Basin, while the floe size and motion studies were confined within the ice climate study area.

4. SOURCES OF DATA

4.1 Ice Climatology

The ice climate of the southern Beaufort Sea has not been documented in detail. An Ice Atlas of Arctic Canada (1960) used only 20 observation points in this area and although the period covered in the analysis was from 1900 until 1958 there were only 2 to 5 years of offshore reports in any one analysis period but up to 25 at one or two coastal sites. Since 1958 Canadian ice reconnaissance flights over the southeastern Beaufort Sea have been flown in support of shipping. Using observations from these flights and meteorological data such as winds and temperatures, weekly charts indicating the location, concentration and age classification of sea ice have been produced for the interval from mid-May until late October of each year. In later years observations from aircraft have been augmented by the use of satellite imagery in the production of these charts. Since the ice observations from aircraft and satellites did not necessarily occur on the fixed dates for which the weekly charts were prepared, adjustments based on wind, temperatures and currents were sometimes made. These weekly historical charts constitute the source of data for the ice climate study.

4.2 Floe Motions

During the summer of 1974, a difficult year for navigation in the southern Beaufort Sea, the Arctic pack remained close inshore throughout the season. Surface current measurements planned by Garrett and MacNeill (1976) using floating radio beacon drifters tracked by aircraft, were modified by using the beacons to track ice floe motions instead. The detailed motions obtained in 1974 were analyzed in relation to the wind velocities obtained from the mean daily atmospheric pressure charts. Similarly, an examination was made of floe motions depicted in satellite imagery. ERTS (Earth Resources Technological Satellite or renamed LANDSAT) is in a sun-synchronous orbit circling the earth once each 103 minutes. Each orbit covers a 300 km wide path partially overlapping the path followed on the previous day. The result is that the earth is scanned once each eighteen days but at high latitudes these paths converge permitting up to four consecutive days coverage at latitude 80°N each 18 days. Since the sensors have a 100 m resolution, ice floe motions can be tracked quite closely as long as the distance from shore where a geographical fix is provided is not too great.

4.3 Prediction of the Retreat of the Summer Pack Ice

For this study the two sets of data used were mean monthly atmospheric pressure charts, available back to the early 1950's, and historical ice charts. These sets were evaluated to determine the extent to which winter or spring meteorological conditions in the Arctic Basin influenced the ice regime of the southern Beaufort Sea in the following summer.

4.4 Ice Floe Sizes in the Southern Beaufort Sea

Two sources of data were available. The weekly historical ice charts referred to earlier formed one source. These not only portrayed the concentration, type and location of sea ice but to some extent included estimates of the diameters of ice floes encountered. The second data source was 5,200 photographs of the surface of the southern Beaufort Sea from a photo-reconnaissance flight for this purpose during August, 1974.

5. RESULTS

5.1 Climatological Study of Ice Conditions

The main work of analyzing historical ice charts was conducted by Foundation of Canada Engineering Corporation Limited (FENCO) under contract to the Department of Environment. Their two-volume report contains a week-by-week analysis of the ice conditions at a series of 170 data points on a 15 X 20 nautical mile grid within the study area (Figure 1). Computer-drawn weekly maps of median ice conditions, best ice year in five, worst ice year in five, frequency of occurrence of open water and of concentrations of two tenths ice or less, information on the proportion of old floes which should be expected, the extent of ridging, an analysis of floe size and of autumn ice build-up are all available in map and table form. These reports can be purchased separately from the FENCO office in Calgary.*

The following analysis is paraphrased from their reports and is based on a breakdown of the southern Beaufort Sea into six separate areas in which ice conditions are fairly uniform. These areas are numbered and separated by dashed lines in Figure 1.

5.1.1 Median Ice Conditions

The ice begins to clear north of Cape Bathurst in the second half of May and in the southern part of Mackenzie Bay in mid-June. The landfast ice has usually disappeared by July 9 and by the end of the month the ice concentration is less than one tenth in the entire area from Herschel Island to Cape Kellett on Banks Island. Minimum ice cover exists on 17 September, then concentrations rise to four tenths over the main area by 15 October and to seven tenths by 22 October (See Appendix II). The variation of the median clearing date and of the median freeze-up date through the area analyzed are shown in Figures 8 and 11.

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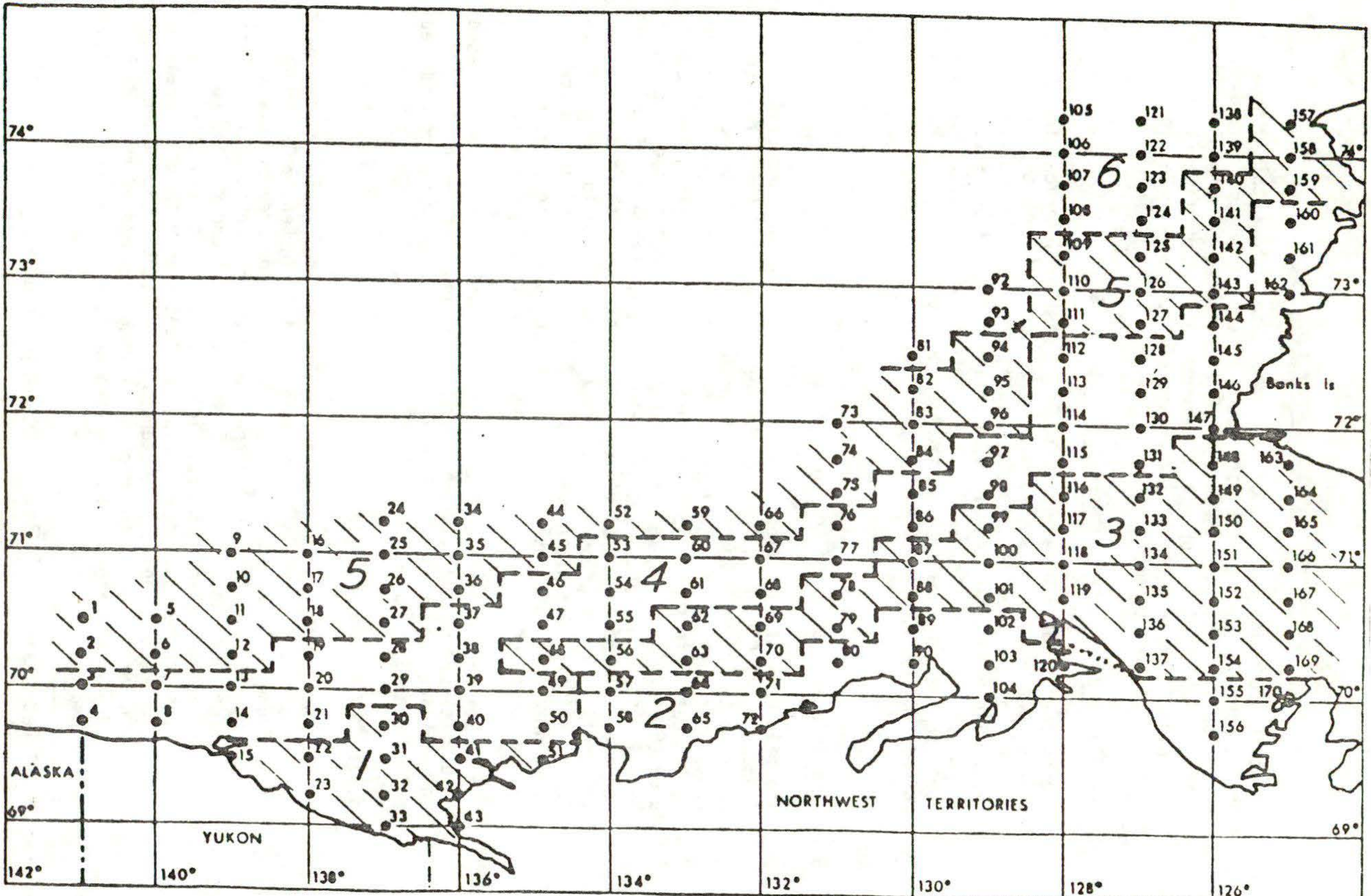

Figure 1. Locations of the 170 data points used in the analysis of weekly historical ice charts.

5.1.2 Frequency of Occurrence of Various Ice Concentrations

The frequency of occurrence of various ice concentrations in percent for each of the six sub-areas, shown in Figure 1, is illustrated in Figures 2 to 7. Using these frequencies it is possible to estimate the expected operating season in each of the six sub-areas. Using the basic data contained in Volume II of the FENCO report is is possible to refine these frequencies for a specific site. The variation in the median length of the operating season (when ice concentration is under two tenths) is shown in Figure 12. Mid-season interruptions due to ice intrusions are not included on this chart.

5.1.3 Best Ice Year in Five

In "good" ice years rather extensive open water is already present in Amundsen Gulf by 21 May and although the fast ice is still in position at the time, clearing is rapid. In Mackenzie Bay the concentration falls to less than one tenth by 18 June. This condition spreads over the entire area by early July and open water remains until mid-October. Freeze-up is then fairly rapid during late October although the ice is thin. The variation of the clearing date is shown in Figure 9. Freeze-up dates are similar to those shown in Figure 11.

5.1.4 Worst Ice Year in Five

In "bad" years the ice concentration remains at seven tenths or more until mid-August except in shallow water areas within thirty nautical miles of shore from Herschel Island to Cape Parry. Minimum ice conditions by mid-September extend this clearing to sixty miles offshore but refreezing begins by 1 October and extensive ice is present by mid-month. The variation of the clearing date is shown in Figure 10.

5.1.5 Number and Timing of Interruptions

Other factors important to ships, besides the total length of the operating season, are those intervals during the summer when ice intrusions occur. Although these cannot be predicted more than a few days in advance, it is interesting to know what has happened in the past. The FENCO report provides a detailed analysis of ice intrusions at a selection of the 170 data points shown in Figure 1, but there are a few broad conclusions which can be reached regarding the duration, time of year and numbers of intrusions which have occurred in the past. These will be touched on later.

Typical results of a FENCO geographical data points analysis are as follows for point #31 at 69° 30'N 137°W.

TABLE 1

#31 at 69° 30'N, 137°W
BEGINNING OF THE OPERATING SEASON - Ice Concentration two tenths or less

	May		June				July				
	21	28	4	11	18	25	2	9	16	23	30
Number of Occurrences	0	0	0	0	6	3	2	4	3	2	1
% on or Earlier	0	0	0	0	28	42	52	71	85	95	100

The first row lists dates in one-week intervals when the ice concentration decreased to two tenths or less at the beginning of the season. The second row shows how often the season has opened on the date immediately above and the third row lists the probability in percent of having the season open earlier. For example there have been three years when the operating season opened on 25 June and there is a 42% probability that the season would open on or earlier than this date at the particular data point. The median in this and the following tables is underlined.

TABLE II

#31 at 69° 30'N, 137°W
LENGTH OF THE OPERATING SEASON

Season Duration In Weeks	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Number of Occurrences	1	2	0	0	1	1	2	1	3	1	1	2	2	2	2	0
% Shorter Season	0	4	14	14	14	19	23	33	38	52	59	61	71	80	90	100

In this table the first row is merely a numerical list of the possible durations in weeks between the beginning of the season when the ice concentration becomes two tenths or less and the end of the season when it increases above two tenths. Ice intrusions during this interval are subtracted. The second row indicates the number of years when a given duration has been observed; i.e. a season of 11 weeks duration has occurred twice. The third row is the probability in percent of having a shorter season; i.e. there is a 23% chance of having a season shorter than 11 weeks.

TABLE III

#31 at 69° 30'N, 137°W
INTERRUPTIONS DURING THE OPERATING SEASON

Number of Interruptions	0	1	2	3	4	5	6	7	8	9	10
Occurrences	7	8	3	2	1	0	0	0	0	0	0
% Occurrences	33	71	85	95	100	100	100	100	100	100	100

This table focusses on those periods when the concentration rises above two tenths in the intervals in the first table, which were subtracted from the total length of the season. The first row lists the possible number of interruptions, the second presents the number of times that a full summer season has had a specific number of interruptions and the third row is the probability of having a season with fewer interruptions. For example there have been seven summers with no interruptions, 8 seasons with one and there is thus a 33% chance of having no interruptions and a 71% chance of having less than two.

TABLE IV

#31 at 69° 30'N, 137°W
DURATION OF INTERRUPTIONS DURING THE OPERATING SEASON

Total Duration of Interruption In Weeks	0	1	2	3	4	5	6	7	8	9	10
Number of Occurrences	7	4	4	4	0	1	1	0	0	0	0
% Shorter	-	33	52	71	90	90	95	100	100	100	100

In this table the total time lost during the operating season is treated, in effect a summation of the number of times that ice intruded and its effect on the operating program. The first row lists the possible total durations, the second the number of times they have occurred and the third is a cumulative percentage probability of having a season with briefer periods of ice intrusion.

TABLE V

#31 at 69° 31'N, 137°W
END OF OPERATING SEASON

	August				September				October					
	6	13	20	27	3	10	17	24	1	8	15	22	29	Later
Number of Occurrences	1	0	0	0	0	1	2	0	2	1	2	2	2	8
% Later	95	95	95	95	95	90	80	80	71	66	57	47	38	

The final table presents the dates on which the ice concentration rose above two tenths and remained so, the number of times it has happened on a particular date and the percentage probability of having a later end to the season. For example, in one year the season ended on September 10, the second earliest on record and there is thus a 90% probability that the end will occur later than this date.

The FENCO report lists eleven different locations in the above format but generalizations are rather difficult to make. At first one would expect that the number and duration of these interruptions would increase with the distance from shore but this is only partially true. In some cases, the opening of a polynya outside the fast ice creates an early start to the operating season but later, break-up of the fast ice results in intrusions at a time when outer sites will retain plentiful ice cover. If this peculiarity is taken into account a longer uninterrupted season in coastal waters becomes apparent. Intrusions are most common in the middle distance from shore where the pack may advance and retreat a number of times during the summer. In even deeper water, the greater decrease in the length of the operating season itself means that interruptions are fewer and will last longer since average ice concentrations are higher.

5.1.6 Ice Zones

In the southern Beaufort Sea there are three ice zones which vary in size from season to season and from year to year. The first of these is the fast ice zone along the continental coast and on the west coast of Banks Island. Its seaward limit is close to the 20 metre isobath and can normally be identified by the abundance of ridges, the change to seaward of ice concentrations from ten tenths to lesser amounts and the presence of open water leads, depending on wind conditions. There is usually a ridged ice zone along the edge of the fast ice where highly deformed ice is created by pressure from moving pack further offshore and the grounding of floes.

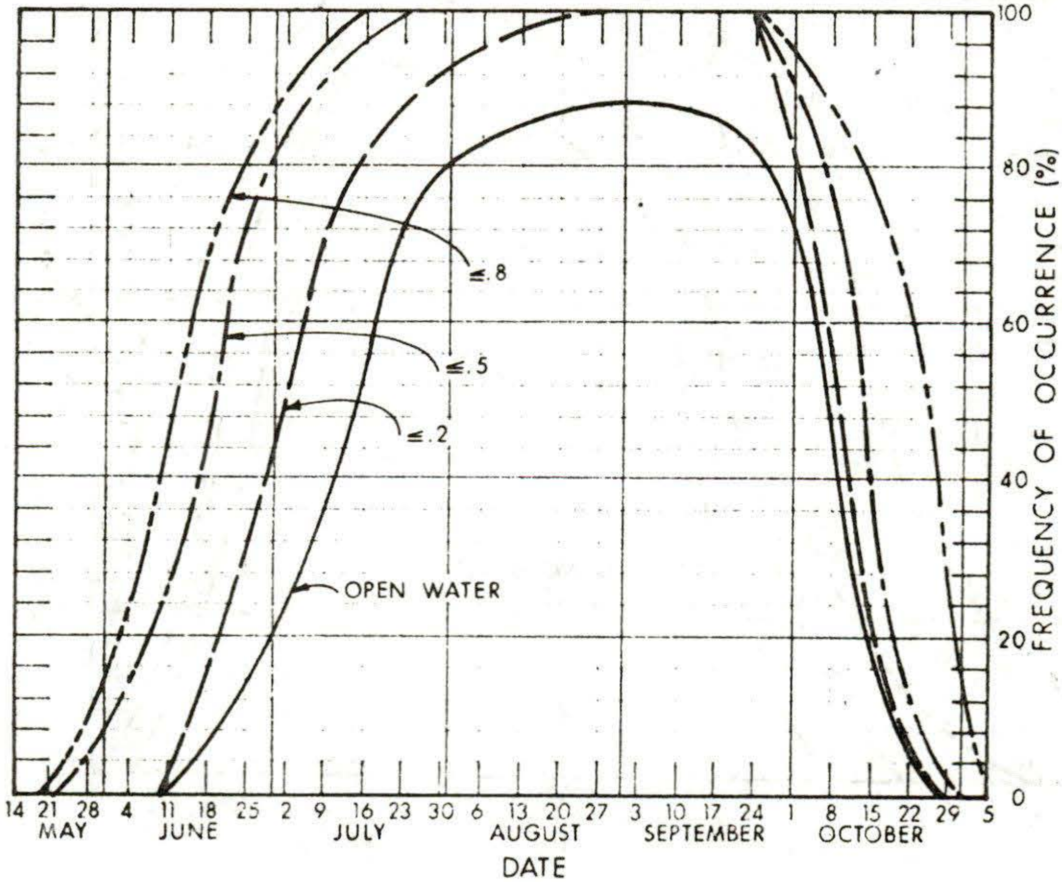

FIGURE 2. TOTAL ICE CONCENTRATION - AREA 1

The coastal area of Mackenzie Bay including data points 15, 22-23, 30-33, 41-43 and 51 (Figure 1). Clearing is early and in most seasons nearly complete. There is only a slight variation in conditions from North to South in the area.

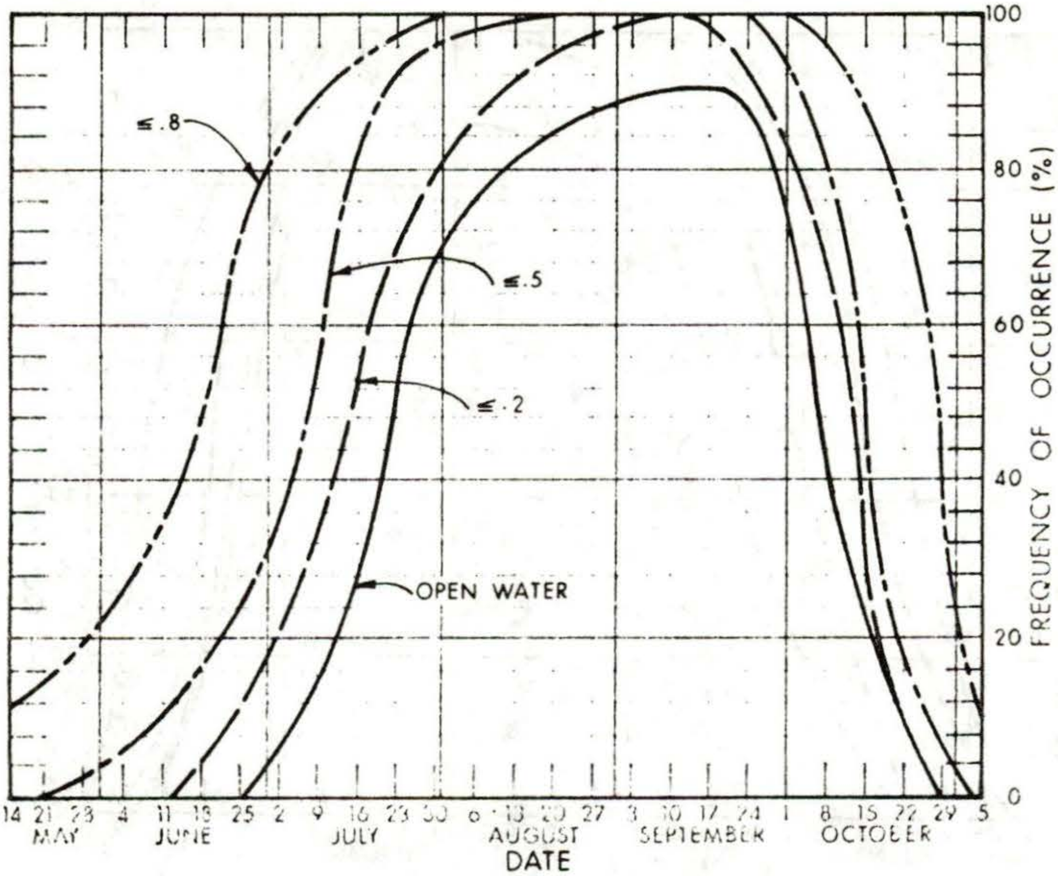

FIGURE 3. TOTAL ICE CONCENTRATION - AREA 2

The coastal area from Richards Island to Cape Bathurst and the entire area of Franklin Bay - data points 57 58, 64 65, 71 72, 80, 89 90, 102-104, 120, 155 156 & 170 (Figure 1).

This is essentially the fast-ice area where clearing is initially somewhat delayed but then progresses rapidly in July. Clearing is just as consistent as in Area 1 but is slightly later in developing.

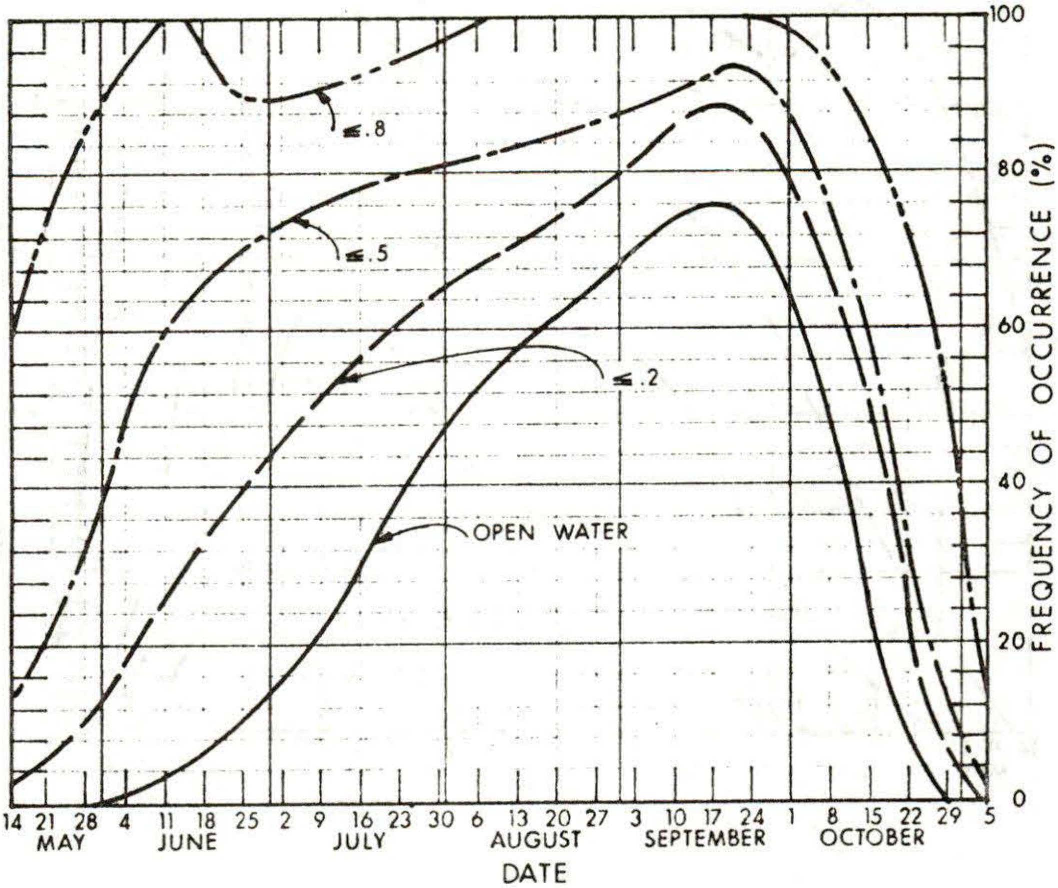

FIGURE 4. TOTAL ICE CONCENTRATION - AREA 3

The near offshore area from Richards Island to Cape Bathurst and Cape Kellett including the approaches to Amundsen Gulf. Data points included are 48, 56, 62 63, 69 70, 78 79, 87 88, 99 to 101, 116 to 119, 132 to 137, 148 to 154 and 163 to 169(Figure 1).

The formation of offshore polynyas results in an early decrease in ice cover but clearing progresses slowly from early June until early September. The frequency of complete clearing is lower than in either Areas 1 or 2.

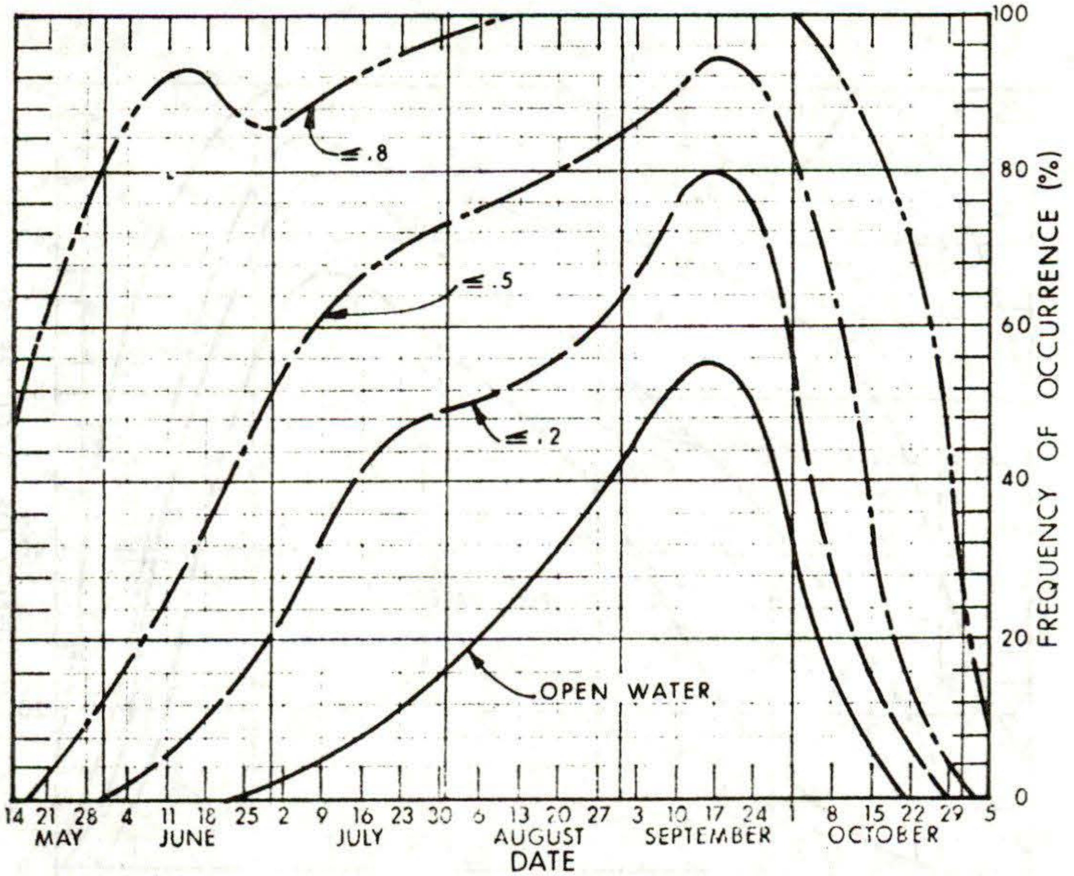

FIGURE 5. TOTAL ICE CONCENTRATION - AREA 4

The offshore area from Herschel Island to the west coast of Banks Island. Data points included are 3, 4, 7, 8, 13, 14, 19 to 21, 28, 29, 37 to 40, 46, 47, 49, 50, 53 to 55, 60, 61, 67, 68, 76, 77, 85, 86, 97, 98, 112 to 115, 128 to 131 and 144 to 147. Clearing is much less common than in inshore areas but there is a lengthy period when the ice is well dispersed.

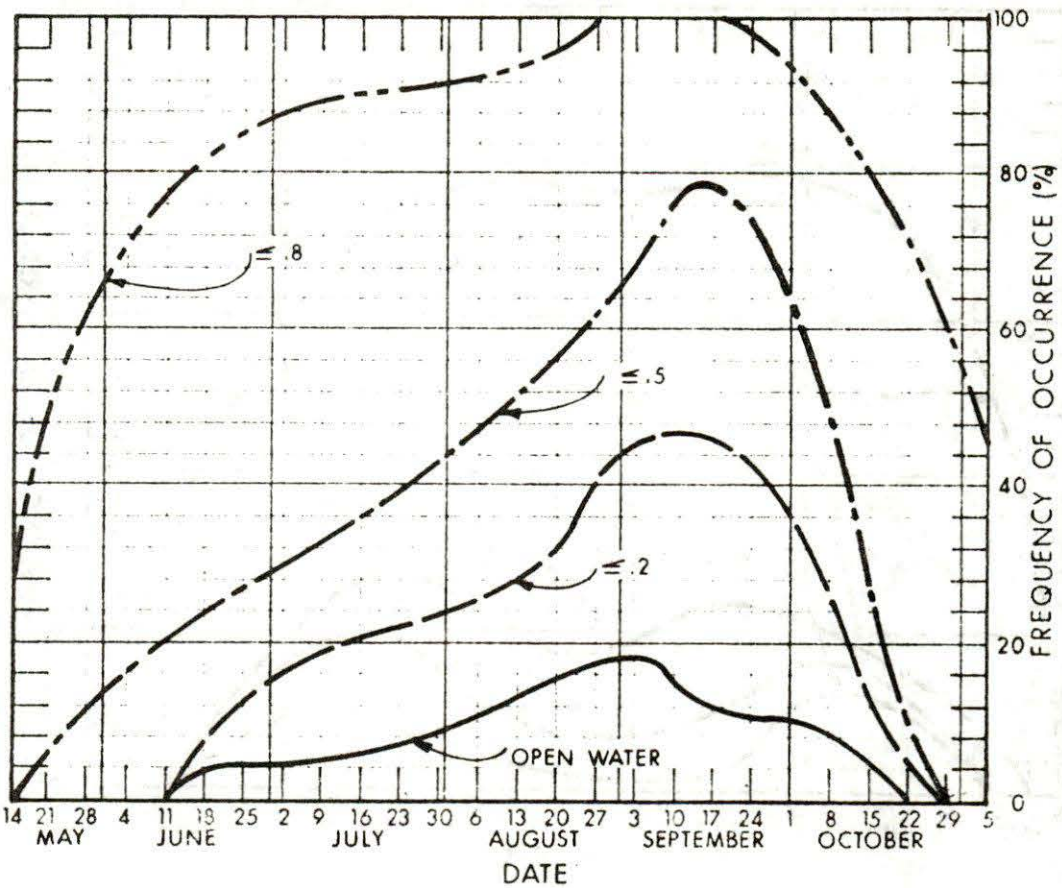

FIGURE 6. TOTAL ICE CONCENTRATION - AREA 5

The deep water area where the fringes of the Arctic Pack are usually present. Data points included are 1, 2, 5, 6, 9 to 12, 34 to 36, 44, 45, 52, 59, 66, 73 to 75, 82 to 84, 94 to 96, 109 to 111, 125 to 127, 140 to 143, 158 and 159 (Figure 1).
Clearing or even dispersed ice is uncommon in this area but the trend for slowly improving ice conditions from May to mid September is evident.

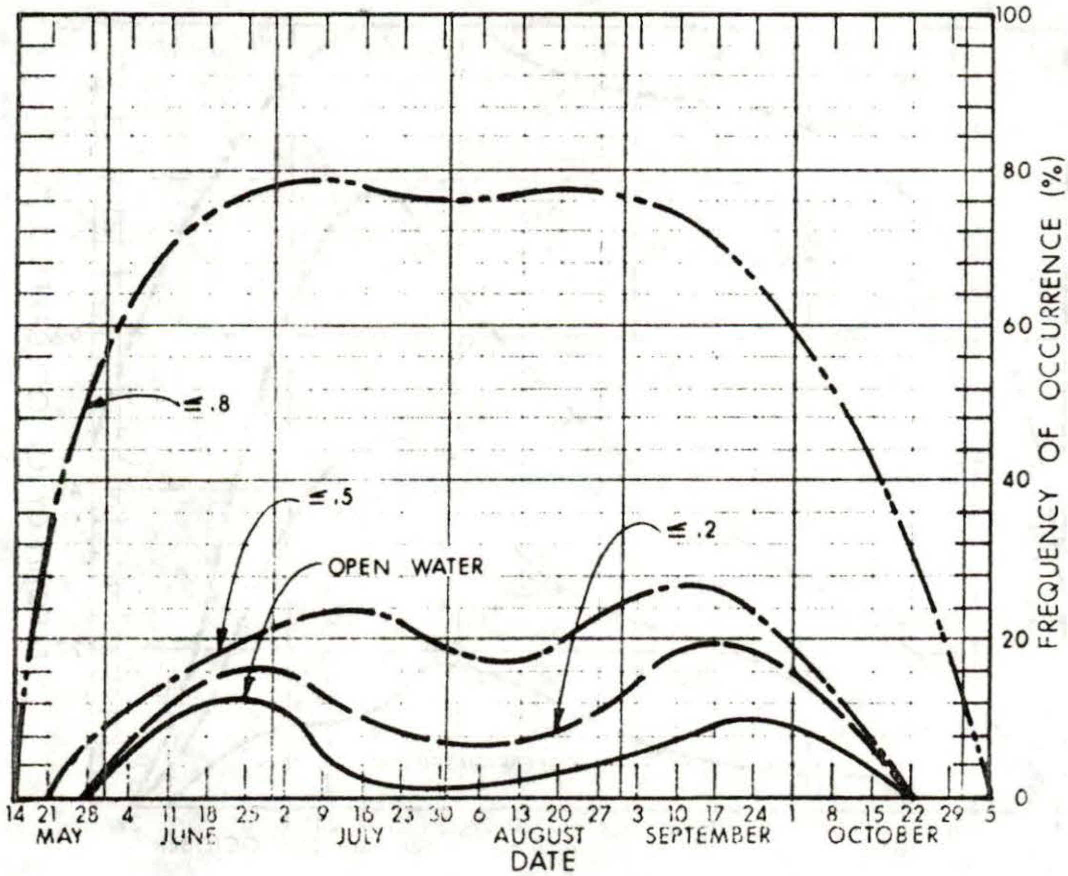

FIGURE 7. TOTAL ICE CONCENTRATION - AREA 6

The northern offshore area west of Banks Island. Data points included are 81, 92, 93, 105 to 108, 121 to 124, 138 and 139. (Figure 1).

Brief ice dispersals can occur in this area at any time during the summer but congested conditions are usually present.

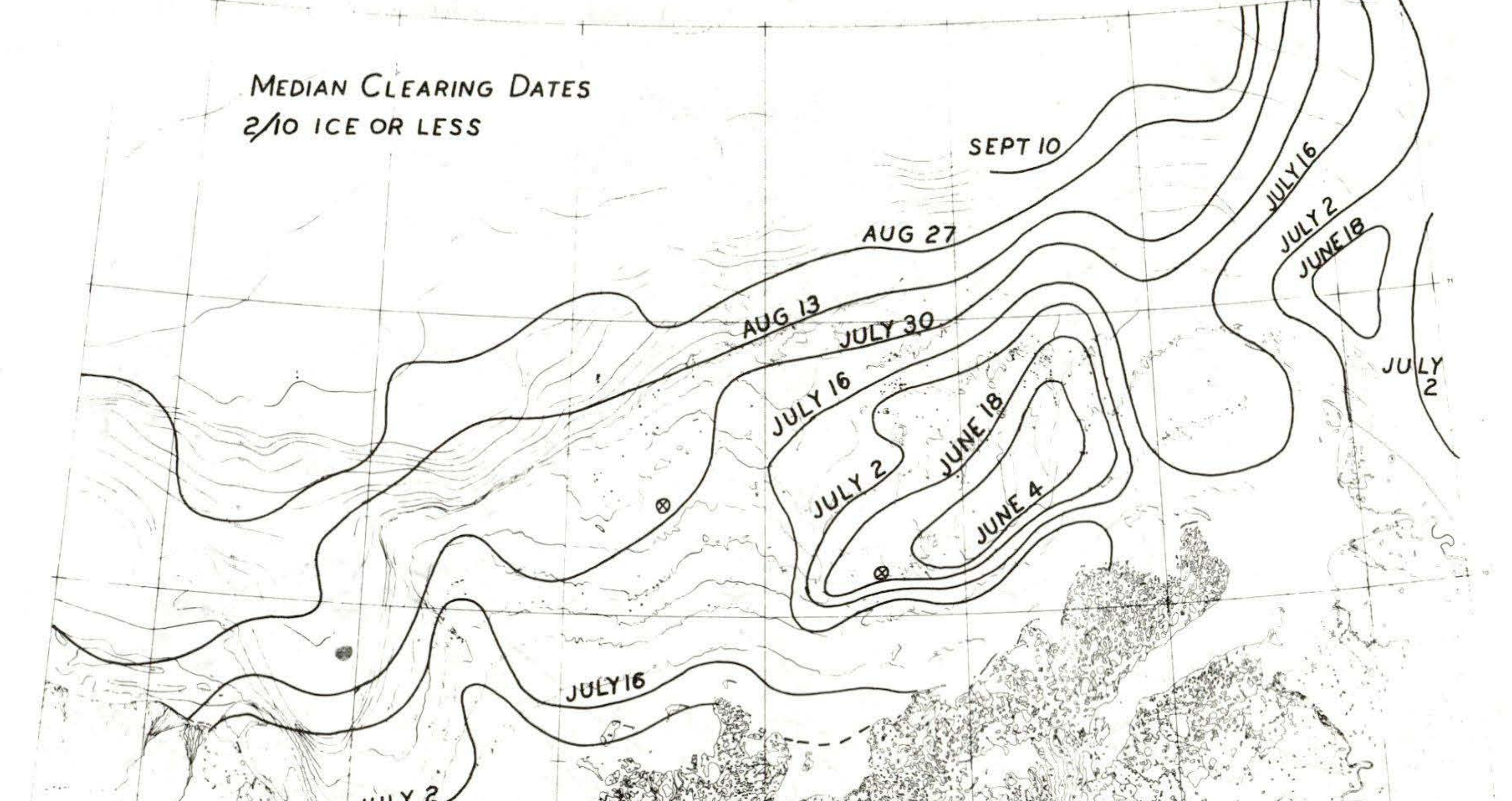

Figure 8. Map of Median Clearing Dates - 2/10 ice or less.

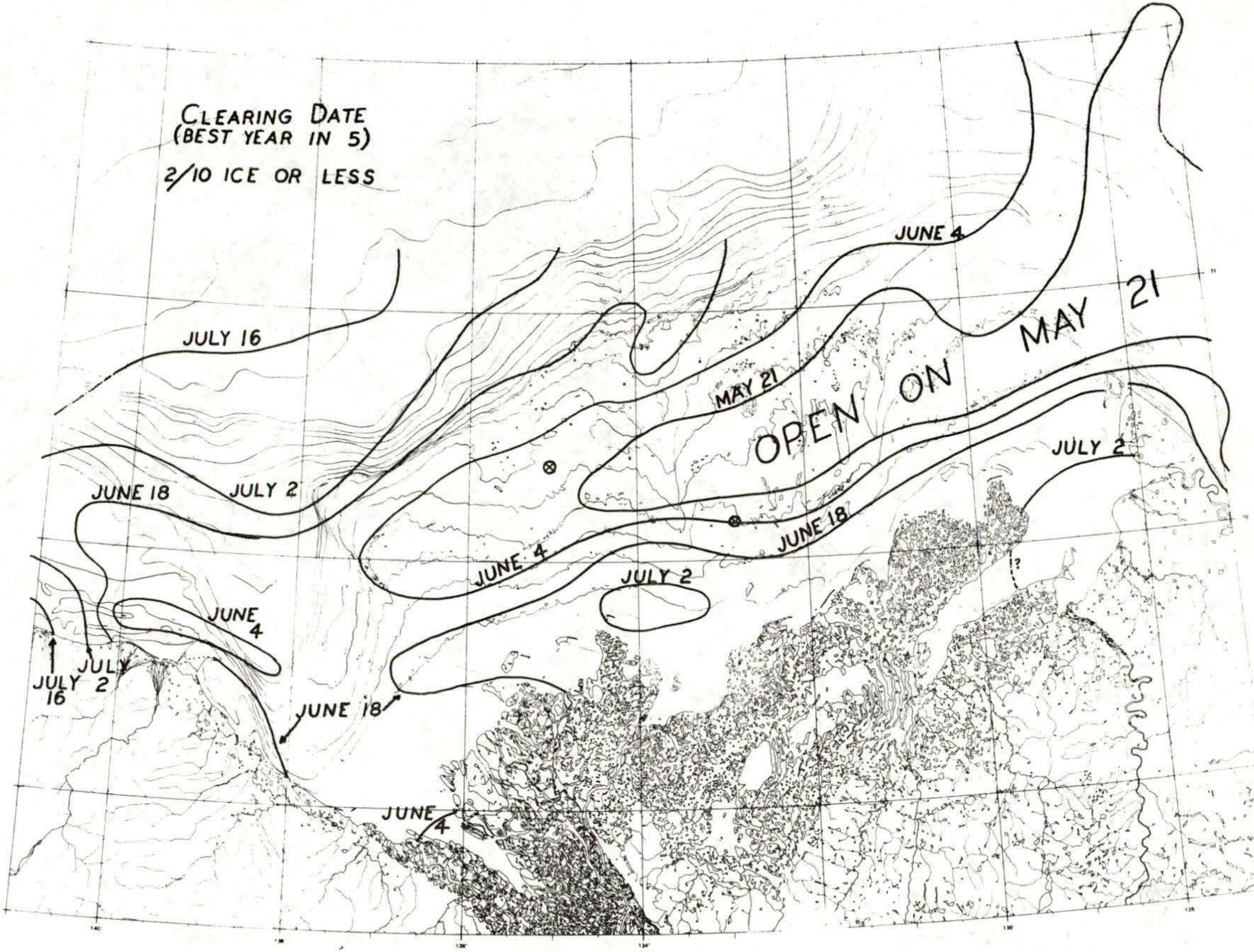

Figure 9. Map of Clearing Date (Best year in 5) - 2/10 ice or less.

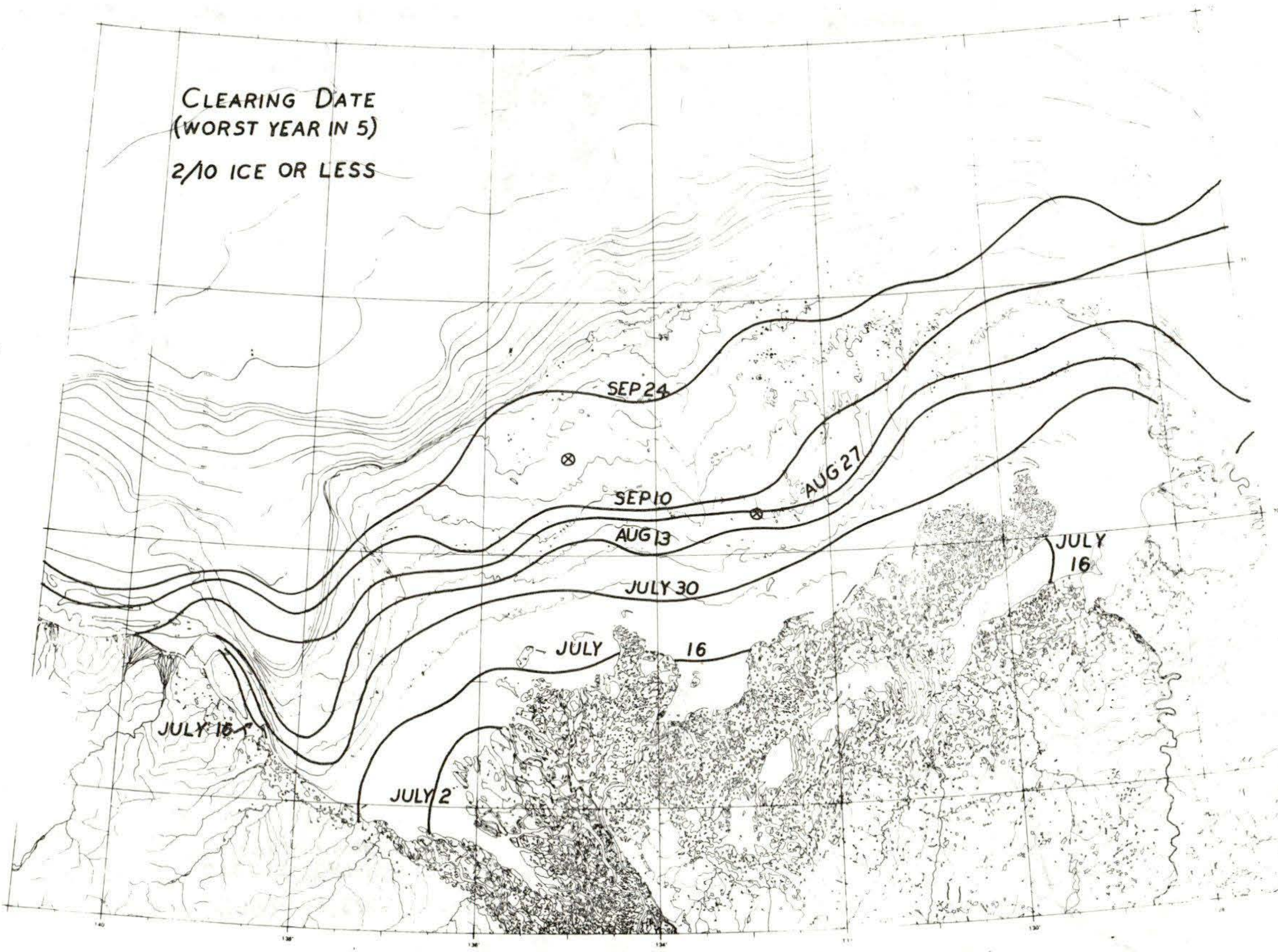

Figure 10. Map of Clearing Date (Worst year in 5) - 2/10 ice or less.

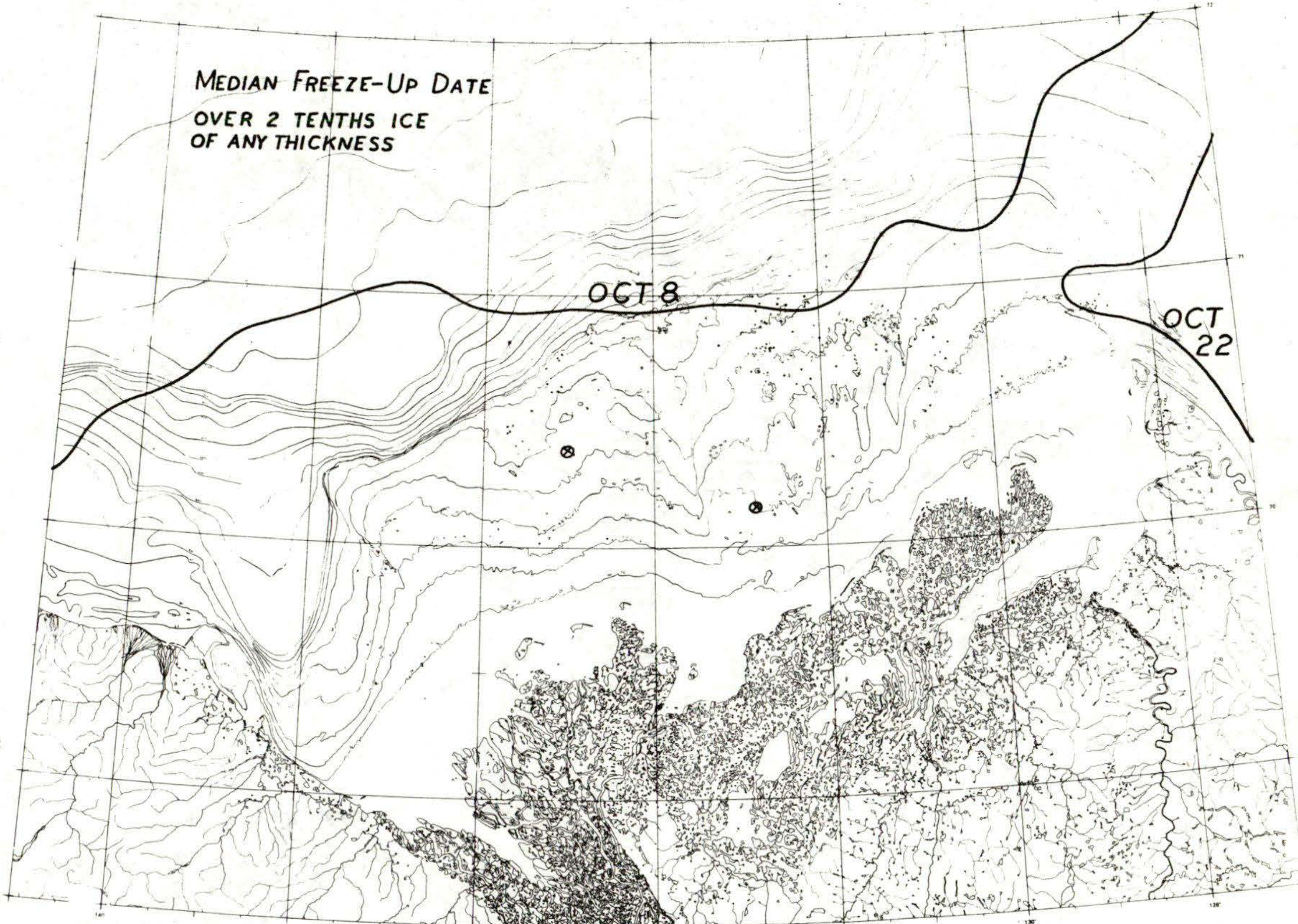

Figure 11. Map of Median Freeze-up Date - Over 2/10 ice of any thickness.

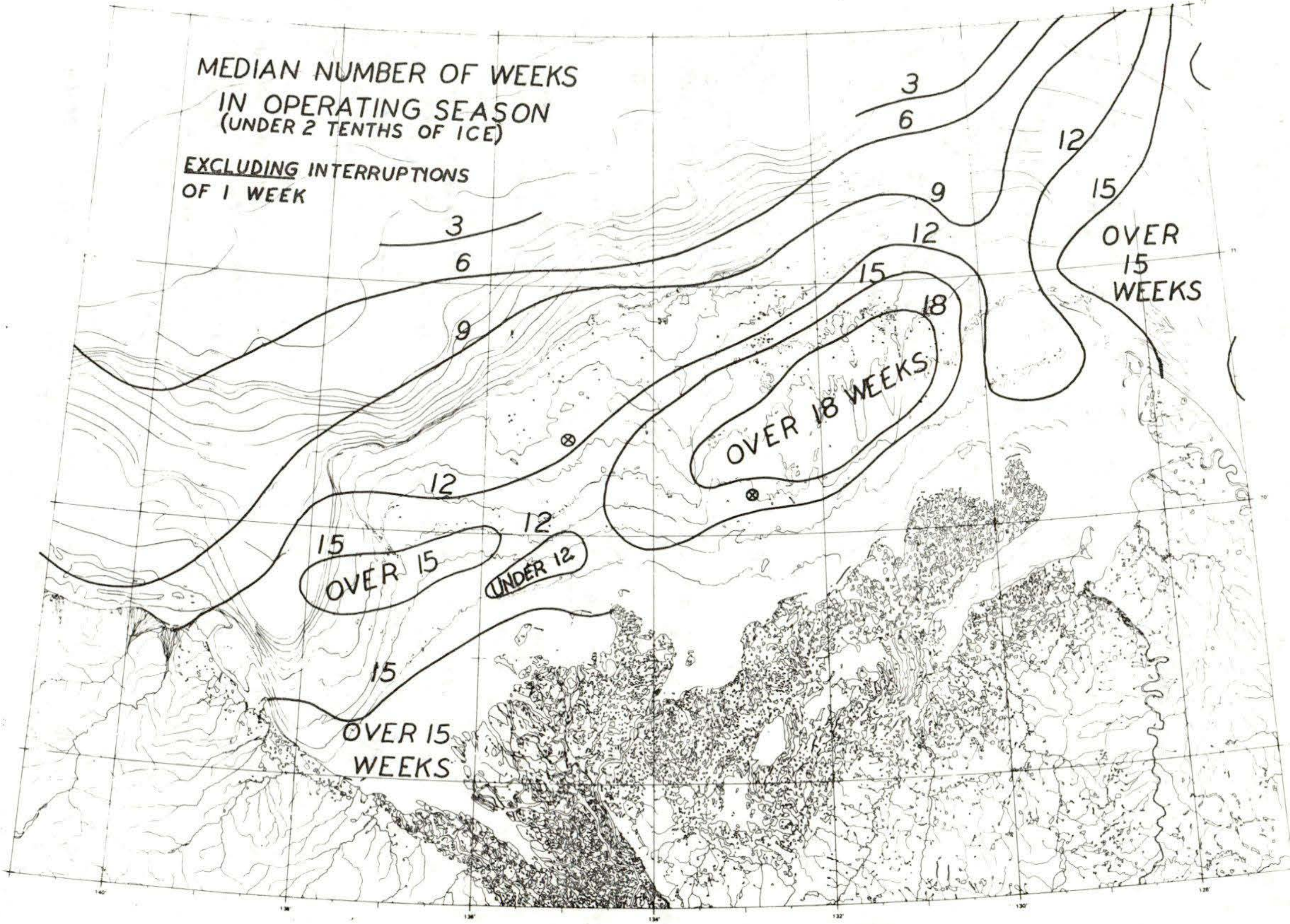

Figure 12. Map of Median number of weeks in Operating Season - under 2/10 of ice.

The second major zone is a part of the drifting offshore pack ice where first-year ice predominates during the colder part of the year and where open water conditions may develop progressively during the melting season. This zone is characterized by variable ice concentrations, floe sizes and ice thicknessess. It also varies in extent from season to season and from year to year.

The third major zone is also within the offshore pack, but there old ice is predominant and the changes in ice concentrations and ice thicknesses are somewhat restricted. The position of the boundary between Zone Two and Three is variable and is dependent on the gross movement of the Arctic pack itself. In most years this third zone lies near the northern limit of the study area and in the offshore area west of Banks Island. In the "worst" ice years, old ice can be driven to the offshore boundary of Zone One because of persistent onshore winds such as those of 1974. Melting of the first-year ice in Zone Two is a prerequisite for a major invasion of old ice.

5.1.7 Autumn Ice Build-Up

In autumn, the termination date of offshore drill ship operations at most sites is related more to ice growth than to intrusions of the Arctic pack from the northern Beaufort Sea. There are two problems here, one being the probable ice conditions at the drilling site and the other, ice conditions on the exit route or at an overwintering site, assumed to be in the Beaufort Sea. Access to drilling sites in the spring from Beaufort Sea harbours can be achieved earlier than is possible from locations west of Point Barrow, and retreat from the sites in the autumn can be delayed somewhat longer since freeze-up is later in the southeastern Beaufort Sea than it is off Point Barrow.

From charts of median ice concentration (Appendix II) it is apparent that the formation of ice away from shore is somewhat slower than in the shallow coastal waters. It follows that ice conditions at an overwintering harbour will control the termination date of drilling operations rather than ice conditions at the drilling site or en route from it.

Good temperature records and ice thickness measurements are available for Sachs Harbour and Cape Parry and from Tuktoyaktuk to a lesser extent. From an analysis of these date the median freeze-over date at Sachs Harbour is 12 October and at Cape Parry 20 October. Thirty percent of the freeze-up dates are within 10 days of this date at Sachs Harbour and within five days at Cape Parry.

The median date for the growth of 30 cm of ice at Sachs Harbour is 27 October. Up to this date, there is an average accumulation of 380 Freezing Degree Days (Celsius).

Thirty percent of the dates lie within 2 days of this median. The median date for 30 cm of ice growth at Cape Parry is 31 October after 270 Freezing Degree Days have accumulated. Thirty percent of the dates lie within 3 days of the median.

At Tuktoyaktuk the median date for 30 cm of ice growth is 4 November after 305 Freezing Degree Days have occurred. Thirty percent of the dates lie between 2 and 5 November. No interpolation of freeze-over dates has been attempted at this site because the run-off from the Mackenzie River has a great influence on the ice formation in the bay.

It is apparent that cessation of offshore operations using drilling vessels should be planned for mid-October. This conclusion is not greatly different from what one would expect from a simple consideration of the offshore ice conditions shown in Figures 2 to 6.

5.2 A Study of the Motion of Individual Ice Floes in the Beaufort Sea

5.2.1 Introduction

Initially offshore exploratory drilling is a summer season operation and hence there is an obvious need for explicit ice forecasts for the area of operations. At present, the Canadian ice prediction service is designed to provide advice to coastal shipping during resupply operations, and as a result refinements in data collection, data analysis, data delivery and ice predictions are needed. In particular the prediction techniques themselves must be improved upon.

With these requirements in mind, an analysis of the motion of specific ice floes was undertaken to provide additional examples of both the mean and extremes of ice motion that may occur. Images from ERTS are available for both the 1973 and 1974 seasons and from these it is possible to plot the tracks of ice floes for two or three days when images from overlapping orbits were sufficiently cloud free. In one case a floe could be identified on consecutive cycles and its total movement over an 18-day interval was plotted.

Further information on the drift of individual floes was obtained in the summer of 1974 during a surface current study (Garrett and MacNeill 1976) where radio beacons placed on floes in the near-shore area were tracked by fixed wing aircraft. The drifts of these floes has been related to winds derived from atmospheric weather charts.

5.2.2 Satellite Imagery

5.2.2.1 Available Data

Marko and Gower (1974) examined the drift of floes in the summer of 1973 and in particular cases plotted their drift in mid-June, early July and late August. Their reported accuracy of location was estimated at 1% of the distance from shore, hence for further studies based on their work one is limited to those cases where the rate of motion was sufficiently large to permit reasonable estimates of both direction and rate of actual drift. An added step in this analysis is to relate the ice motion plotted to the meteorological conditions at the time.

One of the procedures used in Ice Central* is to prepare a daily mean surface-pressure chart from which mean daily wind vectors can be derived. For the past few years, the charts have shown contours of the height of the 1000 millibar pressure surface. The spacing and orientation of the height contours are closely related to surface wind conditions.

Additional floe drifts were examined using Quiklook ERTS imagery for the days 15 to 16, 16 to 17, 17 to 18 and 18 to 19 of June 1973. Only those images showing coastlines and identifiable floes in the same frame were used. Off Cape Bathurst, results showed a median deflection angle of +16° and a median ice drift to wind speed ratio of 0.0262, while in the Cape Kellett area the median deflection angle was 47° for five different floes and the median speed ratio was only 0.0106. In the latter area, water current from the southwest probably existed.

Imagery obtained during 1974 was examined at Ice Central to obtain more examples of the drift of specific ice floes. Unfortunately, the season was a severe one with the pack remaining near shore throughout the summer and free drift of relatively isolated floes rarely occurred. The examples listed in Table 1B were obtained but in most cases these represented floes whose drift was affected by other ice in the vicinity.

5.2.2.2 Analysis

There is little quantitative data that can be derived from Tables 1A and 1B but the internal consistency leads to some interesting qualitative conclusions. Floes A, B and C (Figure 13) moved at comparable speeds and had similar deflection angles until June 19-20 when the deflection angles abruptly changed from 10° to 30° to the right of the wind to 5° to 25° to the left of the wind without a significant change in the drift speed. It would appear either a water current flowing from northeast to

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*Ice Forecasting Central, Environment Canada Trebla Building, Ottawa.

southwest was encountered or the plotted positions are in error. The fact the angle was even greater during the period June 20 to 21 (when only one floe was tracked) indicates that since the wind did not change much, either the current increased or an error in positioning existed. In view of the distance from shore and the circle of possible error, the latter appears to be most likely. Figure 15 shoes a day-by-day plot in June 1973 of Floe B.

Floes D, E and F (Table 1A, Figure 14) are another group whose drifts can be compared. Floe D followed the wind on July 4 to 5 when it was near the shore, but then from July 5 to 7 it moved 75° to 80° to the right of the wind as it drifted seaward under east-southeasterly winds. A southwest to northeast current of 10 to 12 nautical miles per day must be assumed if the same ratio of ice drift to wind speed continued from the previous day.

Floe F was somewhat further from shore but again large positive deflection angles occurred between 5 to 8 July and in this case could have been caused by a current from south-southwest flowing at 10 to 12 nautical miles per day.

Floe E was much further east and had a small deflection to the left of the wind which could have been caused by a water outflow around the south end of Banks Island, a motion that has been noticed during break-up in other summer seasons. With only two position fixes, no quantitative estimate of this current is possible.

Floes G_1, G_2 and G_3 (Table 1A, Figure 14) all observed in the same 48-hour span, moved at comparable speeds with modest deflections to the right of the wind vector.

If all the drift data are combined except where significant water currents appeared to have existed, the median deflection angle is 22° to the right of the wind vector and median ratio of ice drift to wind speed is 0.0337. Both results fit well into the range reported in previous studies going back to the days of Nansen (1897).

Table 1B shows drift data from ERTS imagery 1974 and is to be compared with Table 1A which concerns 1973 imagery. Major differences are immediately apparent. The ice drift to wind speed ratios are only one third of those found in 1973 and the deflection angles, are extremely variable. In 1973, large free-floating floes were studied when ice concentrations were six to eight tenths. Those in 1974 were in concentrations

TABLE 1A

ICE DRIFT INTERPRETED FROM ERTS IMAGERY IN JUNE AND JULY - 1973; AMUNDSEN GULF AND WESTERN BANKS ISLAND

Dates	Ice Velocity V_i Direction Degrees	Ice Velocity V_i Speed nm/day	Wind Velocity V_w Direction Degrees	Wind Velocity V_w Speed Knots	Speed Ratio $\frac{V_i}{V_w}$	Deflection Angle Degrees to Right of Wind
Floe A						
June 15-16	095	9.6	085	16	0.0250	+10
16-17	135	11.7	095	20	0.0244	+40
17-18	145	9.0	115	23	0.0163	+30
Floe B						
June 15-16	110	17.0	085	16	0.0444	+25
16-17	135	25.4	095	20	0.0529	+40
17-18	135	20.0	115	23	0.0363	+20
18-19	125	17.0	115	18	0.0395	+10
19-20	085	9.0	110	18	0.0209	-25
20-21	005	6.4	115	15	0.0296	-110
Floe C						
June 16-17	145	12.7	095	20	0.0500	+50
17-18	135	6.9	115	23	0.0125	+20
18-19	140	9.6	115	18	0.0222	+25
19-20	105	11.1	110	18	0.0258	+20
				Medians	0.0258	+20
Floe D						
July 4-5	130	2.0	130	4	0.0386	0
5-6	185	11.1	110	9	0.0097	+75
6-7	185	10.6	105	8	0.0192	+80
Floe E						
July 4-5	120	17.0	130	4	0.0333	-10
Floe F						
July 5-6	165	10.6	110	9	0.0491	+60
6-8	140	10.1	105	7	0.0565	+35
Floe G_1						
July 8-10	330	15.4	300	6	0.0201	+30
Floe G_2						
July 8-10	310	18.5	300	6	0.0243	+10
Floe G_3						
July 8-10	300	13.2	300	6	0.0174	0
				Medians	0.0243	+30

TABLE 1B

ICE DRIFT INTERPRETED FROM ERTS IMAGERY OFF CAPE KELLETT IN JULY AND OFF TUK PENINSULA IN AUGUST 1974

Dates	Ice Velocity V_i		Wind Velocity V_w		Speed Ratio	Deflection Angle Degrees to Right of wind
	Direction Degrees	Speed nm/day	Direction Degrees	Speed Knots	$\frac{V_i}{V_w}$	
Floe Z						
July 17-18	158°	1.4	145°	6	0.0097	+13
18-19	135	0.8	210	6	0.0056	-55
Floe Y						
August 5	350	14.7	085	44*	0.0029	-95
August 5-6	005	1.4	100	7	0.0081	-95
Floe X						
August 25-26	145	0.8	135	12	0.0028	-10
Flow W						
August 25-26	200	0.7	135	12	0.0059	+65
Floe V						
August 25-26	202	1.5	135	12	0.0052	+65
				Median	0.0056	-10

* Resultant wind over 18 day interval

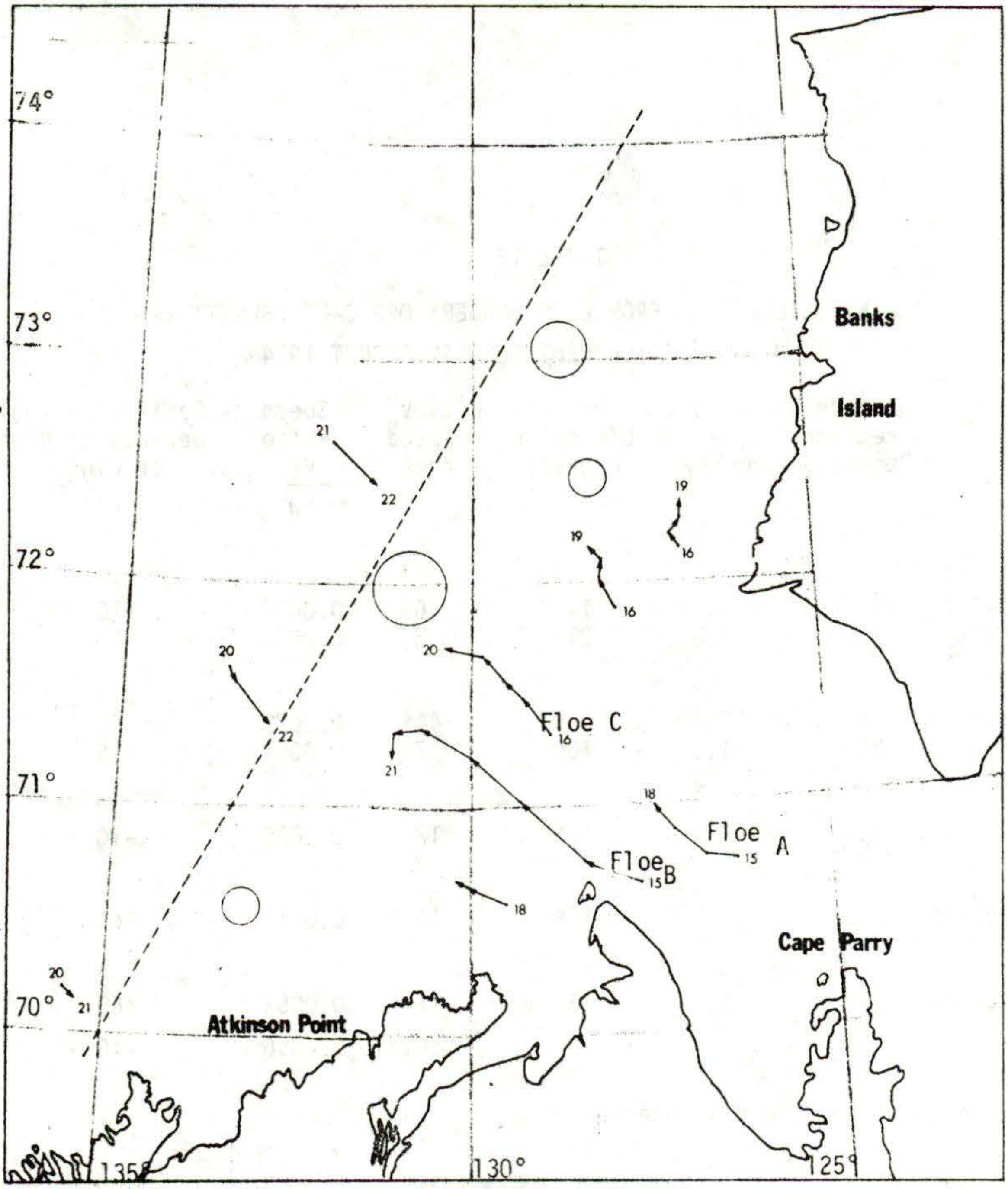

Figure 13. (After Fig. 3a of Marko and Gower)

The daily positions of several ice floes in June 1973. The uncertainties in the determinations are represented by the size of the circles in each area. The dashed line represents the edge of the congested portion of the polar pack.

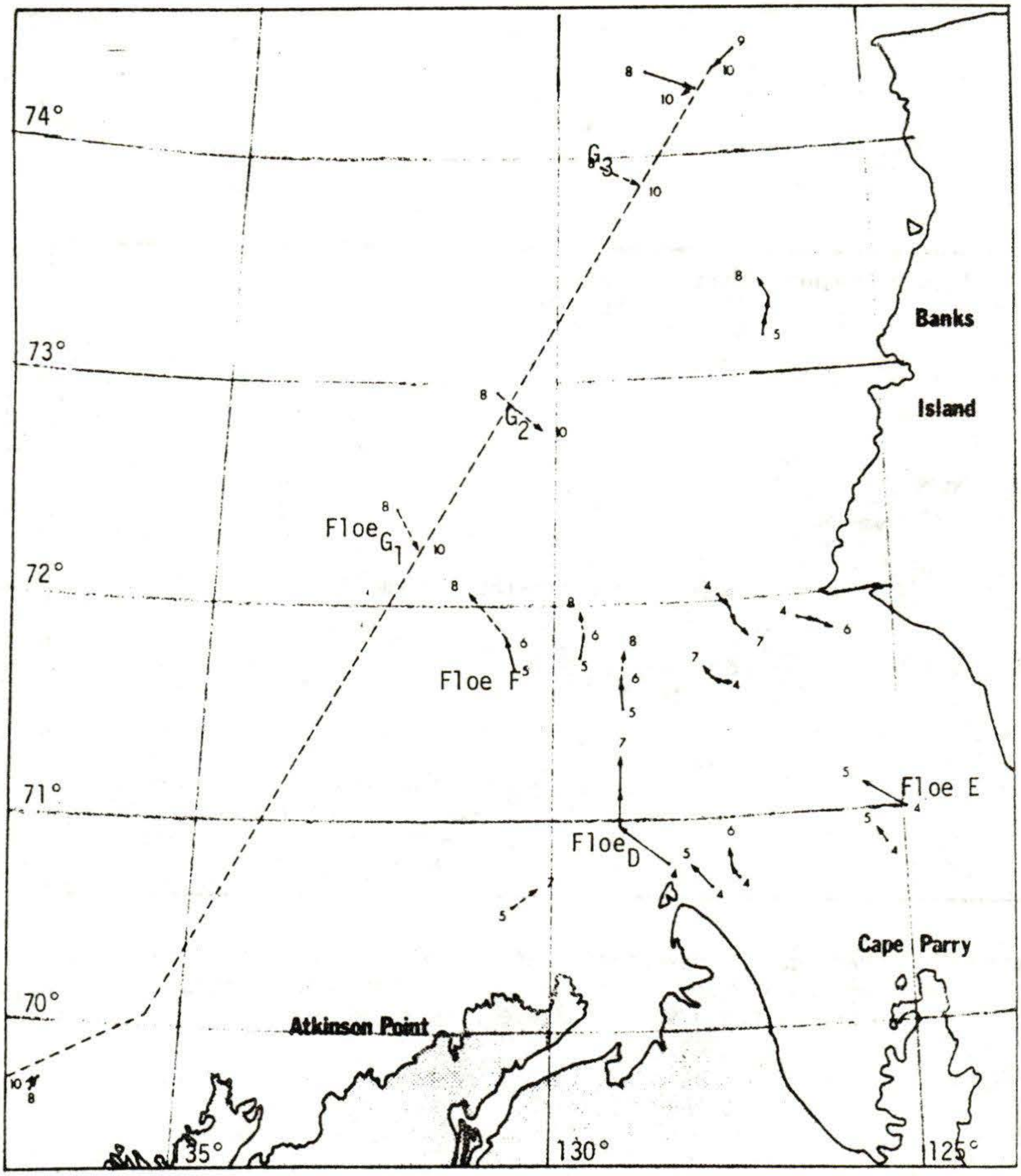

Figure 14. (After Fig. 3b of Marko and Gower)

The daily positions of several ice floes in July 1973. The dashed line represents the edge of the congested polar pack ice.

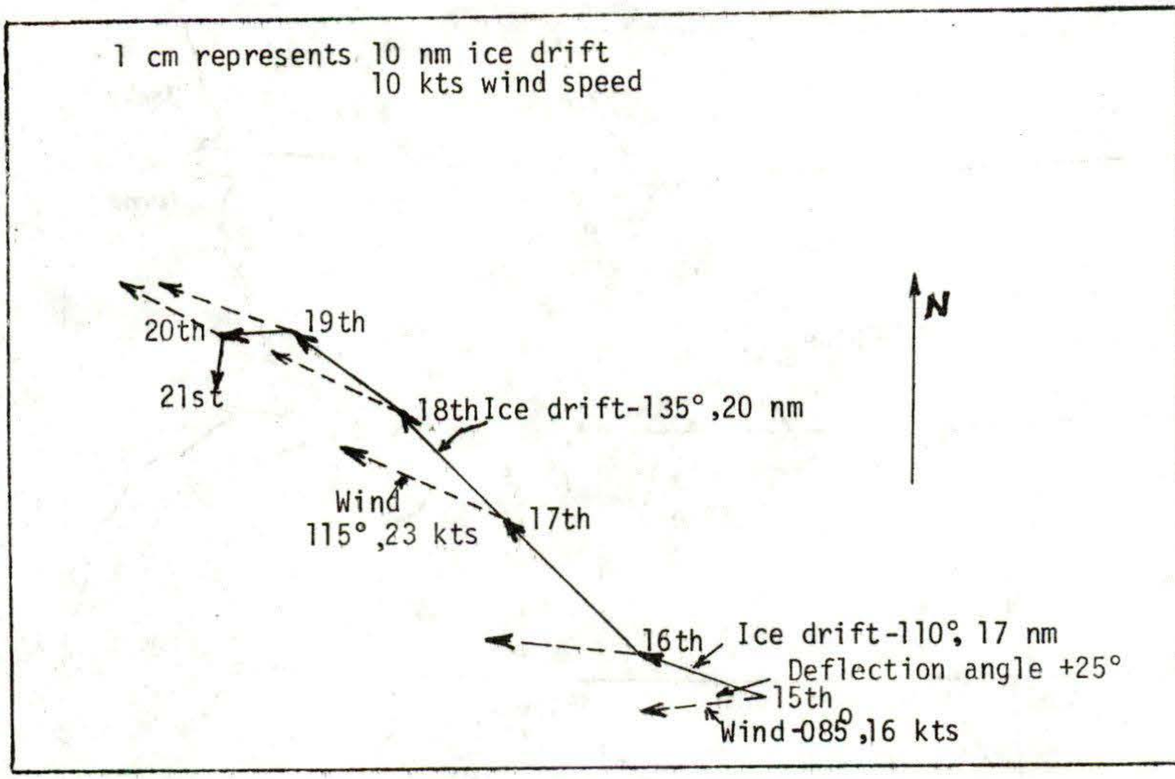

Figure 15. Graphical representation of the drift of Floe B. Ice vectors are solid lines and associated wind vectors are dashed lines. Days indicated are in June 1973.

greater than nine tenths so there was a significant effect on one floe by another. As a result the data in Table 1B is not directly useful in the study of wind drift of individual floes but it does indicate the trend in rates of drift occurring when ice concentrations are high.

5.2.3 Drift Buoys and Beacons

5.2.3.1 Data Available

Additional ice drift data were obtained from a Beaufort Sea Study concerned with the measurements of surface currents (Garrett and MacNeill 1976). Because the ice remained close in-shore during the summer of 1974 it was possible to examine the drift of a few ice floes tagged with radio beacons and tracked by a fixed-wing aircraft. Direct field measurements of floe motions were related to actual winds as well as to those derived from mean daily pressure charts.

Table II shows the detailed drift of one ice beacon. The remainder are listed in Appendix I.

5.2.3.2 Analysis

The orientation and spacing of contour lines on the 1,000 millibar height chart indicates the geostrophic wind velocity at that level. Because of friction, surface winds are deflected to the left by about 25° and speeds are somewhat reduced, the amount being dependent upon the stability of the air, the roughness of the terrain and other factors. When ice motion is being studied, one can first compare the displacement of an ice floe in relation to the surface wind driving it and also compare the ice drift vector derived from the pressure chart depicting the meteorological conditions at the time. This is the procedure followed in most ice forecasting work for predicting surface winds from synoptic and prognostic weather maps and is used to forecast the ice motion during the ensuing period.

In Table II, the median speed ratio of the wind and ice motion and the deflection angles fit quite reasonably into the previous data listed in Table I. In Table II, winds derived from the mean 1,000 mb height charts are compared with ice drift. Since ice moves to the right of the wind and the wind itself is deflected to the left of the contour lines by a similar amount, very small deflection angles are expected. In this case the median was only 5°, close to the limit of accuracy of the wind determination.

TABLE II

MOTION OF DRIFT BEACON #1 NEAR 70° 30'N, 133°W

Dates	Ice Velocity V_i		Derived Wind Velocity V_w		Speed Radio	Deflection
	Direction Degrees	Speed nm/day	Direction Degrees	Speed Knots	$\frac{V_i}{V_w}$	Angle Degrees to Right of Wind
July 14-15	075°	1.7	090°	12	0.0057	-15°
15-16	100	1.7	100	12	0.0079	0
16-17	133	2.0	145	10	0.0080	-12
17-18	313	1.0	210	9	0.0045	+103
18-20	313	4.5	010	10	0.0096	-57
21-22	110	1.0	115	6	0.0067	-10
22-24	103	6.0	090	16	0.0071	+13
24-25	103	3.5	(Light and variable)		-	-
25-26	346	0.3	(Light and variable)		-	-
26-27	160	1.5	(Light and variable)		-	-
27-29	210	0.3	215	6	0.0028	-5
29-30	210	2.0	180	12	0.0056	+30
30-31	238	1.0	125	9	0.0046	+113
31-02	308	5.5	035	11	0.0108	-87
Aug. 02-03	115	4.5	(Light and variable)		-	-
		MEDIAN			0.0067	-5

Some anomalous deflection angles observed within the two week period need further examination. On July 17 to 18 there was a deeping low west of Tuktoyaktuk which subsequently moved across the Beaufort Sea to Melville Island. In this case the derived wind was related to the overall circulation around the centre of a developing low while the ice motion resulted from stronger winds which occurred after the passage of the centre. The observed wind reported by Garrett and MacNeill (1976) at the beginning of the interval between fixes was 180° at 6 knots. A 'storm' was mentioned at this time in their report so it is expected that the ice drift would follow the stronger wind direction. A deflection angle of 57° to the left of the wind occurred similarly in the subsequent 48-hour period. Obviously special procedures should be developed for forecasting the motion of floes in areas close to developing migratory low pressure centres.

Major variations in the direction of the drift also rose in the period July 31 to August 3 when another migratory low developed. The direction of offshore ice drift did not appear to be related to variations in meteorological conditions on July 30 to 31 unless a water current from west to east is assumed. The derived wind averaged over 48 hours from July 31 to August 2 also indicates that a west to east water current existed.

Beacons #3 and 4 were tracked at roughly the same time and in the same areas as #1 while Beacon #2 was located a few degrees of longitude further west (Appendix I). Large deflection angles and unusual speeds occurred at the time for all these floes and in every case the explanations are similar.

Another group of beacons was placed on the ice in the latter half of August near 135°W (#4A, #5, and #6) and a single one near 137°W. In most cases, the drift rates were noticeably higher than in July and the deflection angles at 135°W were extremely variable. On the first day of the drift, the three beacons near 135°W all moved eastnortheast under a northeast wind, consequently water currents rather than winds appeared to control the drift pattern. Northwesterly winds had been blowing for eight days prior to the date. Garrett and MacNeill (1976) reported that in this area a southwest to northeast current occurs with the northwest winds which confirms this observation.

Large deflection angles were also observed in the interval 24 to 25 August when winds were southeasterly and the beacons moved the the northeast. There is no apparent explanation of this drift but it did continue during 25 to 28 August in the same general direction. This may have been the result of the normal wind-generated water current added to the Mackenzie River discharge current through the Middle and West Channels.

Beacon #8 showed a remarkable deflection angle of 84° to the left of the wind for which there is no apparent explanation, where the drift was southwestward with southeasterly winds.

A final group of beacons was monitored during September, except for beacon #19 near 133°W which moved towards the southeast slowly despite fresh but decreasing southeast winds. The prevailing winds prior to this date had been moderate southeasterly or merely light variable.

Table III lists the median and average drift rates and deflection angles for each beacon by data and area. For the first four beacons for which there were twelve to fifteen days of drift data available, median values of the rates and angles were used to reduce the effect of extreme values on the calculations. Later, beacons were only tracked briefly and an arbitrary decision was made to use medians when five or more drift intervals were available, and averages for fewer drift intervals.

If the drift ratios and deflection angles are averaged on a monthly basis ignoring location, the deflection angles are 14° to the left of the wind in July, 22° to the right in August and 15° to the left in September. The ratio of the ice drift speed to windspeed increases from 0.0074 in July to 0.0163 in August and to 0.0253 in September.

Table IV shows one further analysis of the beacon drift data. A comparison was made of the 'spot' winds reported when the beacons were set out with those derived from the mean daily pressure charts. It is recognized that this procedure compares a spot report to a time average but nevertheless some useful results can be obtained. In cases where the drift interval was more than one day, only a single chart was used in deriving the wind because the spot report was for the beginning of the drift period only. For computing the drift deflection angle and speed ratios, average winds over the two or three days of drift were used.

TABLE III

ICE BEACON DRIFT RATES AND ANGULAR DEFLECTIONS

	Near 137°W: Deflection Angle*	Speed Ratio $\frac{V_i}{V_w}$	Near 135°W: Deflection Angle*	Speed Ratio $\frac{V_i}{V_w}$	Near 133°W: Deflection Angle*	Speed Ratio $\frac{V_i}{V_w}$
# 1 July	- 5°	0.0067				
# 2 July					- 2°	0.0096
# 3 July					-10	0.0067
# 4 July					-37	0.0067
# 4A August			- 6°	0.0081		
# 5 August			+55	0.0181		
# 6 August			+60	0.0208		
# 8 August	-19	0.0183				
#12 Sept.					-20	0.0141
#13 Sept.	-12	0.0318				
#14 Sept.	-11	0.0343				
#16 Sept.			- 3	0.0337		
#17 Sept.					-16	0.0152
#18 Sept.					- 1	0.0292
#19 Sept.					-76	0.0065
#31 Sept.	+15	0.0244				
#32 Sept.	-14	0.0381				
MEANS	- 8	0.0256	+53	0.0202	-23	0.0126
MEDIANS	-11	0.0281			-16	0.0096

* Positive angles are to the right of the wind.

TABLE IV

REPORTED WINDS COMPARED WITH DERIVED WINDS

Date	Observed Winds V_o		Derived Winds V_d		Angular Difference	Speed Ratio
	Direction Degrees	Speed Knots	Direction Degrees	Speed Knots	Degrees	$\frac{V_o}{V_d}$
July 15-16	060°	10	100°	12	+40	0.83
16-17	155	7	145	10	-10	0.70
17-18	180	6	210	9	+30	0.67
18-19	145	7	055	6	-90	1.17
19-20	290	11	340	12	+50	0.92
20-21	325	10	325	10	0	1.00
21-22	080	9	(Light and variable)		-	-
22-24	065	13	090	20	+25	0.65
28-29	180	7	215	11	+35	0.64
30-31	175	3	125	9	-50	0.33
Aug. 01-02	315	9	315	12	0	0.75
02-03	355	4	(Light and variable)		-	-
20-21	030	5	055	12	+25	0.42
23-24	135	10	130	10	0	0.67
24-25	155	10	130	15	-25	0.67
25-28	165	10	130	12	-35	0.83
Sept. 06-07	070	5	(Light and variable)		-	-
07-09	050	5	125	6	+75	0.83
09-10	145	13	140	12	- 5	1.08
09-10	135	12	140	12	+ 5	1.00
10-11	185	10	(Light and variable)		-	-
11-13	090	20	125	20	+35	1.00
11-13	095	17	125	20	-30	0.85
		MEDIAN			+ 5	0.83

The median values at the end of the table are not particularly significant because in practical forecasting, the analyst will be working with both derived and reported winds on a real-time basis and will predict the ice motion on the basis of forecast obtained from the prognostic weather chart. It is pertinent to note, however, that the abnormal cases in this table are associated with the same developing storm in the July 18 to 20 period noted in para. 5.2.3.2. In general, abnormal ratios are associated with lighter winds - a rather unfortunate circumstance in actual practice.

5.3 Prediction of the Gross Features of the Summer Retreat of the Polar Pack in the Beaufort Sea

5.3.1 Introduction

Early knowledge of whether the summer operating season in the southern Beaufort Sea is going to develop as a 'good' or 'bad' ice year would be of great value to companies conducting offshore exploration or marine transportation in the area. With this in mind, an examination of about twenty years of ice and meteorological records was undertaken in an attempt to determine factors related to prediction.

5.3.2 Method

As a starting point, the location of the ice edge between Banks Island and Point Barrow, Alaska, was plotted for mid-July, early and late August and late September for each year between 1955 and 1974. Figures 16, 17 and 18 are examples. An arbitrary assessment was made by classifying each of these twenty years as good, bad or fair on the basis of the timing and extent of the clearing. Having made this initial separation, the meteorological conditions in the Arctic Basin which contributed to these good and bad years were examined.

The normal atmospheric pressure pattern in the Arctic Basin is anti-cyclonic with one semi-permanent low pressure area centered near the Aleutian Islands and another over the waters around Iceland. Both these centres vary in intensity and general location from year to year as well as from month to month. Figure 19 is a general geographic reference chart of the Arctic Basin showing also the major ice drift pattern.

During the autumn and early winter, a high pressure centre builds up in northeastern Siberia and a flat centre of high north of the Chuckchi Sea is transformed by November into a strong ridge extending from the New Siberian Islands across the northern Chuckchi Sea towards Amundsen Gulf and the Mackenzie Valley (Figure 20a). At this season, northwest winds are prevalent along the Arctic coast and the normal motion of the pack is onshore. By mid-winter, a separate high develops over the Arctic Ocean (Figure 20b). This centre slowly drifts towards Greenland as spring approaches (Figure 20c). Mean winds in the Beaufort Sea during this period, first decrease to light, then veer slowly towards the southeast as the high becomes established in the Ellesmere-Greenland section in April and May. The resulting southeast winds on the north coast of Alaska, in the Mackenzie Valley and in the Beaufort Sea result in the formation of an extensive polynya in the Cape Bathurst-Cape Kellett area in a normal season.

Over the remainder of the Arctic Basin, a cyclonic circulation is prevalent and the Icelandic low may extend its influence northeastward to Spitzbergen and Novaya Zemlya. In some years it even affects the east Greenland coast and the area extending across the pole into the North American sector of the Arctic Ocean.

In so called 'bad' years, this latter circulation is common while in 'good' ice years, high pressure is dominant in the areas of the Queen Elizabeth Islands and northern Greenland.

The major pressure pattern is reflected in the ice movement and it has been known since the days of Nansen that there is a persistent flux of ice from the area of the Laptev Sea and the New Siberian Islands, across the pole and into the area north of Greenland. Most of this ice continues southward down the east Greenland coast but a portion may remain within the Basin as a constituent of the North American Gyre. This ice massif, centred north of Bering Strait, rotates in a clock-wise direction on the North American side of the Trans-Polar drift stream (Figure 19).

The ice within the Trans-Polar Drift Stream is made up of a high proportion of first year floes as it leaves the Siberian coast but the rate of motion and the degree of melting is such that mainly multi-year floes are present when the ice reaches Greenland waters. Within the North American Gyre, multi-year ice is clearly prevalent except in the Beaufort and Chuckchi Seas where melting is more significant and an offshore component to the drift is common.

Within the context of these major ice drift features it is apparent that a southward flux of ice across the line from Barter Island to Mould Bay (line A-A on Figures 20a, b and c) will increase the amount of second-year and multi-year ice in the southern Beaufort Sea and increase the volume of ice that must be melted before clearing develops since these ice types are thicker than first-year ice.

Using the coordinates 80°N 180°W as an easily identified point within the North American Gyre, it is clear that a flux southward across the line 80°N 180°W to Ellesmere Iland (line C-D in Figures 20a, b and c) will increase the volume of ice in

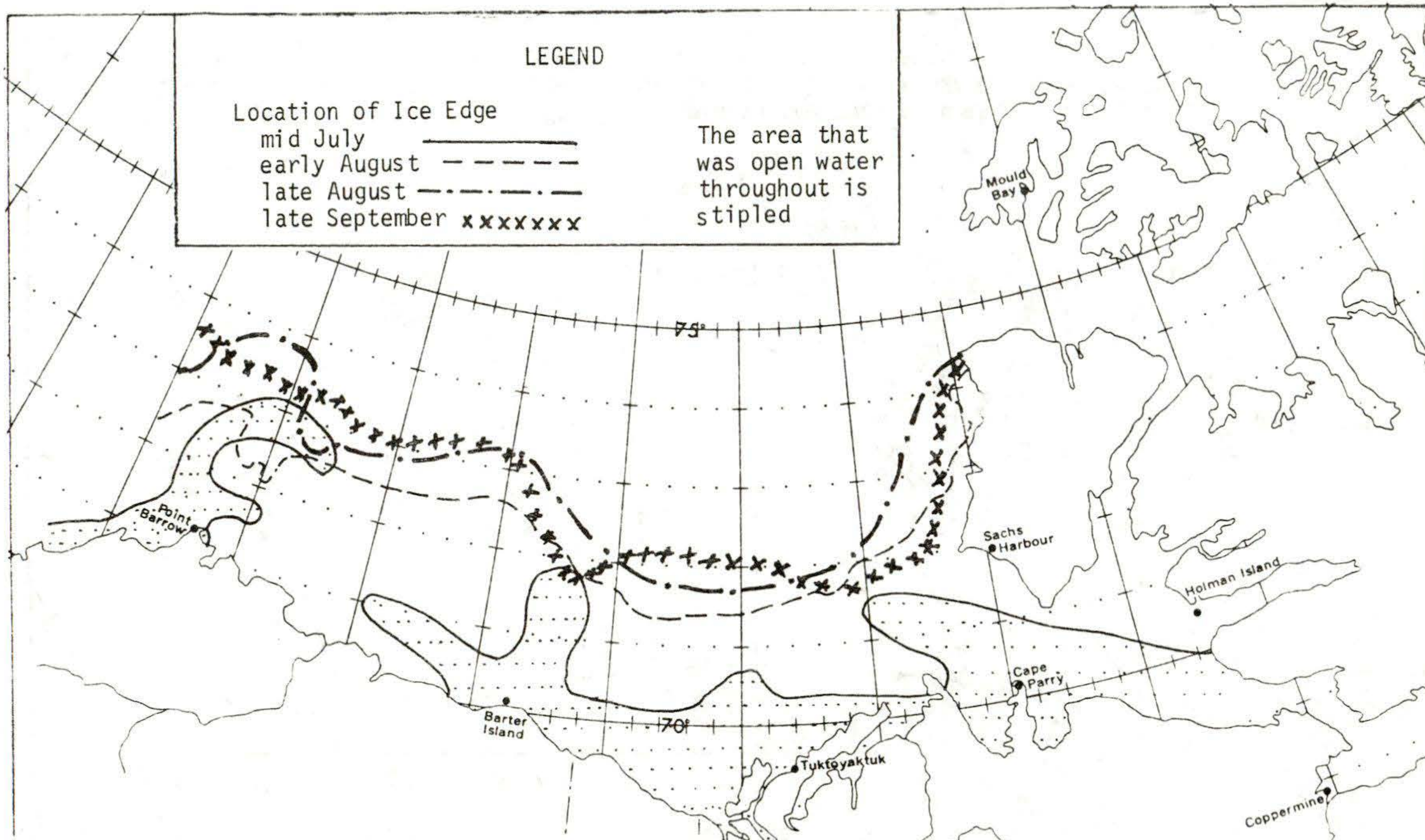

Figure 16. 1968, a 'good' ice year.

Although the Cape Bathurst polynya was poorly developed in May and June, the ice retreated rapidly in July and easy access around Point Barrow was possible by July 20.

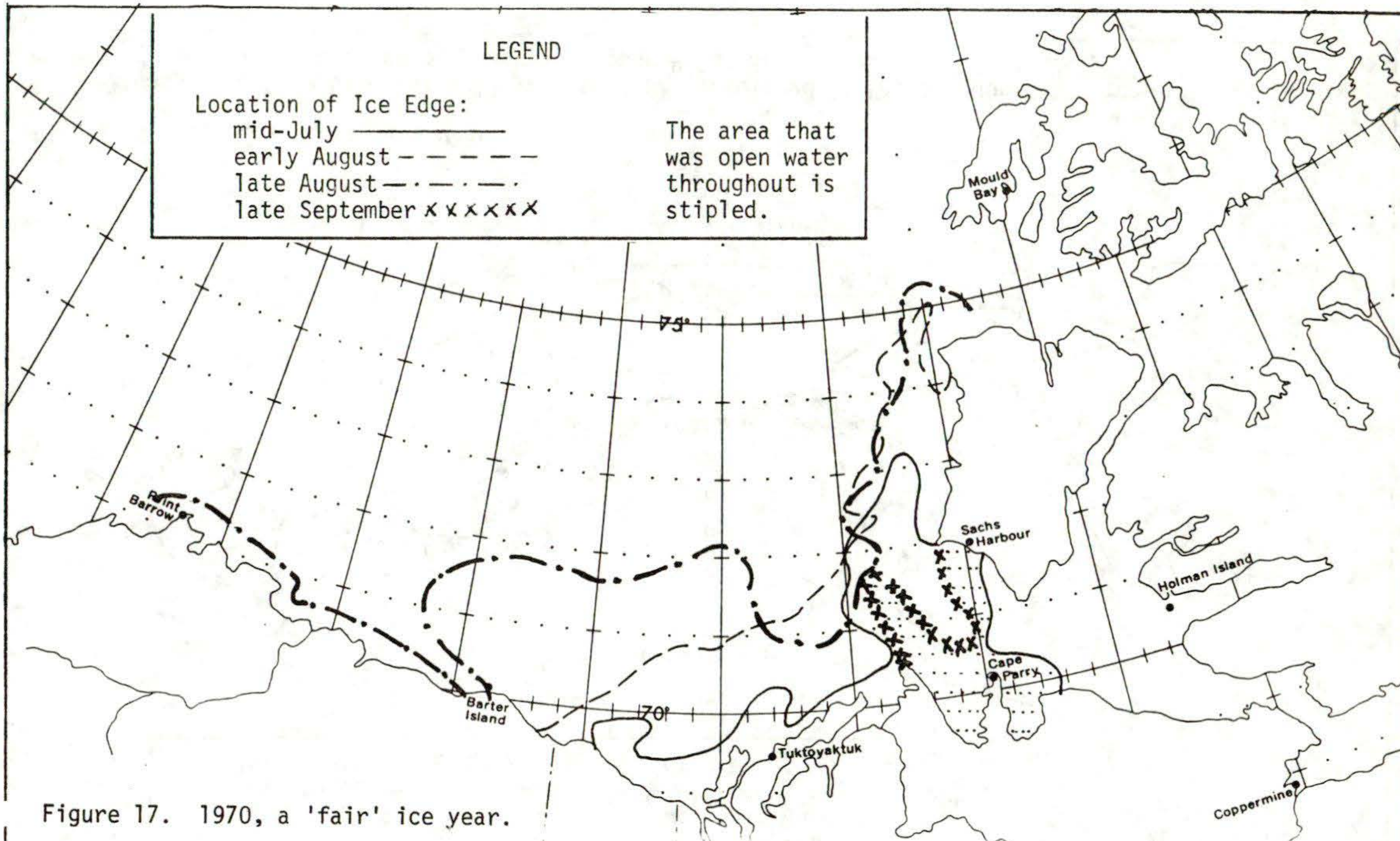

Figure 17. 1970, a 'fair' ice year.

Even though the polar pack was far from shore in the spring months, onshore winds were frequent until mid July and the polynya in the southern Beaufort Sea was slow in developing. Onshore winds and an early freeze up advanced the end of the season.

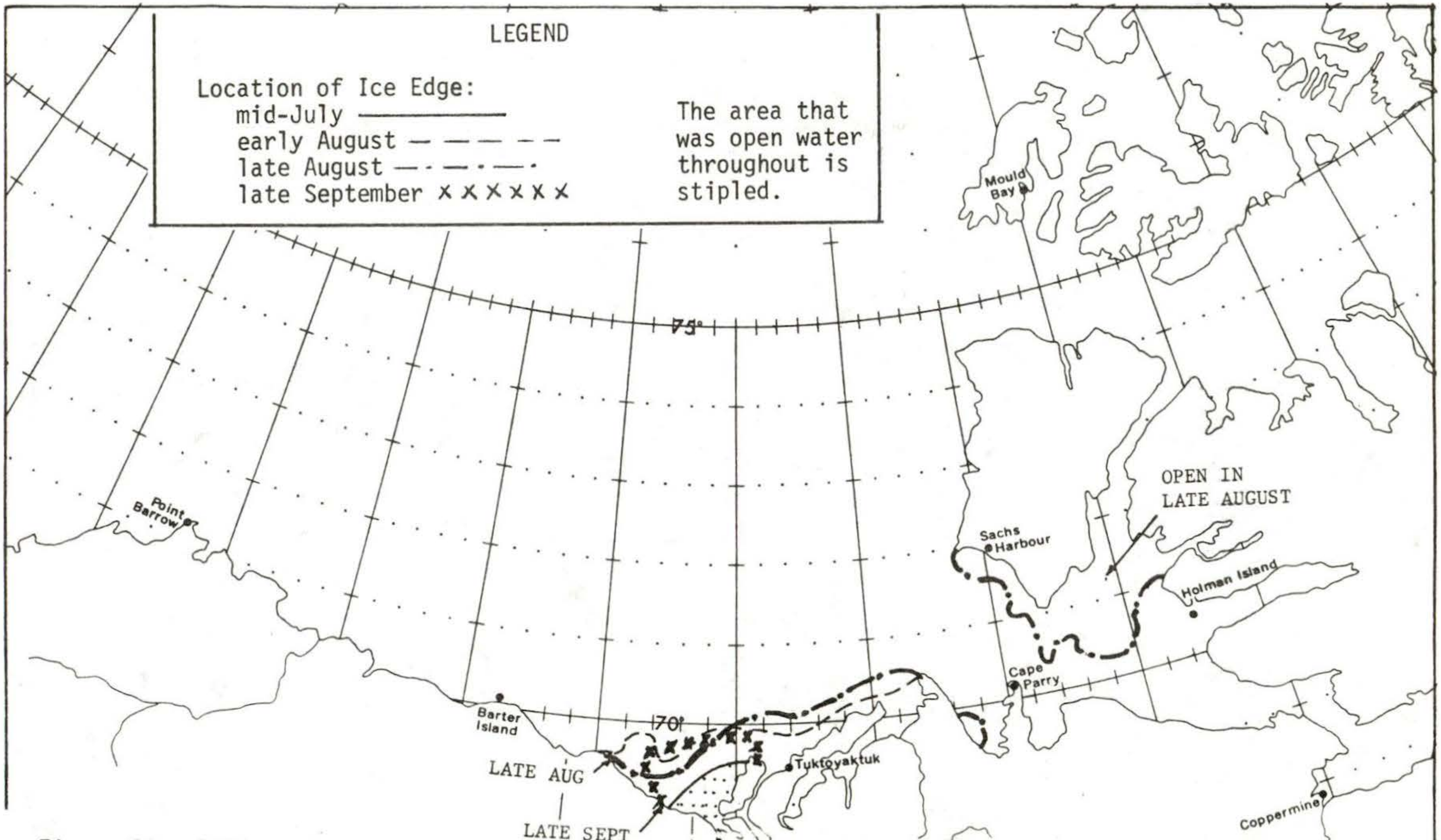

Figure 18. 1974, a 'poor' ice year.

Onshore winds and resulting low temperatures persisted through most of the summer resulting in one of the worst ice years on record.

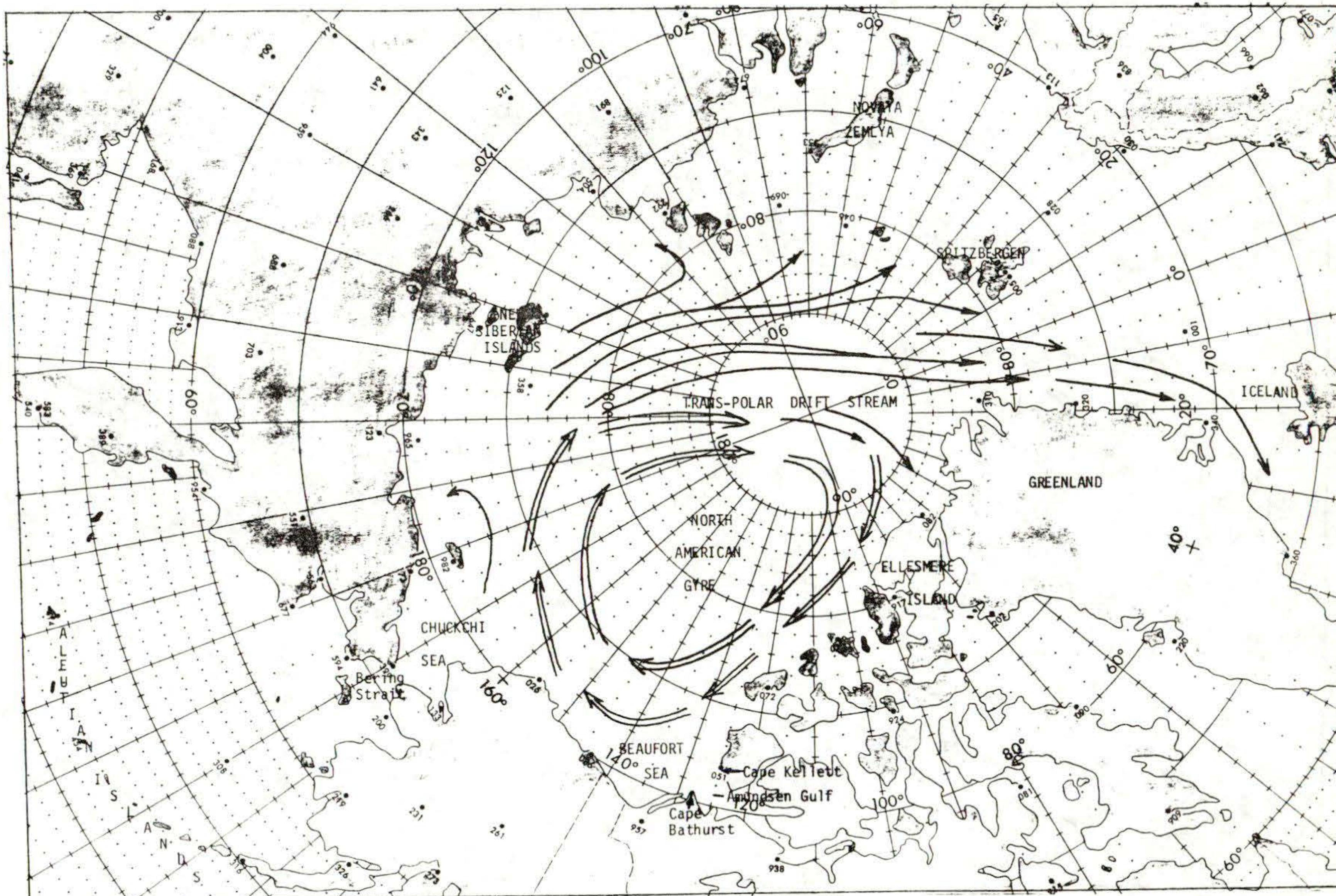

Figure 19. GEOGRAPHICAL REFERENCE MAP.

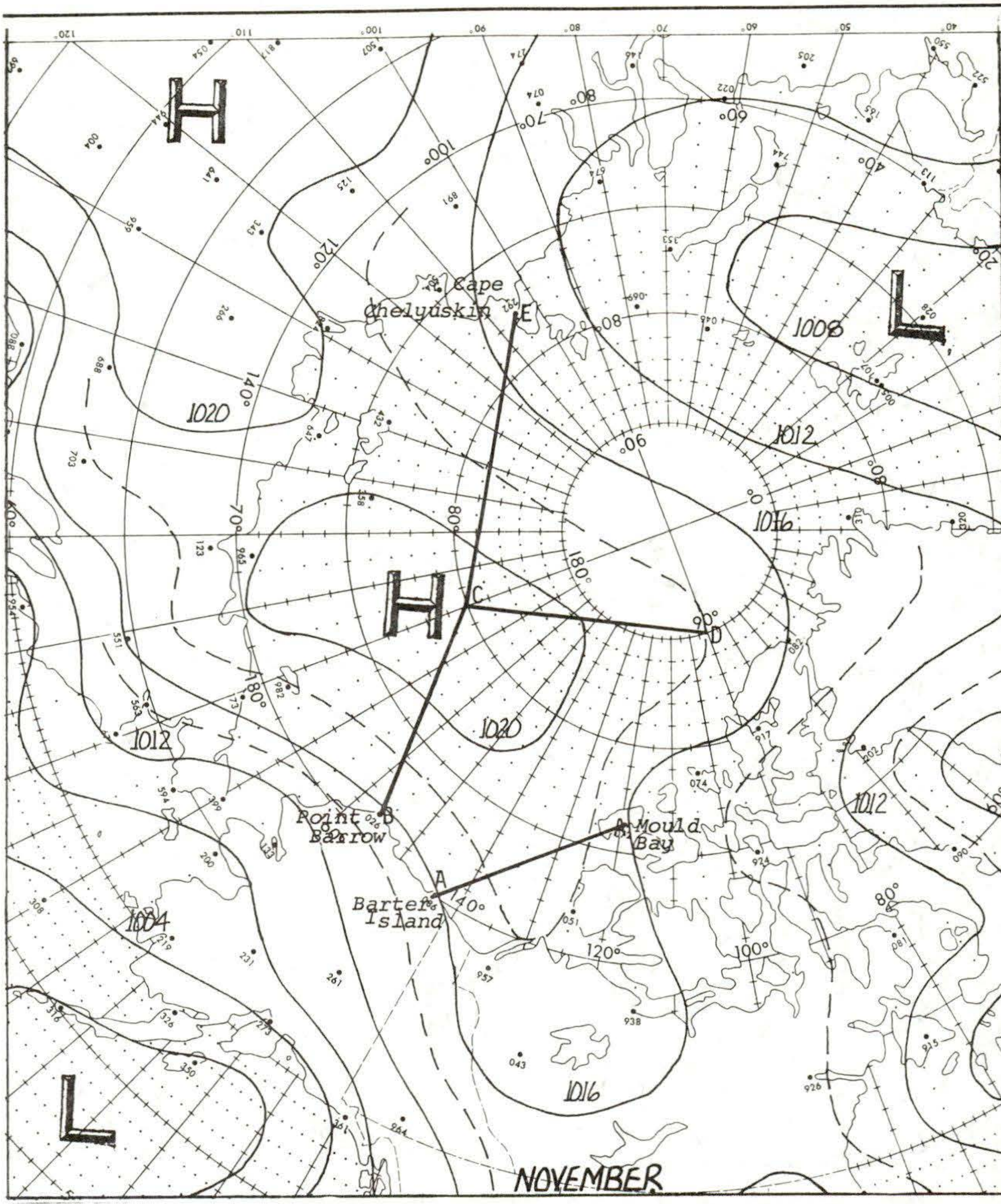

Figure 20a. Mean Sea Level Atmospheric Pressure Chart for November.

A ridge from a growing high pressure area in Siberia is strengthening its influence in the Chuckchi and Beaufort Seas. Onshore winds are common if the ridge line drifts even slightly westward. The flux lines referred to in the text are shown.

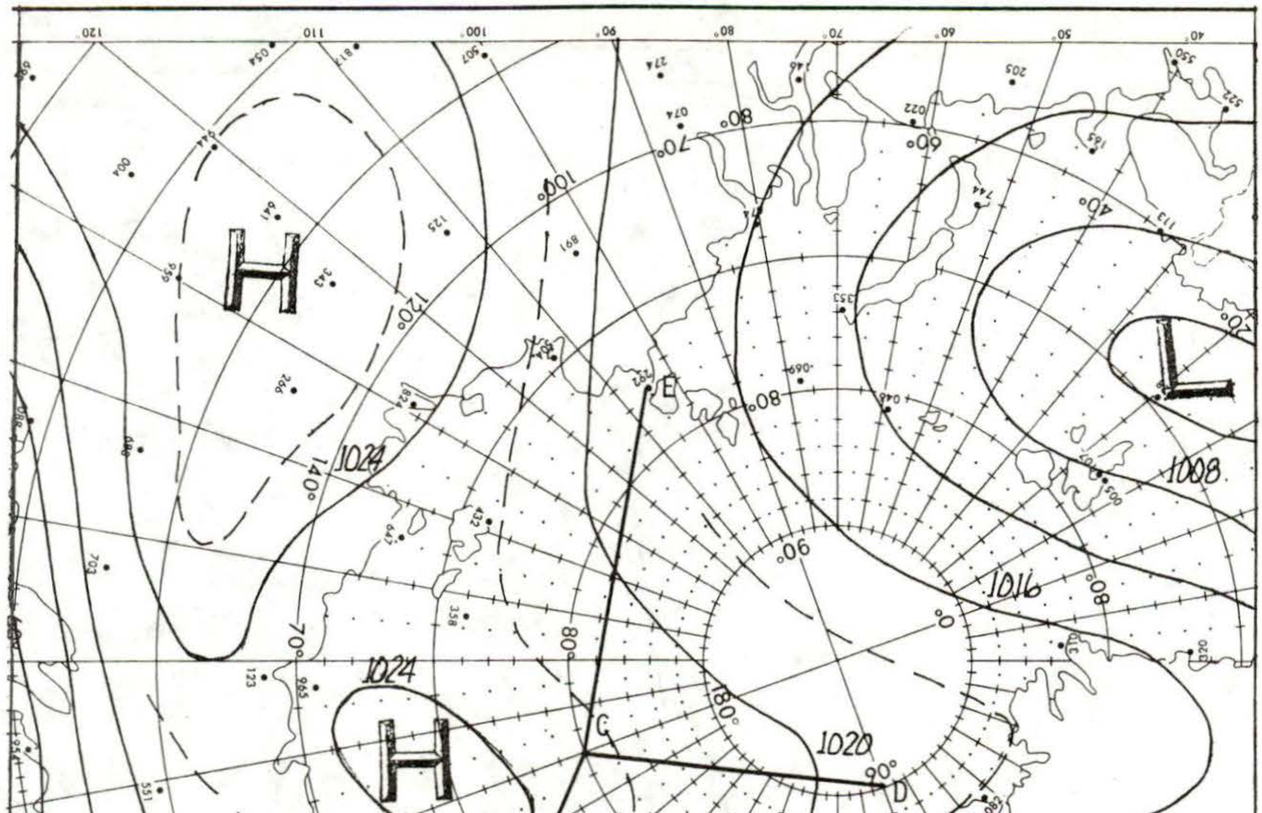

Figure 20b. Mean Sea Level Atmospheric Pressure Chart for February.

Pressures have continued to rise and the ridge from Siberia to the Mackenzie Valley is dominant. Winds in the southern Beaufort Sea are light because of the ridge line.

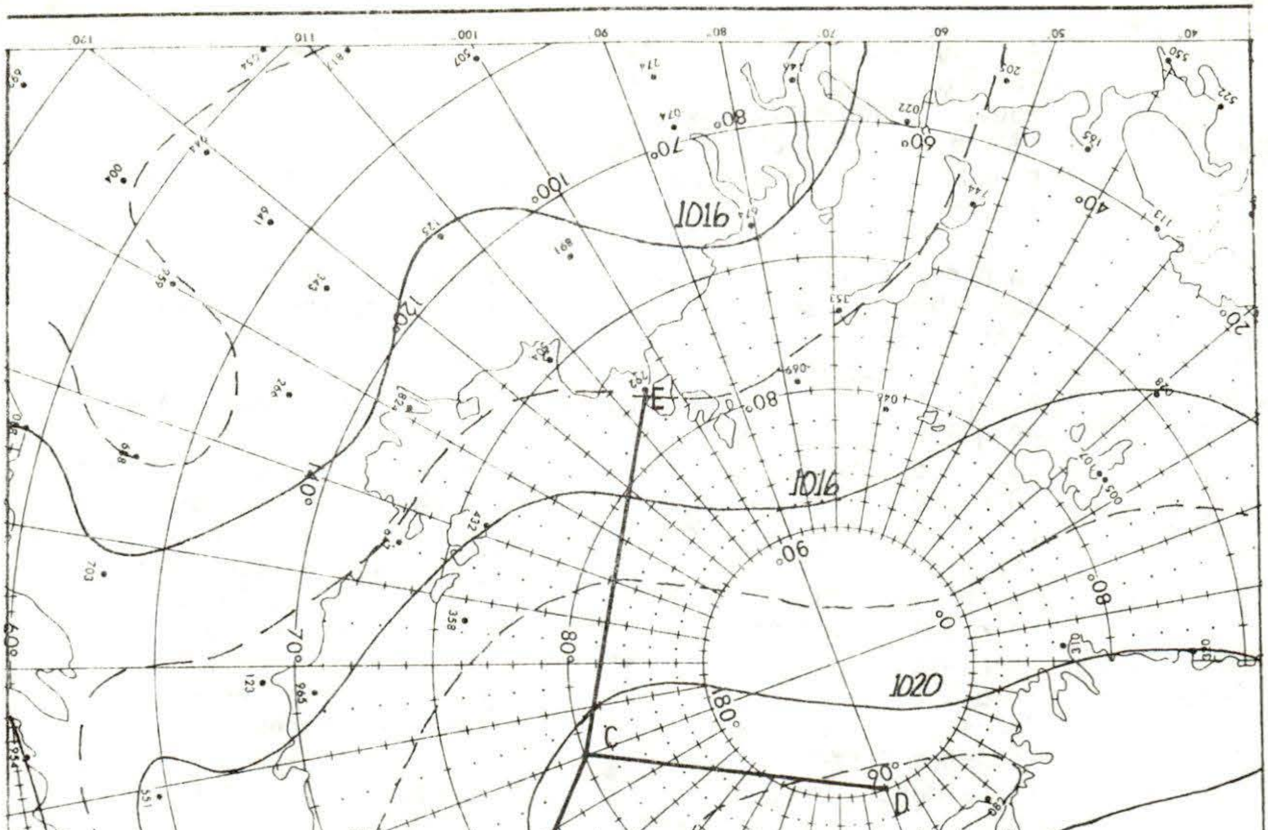

Figure 20c. Mean Sea Level Atmospheric Pressure Chart for May.

The high over the Chuckchi Sea in February has moved eastward and combines with the trough developing in Central Alaska to give southeast winds in the Beaufort Sea. Polynya and lead formation seaward of the fast ice follows quickly.

the approaches to the Beaufort Sea. A flux westward across the line to Point Barrow (line B-C in Figures 20a, b and c) would decrease it. Also a strong northward flux across the line from 80°N 180°W to Cape Chelyuskin (C-E in Figure 20a, b and c) would also tend to increase the volume in the same way.

In order to derive a quantitative measure of these fluxes, sea level pressure differences in millibars were obtained by subtracting the pressure at the second location from that at the first at the following pairs of locations (shown in Figure 20a): Barter Island and Mould Bay, Pt. Barrow and 80°N 180°W, 80°N 180°E and 85°N 90°W and 80°N and 180°W and Cape Chelyuskin. The pressure differences between locations 80°N 180°W and Cape Chelyuskin were arbitrarily reduced by 50% because of their remoteness. It could be argued that the flux resulting from pressure differences between these two points would have little direct influence in the same year on ice volumes in the Beaufort Sea except perhaps by the transmission of internal stress. These pressure differences were obtained from the mean monthly atmospheric charts for January, February and March of the year of concern. The weighted differences between pairs of locations and for these three months were then totalled to produce a flux index.

Some of the termination points of these lines were chosen according to the availability of atmospheric pressure data instead of on the basis of the overall ice drift pattern. The point 80°N 180°W is an example since a location somewhat further to the east would more nearly represent the centre of the North American Gyre.

5.3.3 Results

The final results of these calculations are shown in Table V and are summarized as follows:

- in 9 of the 10 good years, the index (pressure difference total) fell between -20 and 19.
- in 4 fair years the index was -16, -23, 28 and 30.
- in 5 poor years the index fell between 22 and 40.

If 20 is taken as the upper limit of the index in a good year, 20 to 25 as an indication of a fair year and over 25 as a sign of a poor year then:

- 9 of the 10 good years would have been successfully predicted and 2 of the fair years would have been forecast as good.
- the 4 fair years are not predicted correctly, the two mentioned above being called good, and the other two poor.
- 5 of the 6 poor years are correctly forecast and the other would have been forecast as fair.

Thus 14 seasons would have been correctly predicted; three would be one category worse than expected, three would be better than forecast, two of them being one better and the third, two better.

The reason the index is so variable in a fair year is not evident and no reason for it has been identified. Elimination of some of the fluxes, inclusion of December and/or April figures were all tested and no significant improvement was noted. No clarification was found in a study of the position or intensity of the Aleutian Low. Closer correlation with the position and intensity of the Icelandic Low seems unlikely because of its remoteness and this is already taken into account, in part, by the atmospheric pressure at Cape Chelyuskin and the last of the flux lines described above.

What is being done is to estimate the motion of the Arctic Pack according to early winter atmospheric pressure patterns and then to assume that the effect will persist. Major changes in the pressure pattern regime do occur between the first three months of the year and the break-up season and these are responsible for the failure years. As might be expected, long-range forecasting imperfectly predicts the nature of the ice year but nevertheless may be of some use. Years like 1972 which are anomolous in many respects rarely fit patterns developed in this manner. It remains only to identify the reasons for such anomalies so that incorrect predictions can be avoided.

TABLE V

General Ice Conditions - Beaufort Sea

Year	Ice Year Classification	Total Ice Flux Index January, February, March
1955	Fair	-16
1956	Poor	35
1957	Poor	22
1958	Good	6
1959	Poor	37
1960	Good	-11
1961	Good	19
1962	Good	3
1963	Good	14
1964	Poor	40
1965	Fair	30
1966	Good	-21
1967	Poor	26
1968	Good	1
1969	Fair	-23
1970	Good	15
1971	Good	8
1972	Good	54
1973	Fair	28
1974	Poor	29

5.4 A Study of Floe Size in the Beaufort Sea

5.4.1 Introduction

Should exploratory drilling from drill ships be attempted in the coastal zone of the Beaufort Sea, it is apparent that some knowledge of likely floe sizes is necessary if an assessment is to be made of the hazard that could be created by occasional encroaching floes. During the periods of high ice concentrations it is assumed that drill ships would depart.

5.4.2 Available Data

At present both ice reconnaissance aircraft of the Atmospheric Environment Service carry 70 mm Vinten cameras in a trimetragon array which covers the area below the aircraft and to each side at a 62° angle. In 1974, the orientation of the oblique cameras was such that a narrow strip was omitted between the vertical and oblique fields of view but this problem has since been eliminated. Except for this narrow strip, the camera array covered the area below the aircraft and to the sides in a swath that was 3.26 times the aircraft's altitude. In late August, 1974 a special photographic mission was flown during nearly perfect weather conditions and provided a total of 5,200 photographs from an altitude of about 1,850 metres resulting in lateral coverage of 6 km along a 2,470 km flight track. The sad part of the mission was that 70% of it was flown over ice concentrations greater than seven tenths with the result that only the data from the edges of the pack was useful. This report concerns those areas near the edge of the pack and specifically deals with the portions shown in Figure 21. An example of the imagery on leg C is presented in Figure 22.

The weekly historical ice charts referred to in Section 4.1 portray the amount, type and location of the ice pack in the Beaufort Sea and also a limited indication of the sizes of floes encountered. As part of the study conducted by FENCO, the proportion of floes greater than 100 metres in size were recorded and analyzed. For the years 1966 to 1973 this data appears on the ice charts directly although size reporting is not always as completely specified as is the concentration and age of the ice. Part of the reason for this is the use of satellite imagery which does not permit this refinement. For the years 1953 to 1965 the data is again only partially complete where the size interval reported in those years was: up to 10 metres, 10 to 1,000 metres and over 1,000 metres. Arbitrarily, the tenths of ice in the middle category were halved to represent the proportions greater and less than 100 metres. These two data sets were the input to the FENCO analysis.

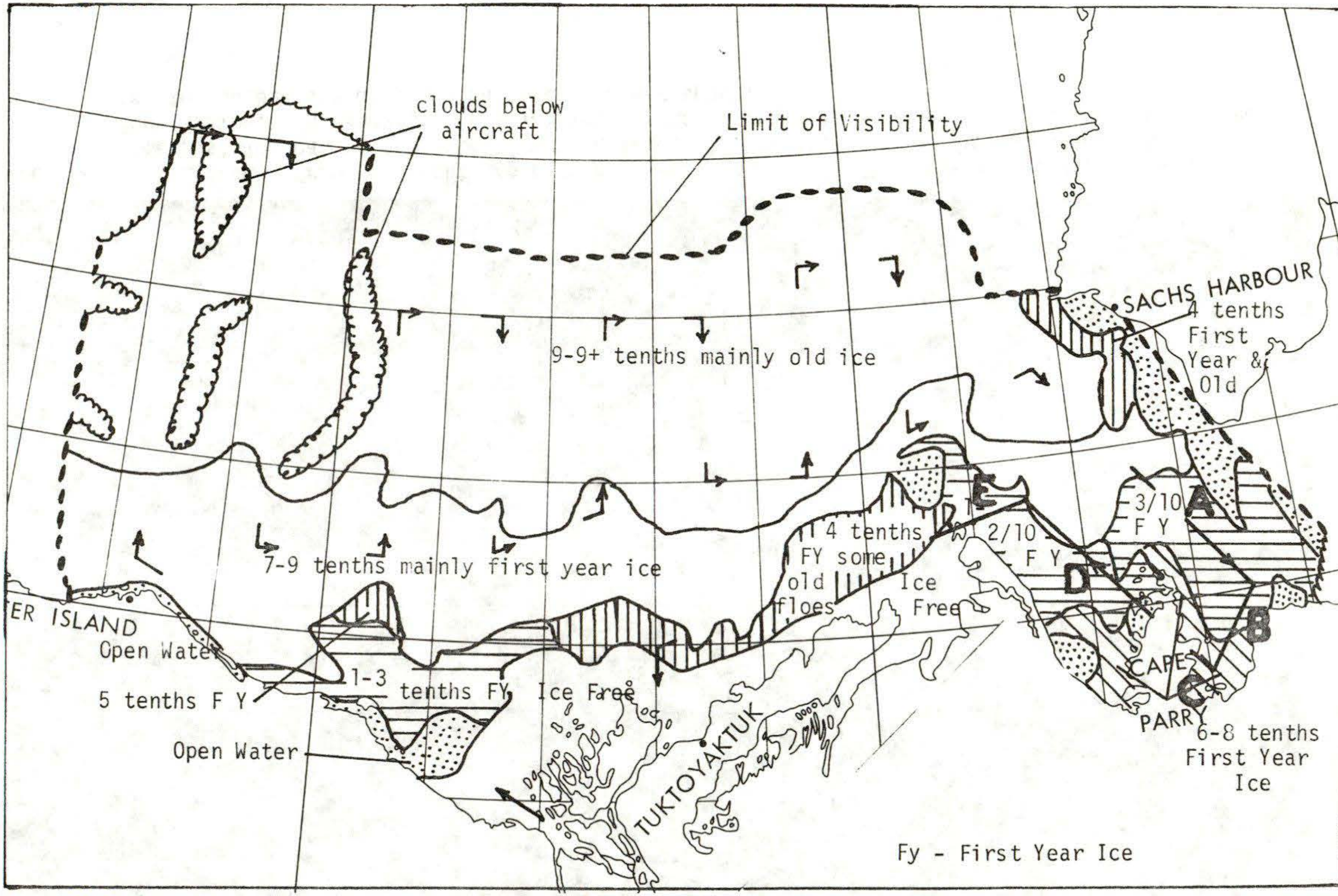

Figure 21. Photographic Ice Reconnaissance Mission of 27 August 1974 showing track of aircraft, ice concentrations and location of legs A to E which were analyzed for floe sizes. Flight altitude was 1850 m.

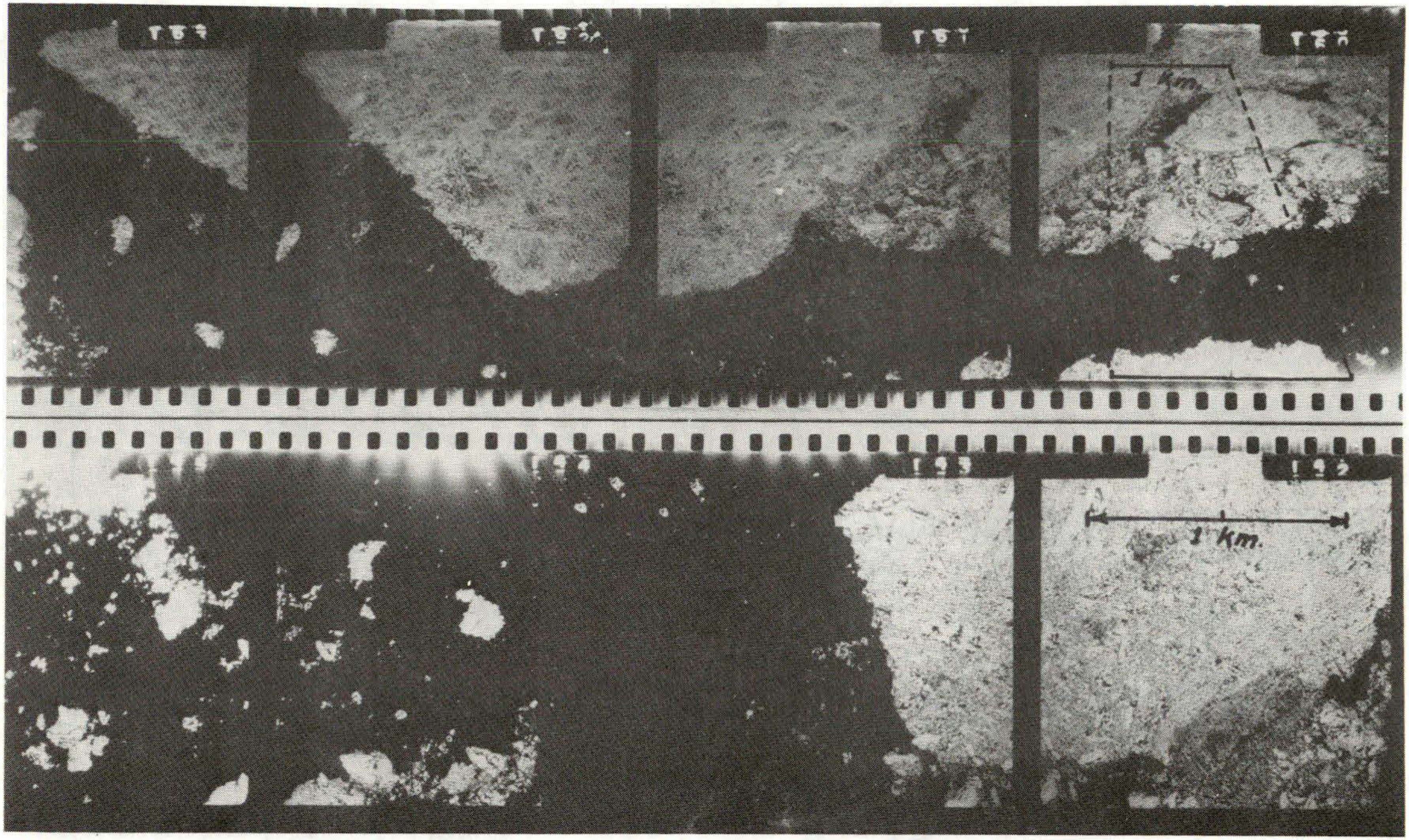

Figure 22. Sample frames from the right and centre cameras on leg E. The size of the gap between the camera strips can be estimated from the large floe on the lower right which appears in four frames. The amount of overlap from frame to frame is also evident but this varies from leg to leg because of the wind effect on air speed.

5.4.3 Analysis

Contact prints derived from the August photo mission were studied at length and although the left side imagery was partially obscured by fogged film (before or after exposure but not during the mission) it was possible to extract considerable data. From the basic specifications concerning camera angles, fields of view and altitude of the aircraft, it was possible to quantify the area appearing in both vertical and oblique frames and thus to estimate quite accurately the length (size) of all the floes appearing in the imagery. The following is a summary of this analysis.

NUMBER OF FLOES OF VARIOUS SIZES - 27 August 1974

	Over 1000 m	500 to 1000 m	100 to 500 m	Under 100 m	Number of Frames	Ice Concen.
Leg A	76	65	1805	13720	724	3 tenths
B	13	38	1200	6540	140	6
C	25	64	1740	2300	60	6
D_1	6	6	1800	13720	113	2
D_2	57	93	2845	4770	123	9+
E	36	26	190	2160	107	2

Individual floes in numbers approaching one hundred in a single frame could not be accurately counted. Instead, three designators, (plentiful,many, and very many) were assigned when counting became difficult and arbitrary numbers 25, 50 and 67 were assigned to these. These were used in summations and as a result, data columns 3 and 4 above are only approximate. Nevertheless, the preponderance of small floes and ice cakes is evident.

The next step was to examine the number of floes relative to the over 1000 m floe size. For instance, on leg B, there were 38 floes in the 500 to 1,000 m size range while 13 floes of the over 1,000 m size were counted: a 1:3 ratio. The relative floe sizes on each of the legs were rounded off as follows:

	Over 1000 m	500 to 1000 m	100 to 500 m	Under 100 m	Total Ice Concen. (Reported)	Tenths larger Floes
Leg A	1	1	25	180	3	1
B	1	3	90	500	6	2
C	1	2	70	90	6	2
D_1	1	1	300	2300	2	1
D_2	1	2	45	80	9	5
E	1	1	5	60	2	1

Referring to the floe size ranges above, one can say that on Leg A there were 27 floes greater than 100 m in length (1+1+25) for every 180 smaller floes, a ratio of about 1:7.

Similarly, on Leg B there were 94 floes larger than 100 m for each 500 smaller ones, a ratio of 1:5. On Leg C the ratio is nearly even: on D_1 it is 1:7; on D_2 it is 1:2 and on Leg E it is 1:8. It is significant that the ratio is lowest on Leg D_2 where the ice concentration was highest.

The floe size analysis conducted by FENCO is summarized in Figures 18 to 23 for the same areas used in the ice concentration study (Figure 1). In the spring the larger floe sizes in all areas are to be expected and points out that any effort to extend the season of operation should be concentrated in the autumn when the ice is thin and the floes present are generally weaker than in the spring and the early summer.

To get a better appreciation of the factors influencing floe sizes one must consider the processes at work on the ice. During the winter, the shallow coastal waters are covered with a strip of fast ice - in effect a single floe of immense dimension. It is usually made up of a multitude of ice cakes and small floes which were broken by waves after their initial formation early in the autumn; were later pushed together by onshore winds and were then cemented together by subsequent freezing which also increased their thickness. As a consequence the fast ice usually has a number of "seams" within it which will have a tendency, on subsequent break-up to produce floes in the "small floe" or low size range. It seems therefore, that the decay of ice from fast ice down to small floes and ice cakes will relate to conditions during freeze-up and to those during break-up. In the autumn, meteorological conditions will determine the spacing of the seams but at break-up, geographic location will also dictate that partially protected areas will produce young floes that are larger than those in exposed areas. Similarly, mechanical fracturing by wave action will depend on the extent and configuration of early polynyas, to wind direction and to wind strength once a polynya is formed.

6. DISCUSSION

6.1 Ice Climatology

The analysis reported in Section 5.1 is related to conditions between mid-May and late October and is given in some detail for this portion of the year which includes the open water period. Very little actual data for the darker months is available but in recent years infrared satellite imagery has begun to fill this gap. On the basis of this limited amount of information, the following conditions are thought to occur during the darker months.

(a) During November and December the fast ice grows steadily in thickness but it also expands in width in a series of steps that are related to periods of onshore winds. Floes are consolidated onto the previous fast ice edge which then remains fixed in place during subsequent offshore drifts. This is variable from one year to another

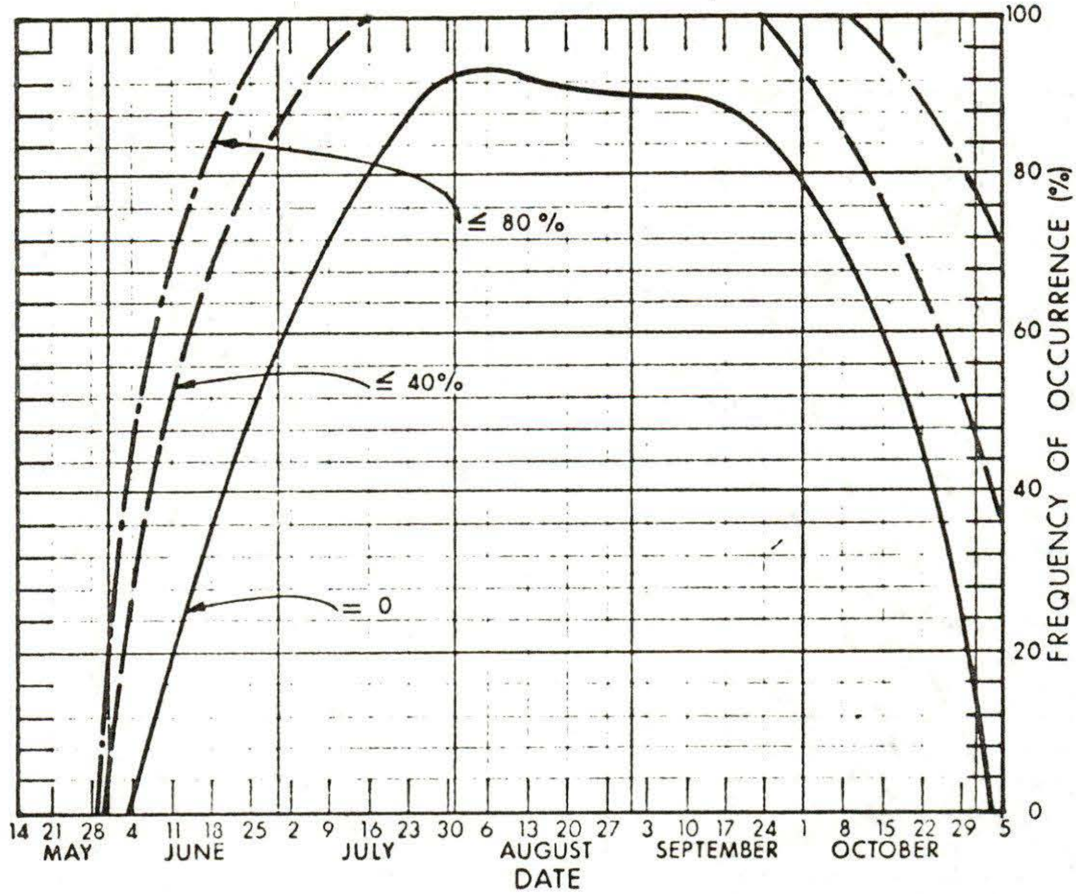

FIGURE 23. FREQUENCY OF OCCURRENCE OF FLOES: MEDIUM SIZE OR GREATER (OVER 100 METRES) AREA 1 (Figure 1).

The very dramatic decrease in floe size in Mackenzie Bay in June is also accompanied by a similar change in the total ice concentration. The remnant proportion of large floes during August and September occur during "poor" seasons when plentiful ice is present or when coastal intrusions develop from the west of Herschel Island.

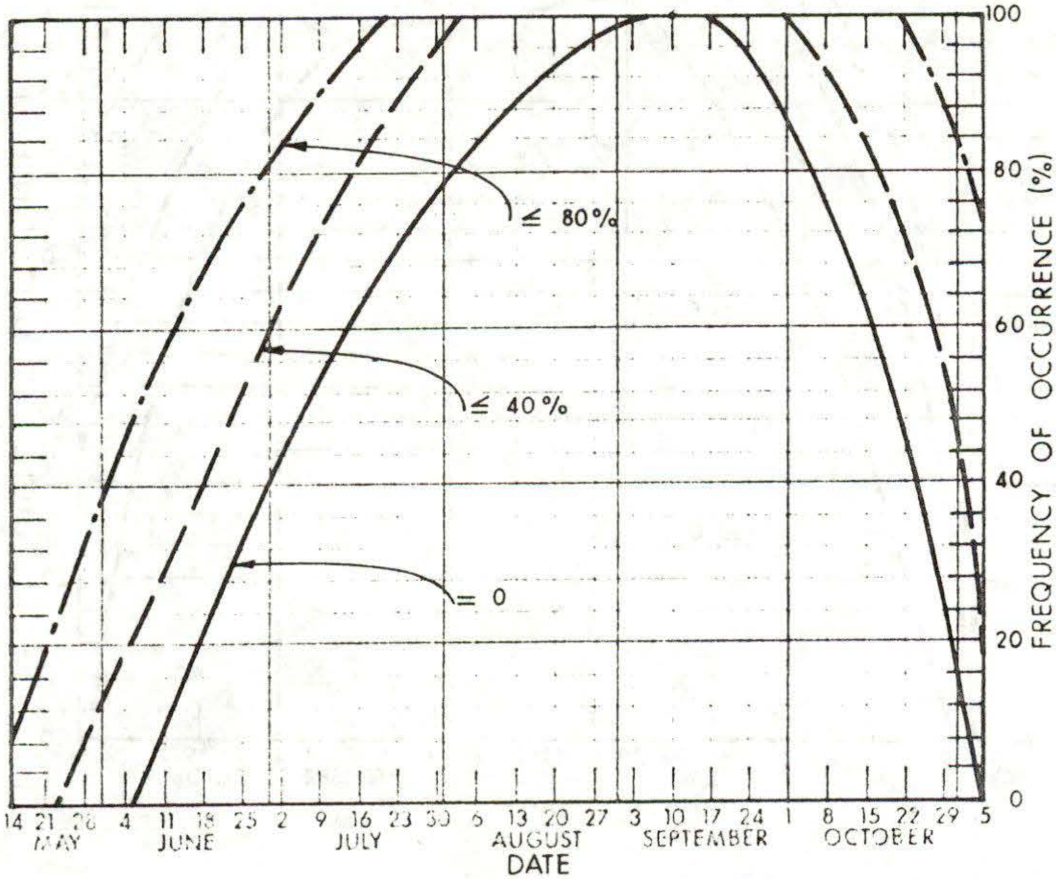

FIGURE 24. FREQUENCY OF OCCURRENCE OF FLOES: MEDIUM SIZE OR GREATER (OVER 100 METRES) AREA 2 (Figure 1).

A decrease in floe size is rapid in the fast ice zone and a very rapid decrease in the amount of ice also occurs. The complete absence of larger floes in early September is thought to be related to wave action, and to the fact that this is the eastern coastal zone which is most difficult for encroaching ice to reach.

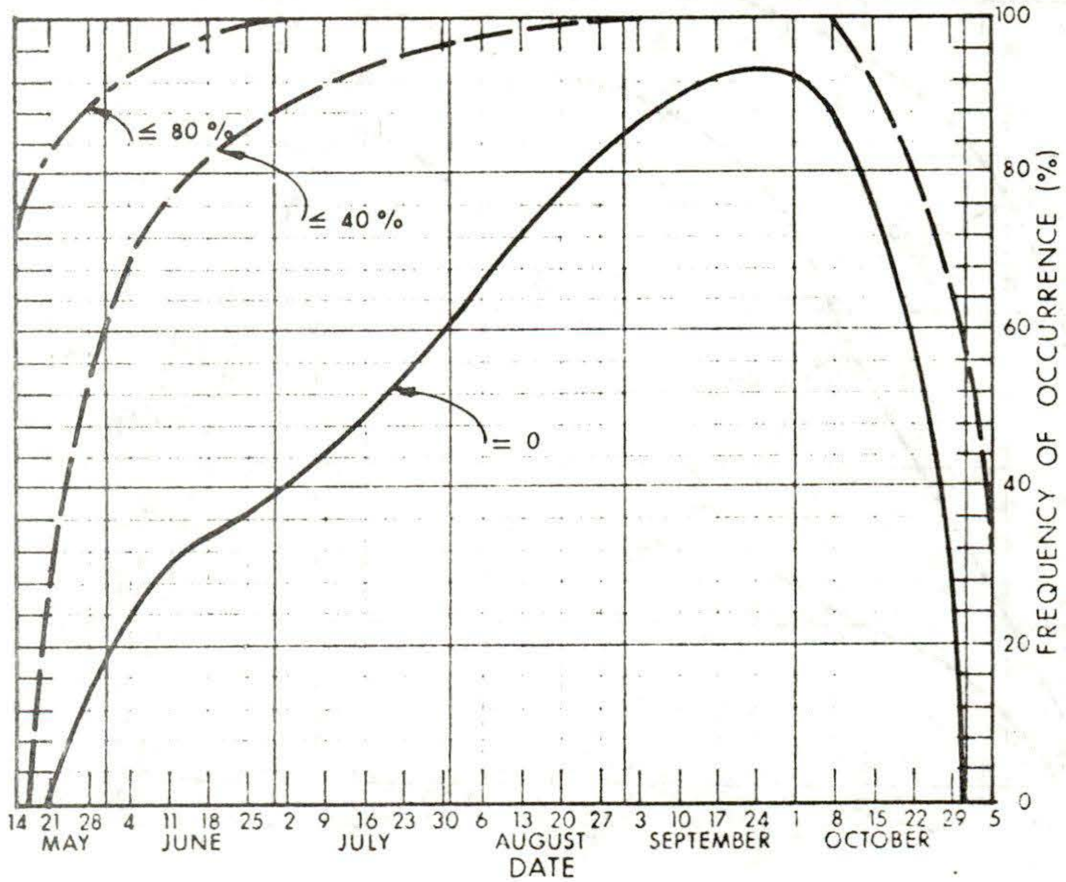

FIGURE 25. FREQUENCY OF OCCURRENCE OF FLOES: MEDIUM SIZE OR GREATER (OVER 100 METRES) AREA 3 (Figure 1).

In the Amundsen Gulf area, the proportion of larger floes is lower in the spring because of the continual motion of the offshore pack and because of the formation of leads and polynyas. The decrease in numbers of larger floes during the summer is much slower than in the coastal areas.

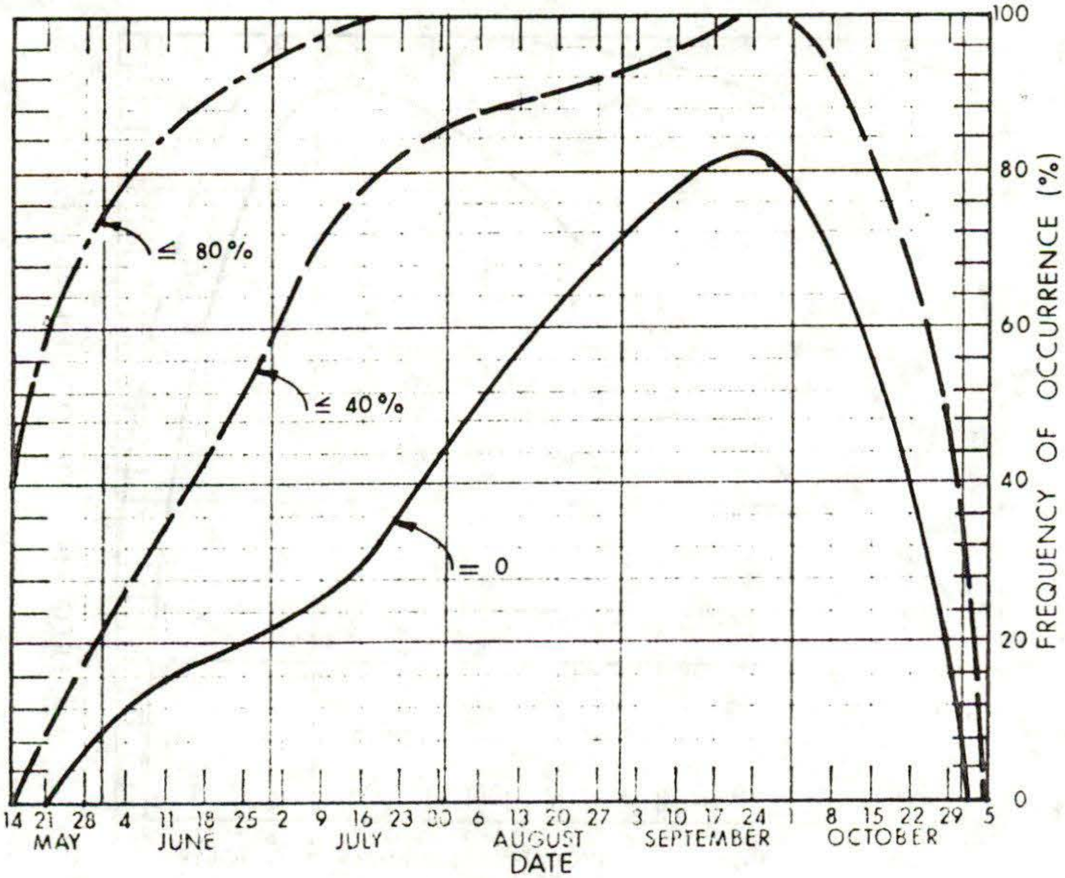

FIGURE 26. FREQUENCY OF OCCURRENCE OF FLOES: MEDIUM SIZE OR GREATER (OVER 100 METRES) AREA 4 (Figure 1).

In this intermediate area the rate of decrease in floe size is very much reduced because the ice concentration itself remains considerably higher. The number of larger floes is significantly greater, particularly in August.

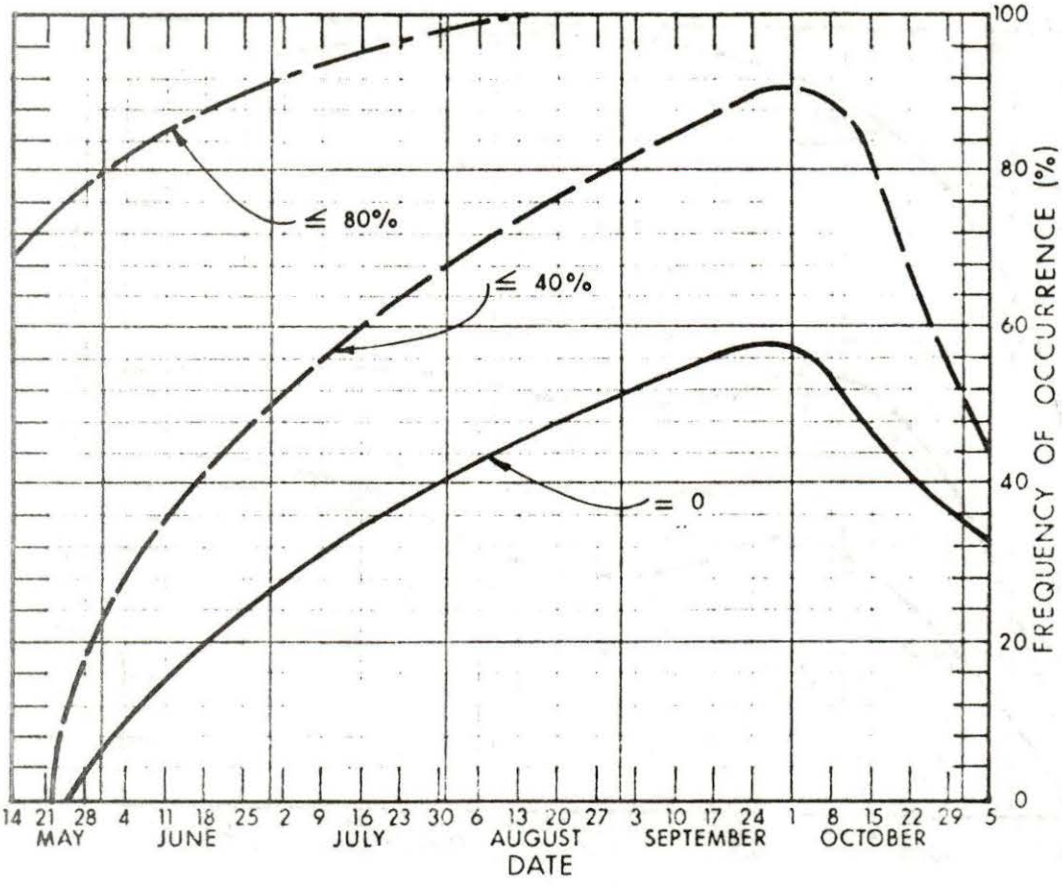

FIGURE 27. FREQUENCY OF OCCURRENCE OF FLOES: MEDIUM SIZE OR GREATER (OVER 100 METRES) AREA 5 (Figure 1).

The proportion of larger floes is always significant in this offshore area and at the same time only partial dispersal of the ice can be expected.

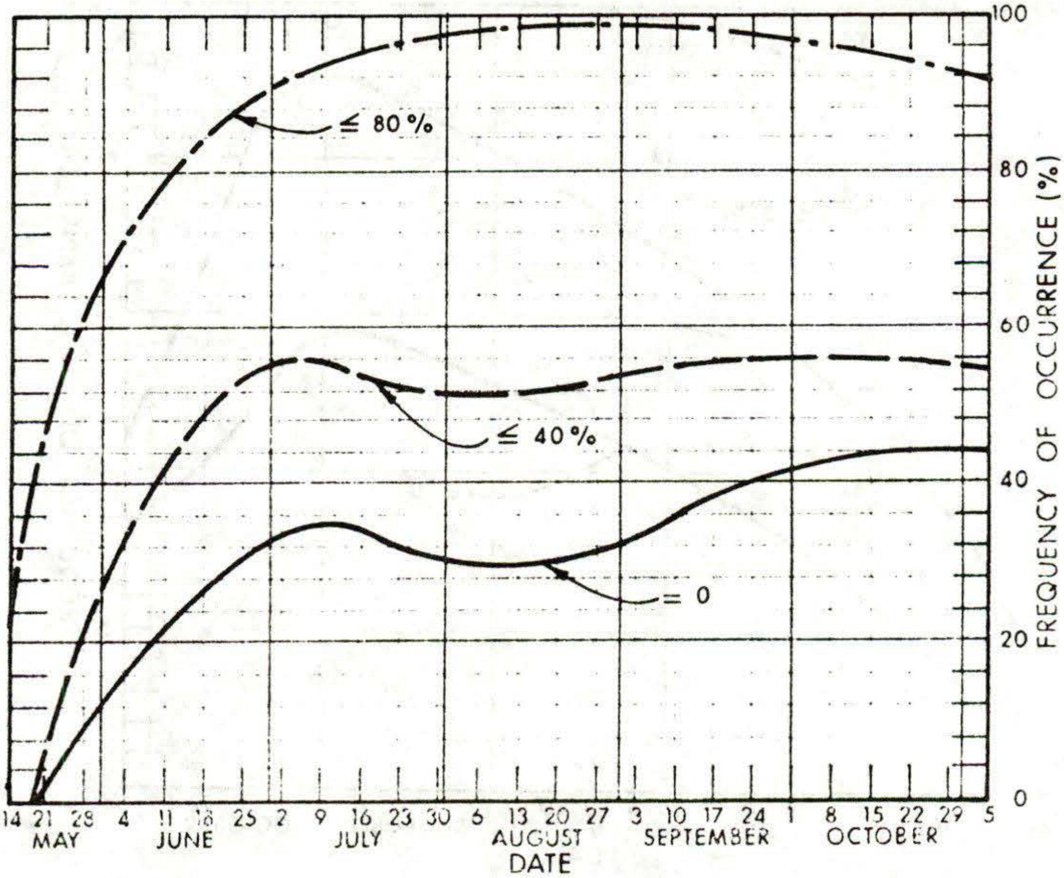

FIGURE 28. FREQUENCY OF OCCURRENCE OF FLOES MEDIUM SIZE OR GREATER (OVER 100 METRES) AREA 6 (Figure 1).

In the northern offshore area a significant number of larger floes are always present and congested ice conditions are normal.

but the ultimate extent of the fast ice is related to water depth. The 20 metre isobath normally defines the offshore limits of the fast ice and this extent is thought to be attained in February or March. There is probably a slight relationship between the average fast ice thickness and the location of the seaward edge but the variation is not great. Essentially the keel depth of significant ridges is expected to be partially related to ice thickness and subsequent grounding of the keels influences the location of the fast ice edge.

(b) The fast ice can extend well beyond its usual range of width in those seasons when onshore winds are prevalent or the dispersing offshore winds are weak when they do develop. 1974 was an example of this condition. Such cases are unstable and reversion to the normal extent defined by the 20 metre isobath can quickly occur. The opposite extreme, when the fast ice is much narrower than usual is much less likely to occur because of the grounded ice at the normal edge of the fast ice zone.

(c) During the winter, the offshore pack remains in steady motion in response to mean wind conditions but concentrations of the thicker ice are usually eight to ten tenths despite the movement. Flaw leads can develop but are quickly covered with new, young ice which subsequently grows into first-year ice. Depending on timing, there may be extensive areas of first-year ice cover which are substantially thinner than in other areas. The most likely place to encounter this thinner pack is in the Cape Bathurst to Cape Kellett area (See Figure 19).

(d) The development of flaw leads and offshore polynyas mostly occur in April when refreezing is slower. Their relation to offshore wind flow is paramount and temperature considerations are secondary. Figure 20c, the long-term normal surface pressure charts for May, illustrates the normal development of offshore winds. In a specific year, wind patterns of this type can vary significantly where in 1975 the dispersal developed in March, in 1974 it was delayed until late May.

(e) A pattern of regularly spaced leads among the moving offshore pack is sometimes seen in satellite imagery and has also been reported by April ice reconnaissance flights. As yet though, there is no data regarding their spacing in relation to ice type, wind strength or wind direction.

(f) Because of prevailing ice thickness, mean floe size and ice strength, the early part of the operating season would be more hazardous for drill ships than the middle and end of the season. Therefore, any lengthening of the operating season should be in the fall when the ice is thin and weaker because of its high salinity.

6.2 Individual Ice Floes

A better knowledge of the water currents in the surface waters of the southern Beaufort Sea is required to more fully understand specific floe motions. On the basis of radio beacon tracking of floes there appears to be a real seasonal increase in drift-rates relative to the wind speed which should be taken into account in future ice forecasting in the area. Drift measurements are in general agreement with earlier studies by Zubov (1945), Shuleikin (1953) and Fukutomi (1958), but the problems of unknown and variable currents remain.

6.3 Gross Features of the Summer Retreat of the Pack

Using the methodology for long-range prediction described in Section 5.3, the index value for the 1975 ice season is 9, comfortably fitting into the 'good' range. Up until early August, this year had developed as expected, but in the late summer a major return of the pack occurred. Further refinement of this forecasting procedure may be possible by adjusting the central point of the pressure intercepts so that it more nearly conforms to the centre of the North American Gyre. A further problem still remains, that of the availability of reliable meteorological observations from the midst of the Arctic Pack.

6.4 Floe Sizes

The percentage of medium or greater sized floes within the Beaufort Sea pack ice on a weekly basis is illustrated in Section 5.4.

For practical purposes, the coastal fast ice in the spring is a floe of infinite size. Offshore, the pack, moving in response to wind and current, undergoes translational and rotational stresses but collisions are not common and waves are almost non-existent. Compressive forces deform the thinner ice much more than the thicker first-year or old floes and hence do not affect floe size directly. The result is that floe size is great although there is probably some tendency for elongated floes to develop rather than round or squarish ones. These conditions are evident in LANDSAT imagery in April and May.

No data is available concerning the median floe size of the offshore pack in May but for argument's sake, let us assign 20 km as a size estimate. After several weeks, further deformation will have occurred, the fast ice may have begun to break up and in general, the majority of the floes will have broken at least once because of impacts with other floes, or because of thermal stress, so that the median size will now be in the 10 km range. The number of floes will have doubled and the number of 20 km floes remaining will have decreased markedly. In another few weeks the median size may decrease to 1 km. Using this argument:

- The average floe size of pack ice decreases progressively during the summer.

- The total number of floes increases in early summer as the large floes break up but subsequently melting decreases the numbers.

- There will be a period in early summer when big floes are predominant; then their population will decrease steadily. Medium floes will predominate somewhat later than big floes, then they too will decrease in number.

- Because of floe thickness and ice strength it is likely that the variations with time of the population of first-year floes of a specific size is somewhat different that than for old floes. Their numbers should peak earlier and decrease quicker than for stronger old ice. However, the old floes constitute less than 10 percent of the total pack in even the worst years in areas 1, 2, 3 and 4 and only become significant in area 6 (Figure 1).

7. IMPLICATIONS AND RECOMMENDATIONS

If full detailed ice forecasts with acceptable accuracy are to be provided, a full understanding of the annual and seasonal variation of near surface currents in the southern Beaufort Sea is required.

It is recommended that Side-looking Airborne Radar be provided in AES ice reconnaissance aircraft as soon as it is practically possible. A day-by-day knowledge of the location of the edge of the Arctic ice pack will be needed should drilling operations commence. Reconnaissance at no more than 48-hour intervals would be obligatory until detailed computer ice prediction programs are developed. These programs could include the results of the AIDJEX project now studying the basic physics of ice motion. Considering that low cloud and fog obstruct the present aerial observations, Airborne Radar presents a solution to the problem. There will no doubt be data available from ship-based radars as soon as drilling platforms are in position but in rough seas these have limited effectiveness. An airborne system will be necessary to provide the consistent coverage required to supplement the proposed drilling platform radar observations.

8. NEEDS FOR FURTHER STUDY

A climatological study looks backward at what is on record concerning previous variations in environmental events. If the record is lengthy, many manipulations of the data are possible but if the record is short, little detailed work can be done. There is a need to differentiate between ice-free conditions and open water with a few floes present in ongoing observation programs.

Study of water motions in the upper ten metres and their variation in space and time could result in improved accuracy of ice forecasts for the southern Beaufort Sea.

One of the studies included here concerns the variation of floe size along the edge of the Arctic pack. Further study in this area could be of value because the amount of data available is sparse. A broad-based study on size frequency, possibly including temporal variations on a monthly basis, would be pertinent to the design of drilling platforms. Because of the nature of the offshore ice and its direction of drift a study of this type must be conducted in the Beaufort Sea itself where the exposure is unique. Studies of floe sizes encountered in other areas are not applicable.

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APPENDIX I

DETAILS OF ICE BEACON DRIFTS

Date	Ice Drift V_i Degrees	Ice Drift V_i Nautical Miles	Wind Velocity V_w Wind Degrees	Wind Velocity V_w Knots	Speed Ratio $\frac{V_i}{V_w}$	Delfection Angle Degrees to Right of Wind
BEACON #2 near 70°N 137°W						
July 13-14	050	2.0	070	10	0.0061	-20
14-15	050	1.5	090	12	.0050	-40
15-16	126	2.0	100	12	.0093	+26
16-18	145	2.0	175	9	.0045	0
18-19	144	1.5	035	6	.0104	-66
19-20	306	4.5	340	12	.0134	-34
20-21	342	1.5	340	10	.0062	+ 2
21-22	090	1.5	115	6	.0178	- 5
22-24	092	3.0	090	16	.0189	+ 7
24-25	112	6.5	Lgt	Vrbl	-	-
25-26	135	0.5	Lgt	Vrbl	-	-
26-27	202	3.0	Lgt	Vrbl	-	-
27-29	250	2.5	215	6	.0099	+35
29-30	284	2.5	180	12	.0069	+104
30-31	360	4.0	125	9	.0185	-125
		MEDIAN			.0096	- 2
BEACON #3 near 70°N 133°W						
July 13-14	060	1.0	070	10	0.0072	-10
14-15	060	1.3	090	12	.0049	-30
15-16	068	1.7	100	12	.0059	-32
16-17	096	1.7	145	10	.0059	-49
17-18	276	0.6	210	9	.0033	+66
18-19	310	1.0	075	6	.0067	-125
19-20	306	4.5	340	12	.0139	-34
20-21	322	1.7	340	10	.0090	-18
21-22	048	1.7	115	6	.0098	-67
22-24	082	5.0	085	13	.0080	- 3
24-25	072	4.0	Lgt	Vrbl	-	-
25-26	075	1.0	Lgt	Vrbl	-	-
26-27	220	1.0	Lgt	Vrbl	-	-
27-29	223	5.0	215	6	.0198	- 8
29-30	251	1.5	180	12	.0040	+71
30-31	263	0.5	125	9	.0024	+138
31-02	273	8.7	045	3	.0053	+32
Aug 02-03	307	1.6	Lgt	Vrbl	-	-
03-06	089	6.0	095	6	.0109	- 6
		MEDIAN			.0067	-10

BEACON #4 near 70° N 133°W

July	13-14	030	1.0		070	10	0.0036	-40
	14-15	061	1.7		090	12	.0064	-29
	15-16	070	2.0		100	12	.0069	-30
	16-17	110	1.0		145	10	.0069	-35
	17-18	290	0.5		210	9	.0028	+80
	18-19	320	2.5		075	6	.0173	-115
	19-20	286	3.0		340	12	.0089	-54
	20-21	315	1.5		340	10	.0063	-25
	21-22	015	1.0		115	6	.0069	-100
	22-24	015	1.0		090	16	.0012	-75
	24-25	195	0.2		Lgt	Vrbl	-	-
	25-26	195	0.2		Lgt	Vrbl	-	-
	26-27	180	1.5		Lgt	Vrbl	-	-
				MEDIAN			.0067	-37

BEACON #4A near 70°N 135°W

Aug	20-21	238	2.2		055	12	.0073	-177
	21-22	017	0.5		Lgt	Vrbl	-	-
	22-23	187	3.0		125	13	.0089	+62
	23-24	118	2.7		135	15	.0078	-17
	24-25	180	1.5		135	18	.0159	+105
				MEAN			.0081	- 6

BEACON #5 near 70°N 135°W

Aug	20-21	267	5.0		055	12	.0181	-148
	21-22	260	8.0		Lgt	Vrbl	-	-
	22-23	010	2.5		125	13	.0077	-15
	23-24	190	13.0		135	15	.0394	+55
	24-25	245	7.5		130	15	.0172	+95
	25-28	190	22.0		130	12	.0270	+60
				MEDIAN			.0181	+55

BEACON #6 near 70°N 135°W

Aug	20-21	254	6.0		055	12	.0208	-161
	21-23	352	5.5		125	7	.0154	-133
	23-24	195	16.5		135	15	.0521	+60
	24-25	200	10.0		130	15	.0230	+70
	25-28	212	4.0		130	12	.0049	+82
				MEDIAN			.0208	+60

BEACON #8 near 70°N 137°W

Aug	23-25	153	10.5		130	15	.0146	+23
	25-26	051	5.0		135	18	.0107	-84
	26-28	128	18.0		125	12	.0295	+ 3
	28-29	163	10.0		Lgt	Vrbl	-	-
				MEAN			.0183	-19

BEACON #12 near 70°N 133°W

Sept 5-6	140	4.5		Lgt	Vrbl	-	-
6-7	087	6.0		150	20	.0103	-63
7-9	093	7.5		125	6	.0260	-32
9-10	176	1.5		140	12	.0059	+36
10-11	310	3.0		Lgt	Vrbl	-	-
			MEAN			.0141	-20

BEACON #13 near 70°N 137°W

Sept 6-7	132	5.0		150	20	.0086	-18
7-9	117	14.5		125	6	.0550	- 6
			MEAN			.0318	-12

BEACON #14 near 70°N 137°W

Sept 5-6	075	3.3		Lgt	Vrbl	-	-
6-7	126	3.0		150	20	.0054	-24
7-9	121	7.5		125	6	.0284	- 4
9-10	136	24.0		140	12	.0690	- 4
10-11	127	16.0		Lgt	Vrbl	-	-
			MEAN			0.343	-11

BEACON #16 near 70°N 135°W

Sept 6-7	135	6.0		150	20	.0091	-15
7-9	111	7.5		125	6	.0255	-14
9-10	147	8.0		140	12	.0317	+ 7
10-11	279	4.0		Lgt	Vrbl	-	-
11-13	115	21.0		115	20	.0239	0
13-14	117	33.0		120	25	.0440	- 3
			MEDIAN			.0255	- 3

BEACON #17 near 70°N 133°W

Sept 6-7	040	1.7		Lgt	Vrbl	-	-
7-9	102	2.5		125	6	.0085	-23
9-10	131	5.5		140	12	.0218	- 9
10-11	305	3.5		Lgt	Vrbl	-	-
			MEAN			.0152	-16

BEACON #18 near 70°N 133°W

Sept 5-6	030	0.5		Lgt	Vrbl	-	-
6-7	100	6.5		150	20	.0125	-50
7-9	070	6.0		125	6	.0108	-55
9-10	155	7.5		140	12	.0297	+15
10-11	281	32.0		Lgt	Vrbl	-	-
11-13	119	29.5		115	20	.0292	+ 4
13-14	119	23.0		120	25	.0307	- 1
			MEDIAN			.0292	- 1

BEACON #19 near 70°N 133°W

Sept 15-16	230	4.5	110	25	.0106	-150
16-17	337	0.5	128	20	.0010	-151
17-18	315	2.5	115	10	.0108	-160
18-19	228	0.5	130	5	.0038	+158
		MEAN			.0065	-76

BEACON #31 near 70°N 137°W

Sept 10-11	353	3.0	Lgt	Vrbl	-	-
11-13	130	21.5	115	20	.0244	+15

BEACON #32 near 70°N 137°W

Sept 9-10	106	17.5	140	12	.0584	-34
10-11	212	1.0	Lgt	Vrbl	-	-
11-13	110	21.0	115	20	.0244	- 5
13-14	118	5.0	120	25	.0072	- 2
		MEAN			.0381	-14

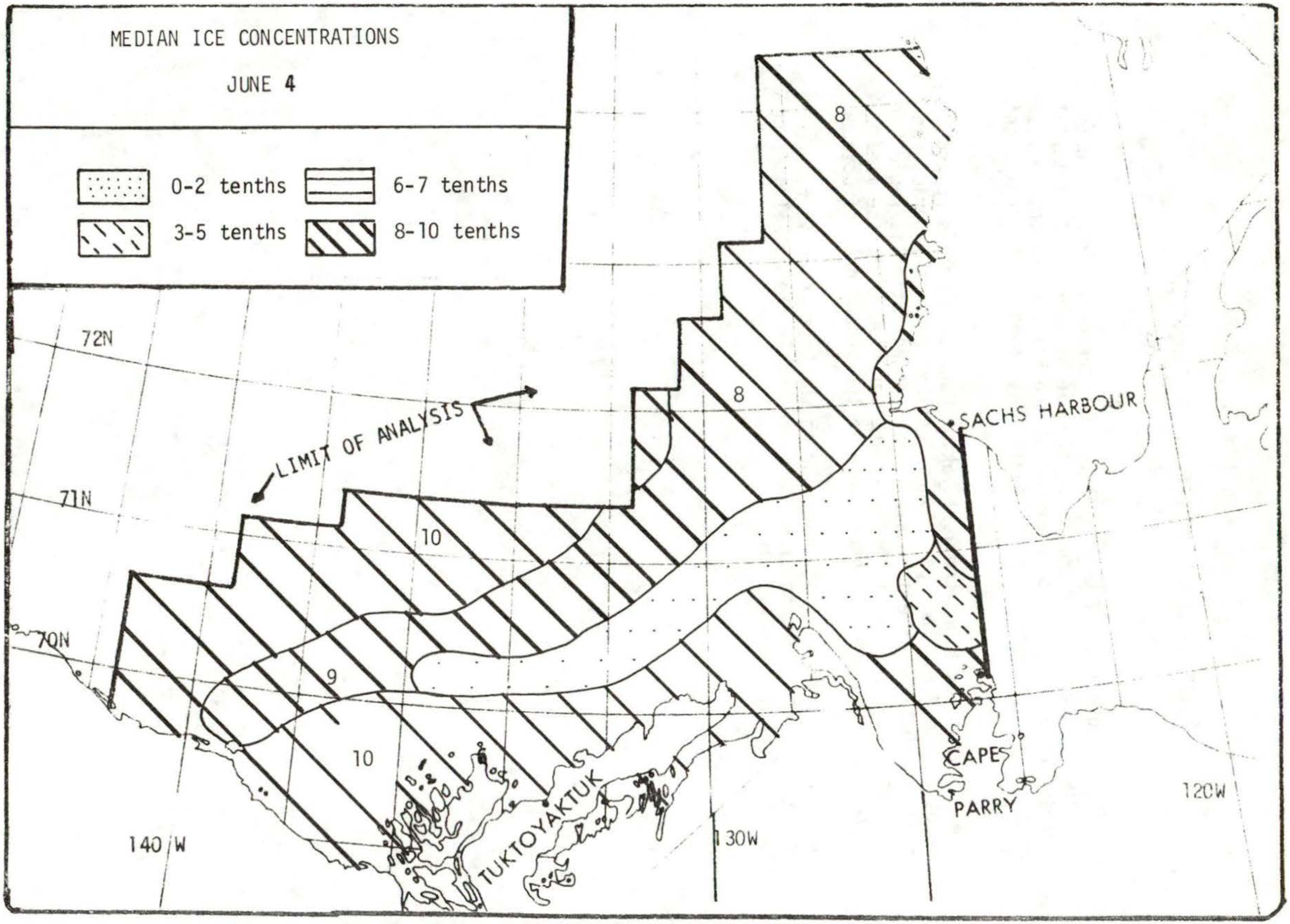
APPENDIX II

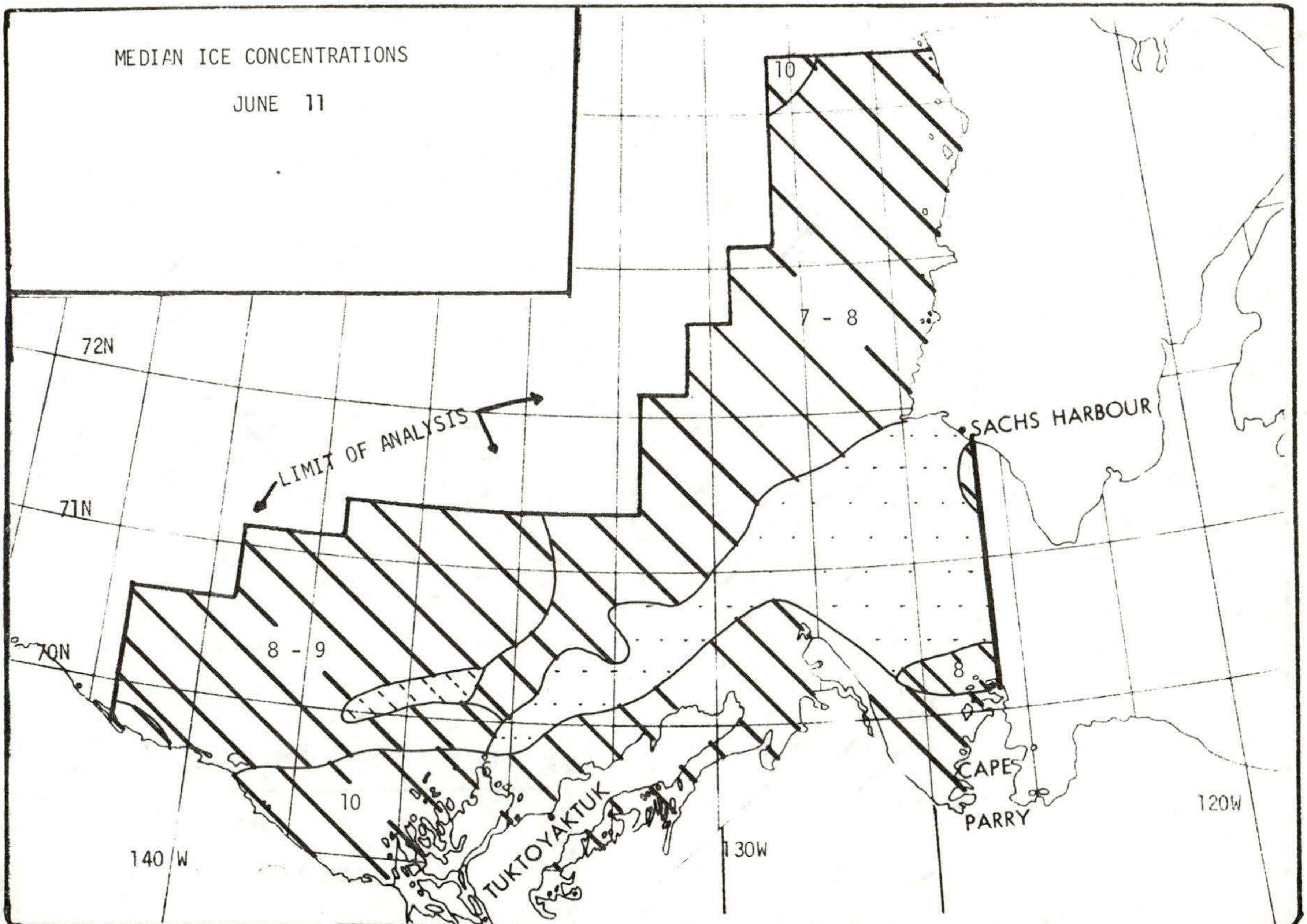
WEEKLY CHARTS OF MEDIAN ICE CONDITIONS

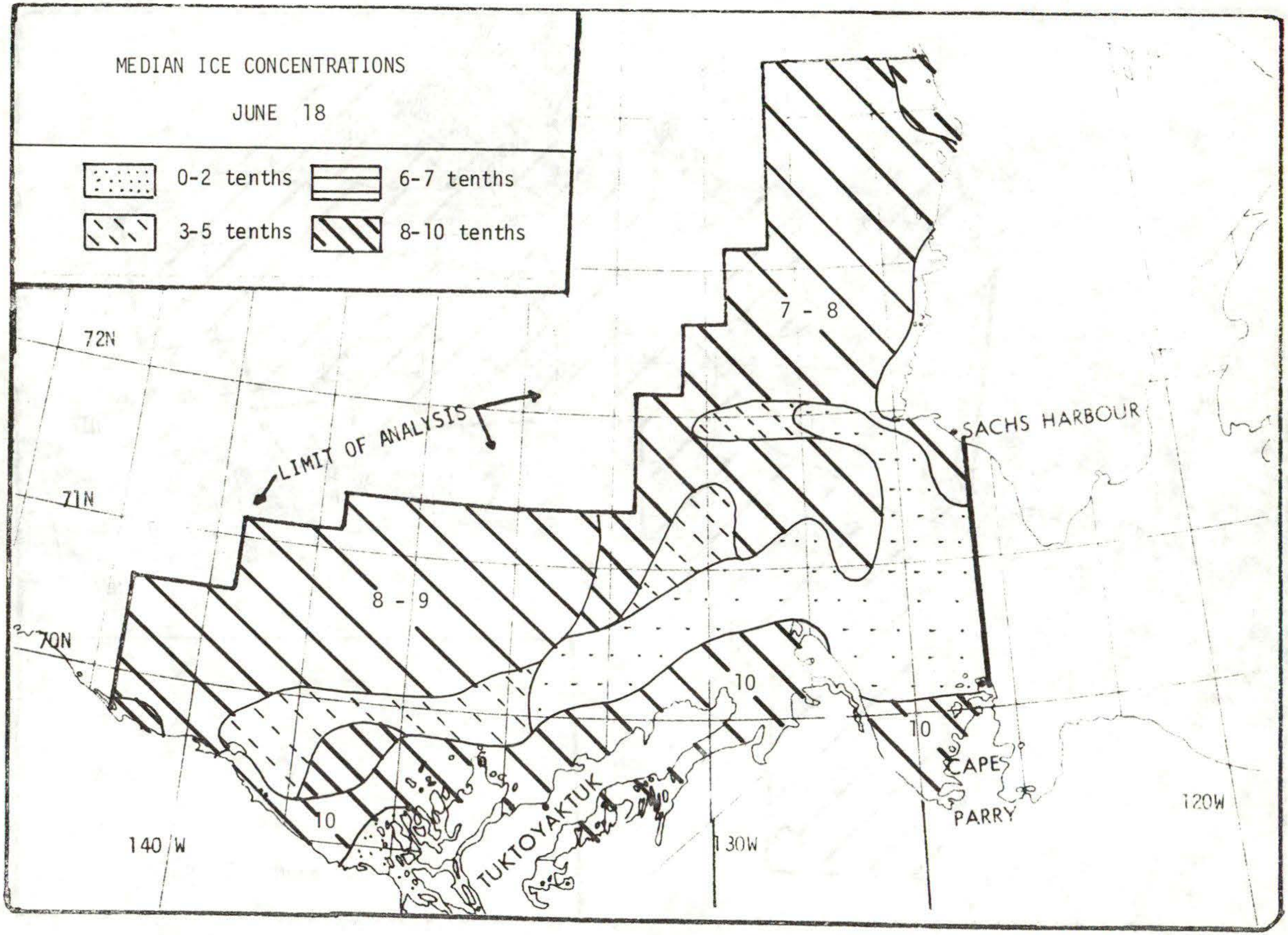
The following series of weekly charts is reproduced from the data contained in the FENCO report described in Section 1. A pictorial representation of the median amount of ice has been attempted using the groupings of concentration levels that appear to be most significant.

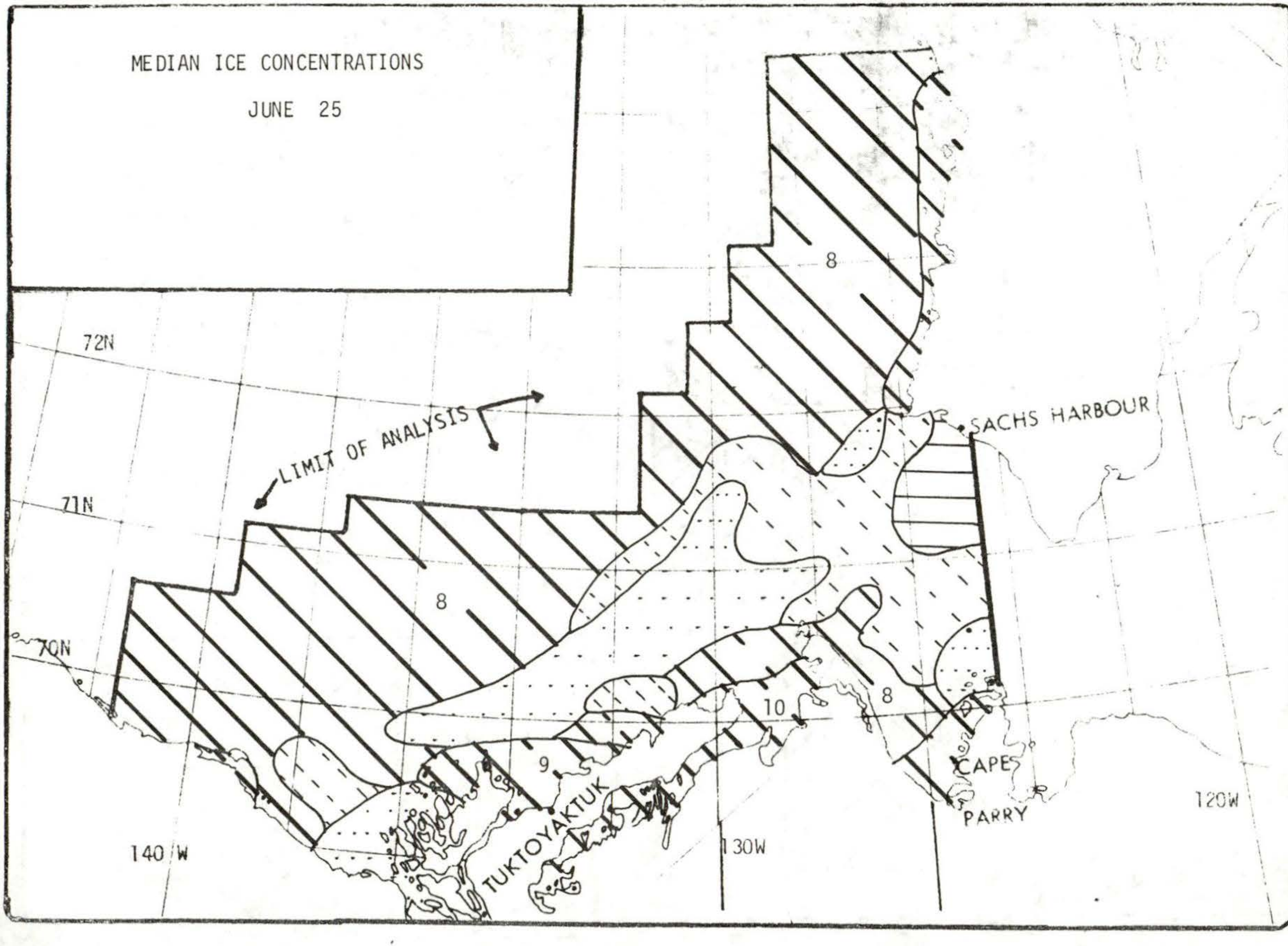
Once the fast ice along the Tuktoyaktuk Peninsula breaks up and disperses in the first half of July, a lengthy open water period can occur. In October, the increase in ice concentration is rapid but thickness and strength of the floes are very low until the ice reaches the 15-30 cm thickness range in the second half of October.

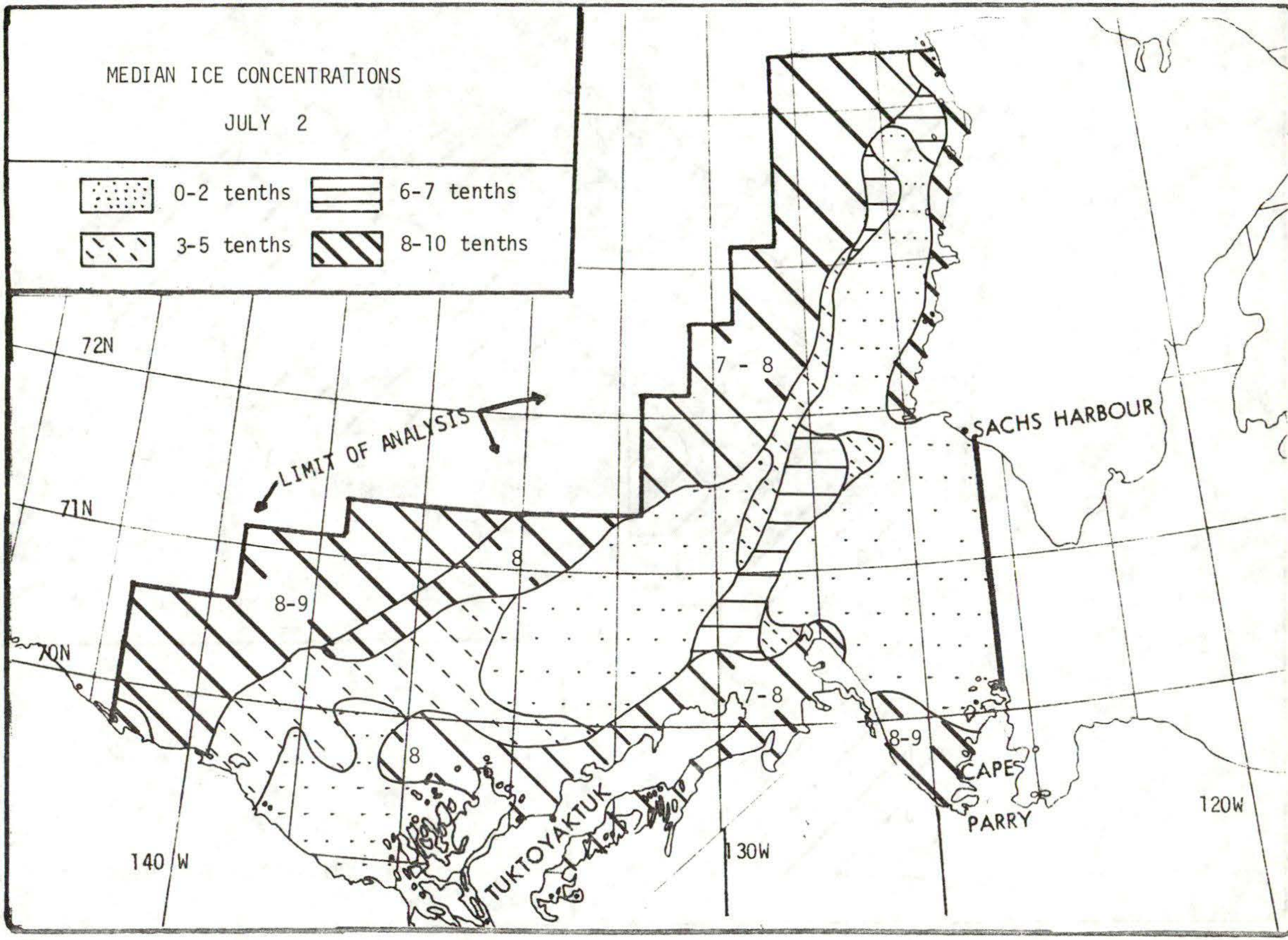
Charts showing median conditions during the best years in five and during the worst years in five are contained in the detailed FENCO report referred to previously.

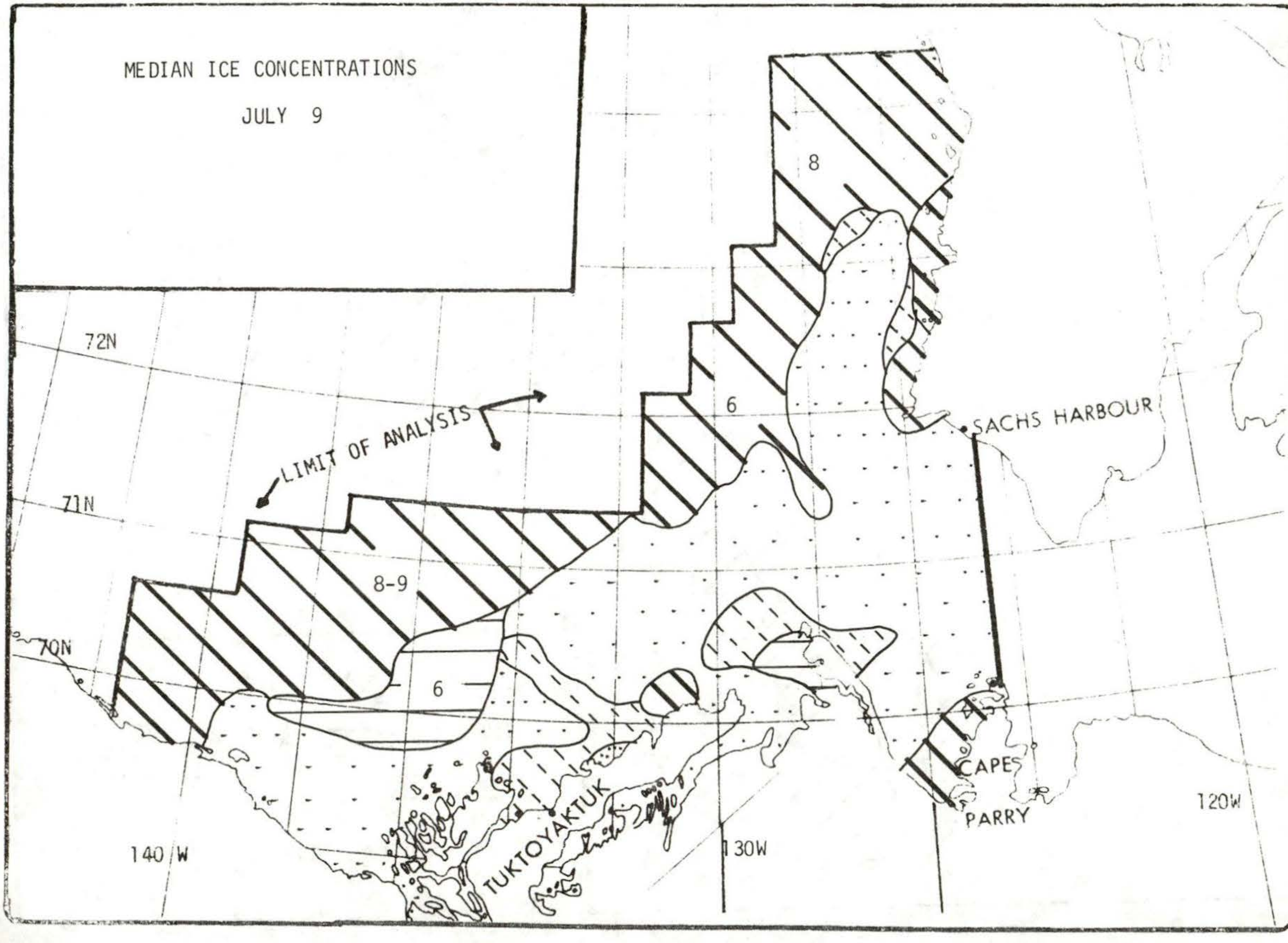

MEDIAN ICE CONCENTRATIONS
JUNE 4
0-2 tenths
6-7 tenths
3-5 tenths
8-10 tenths
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
CAPE PARRY
TUKTOYAKTUK
140 W
130W
120W
8
8
10
9
10

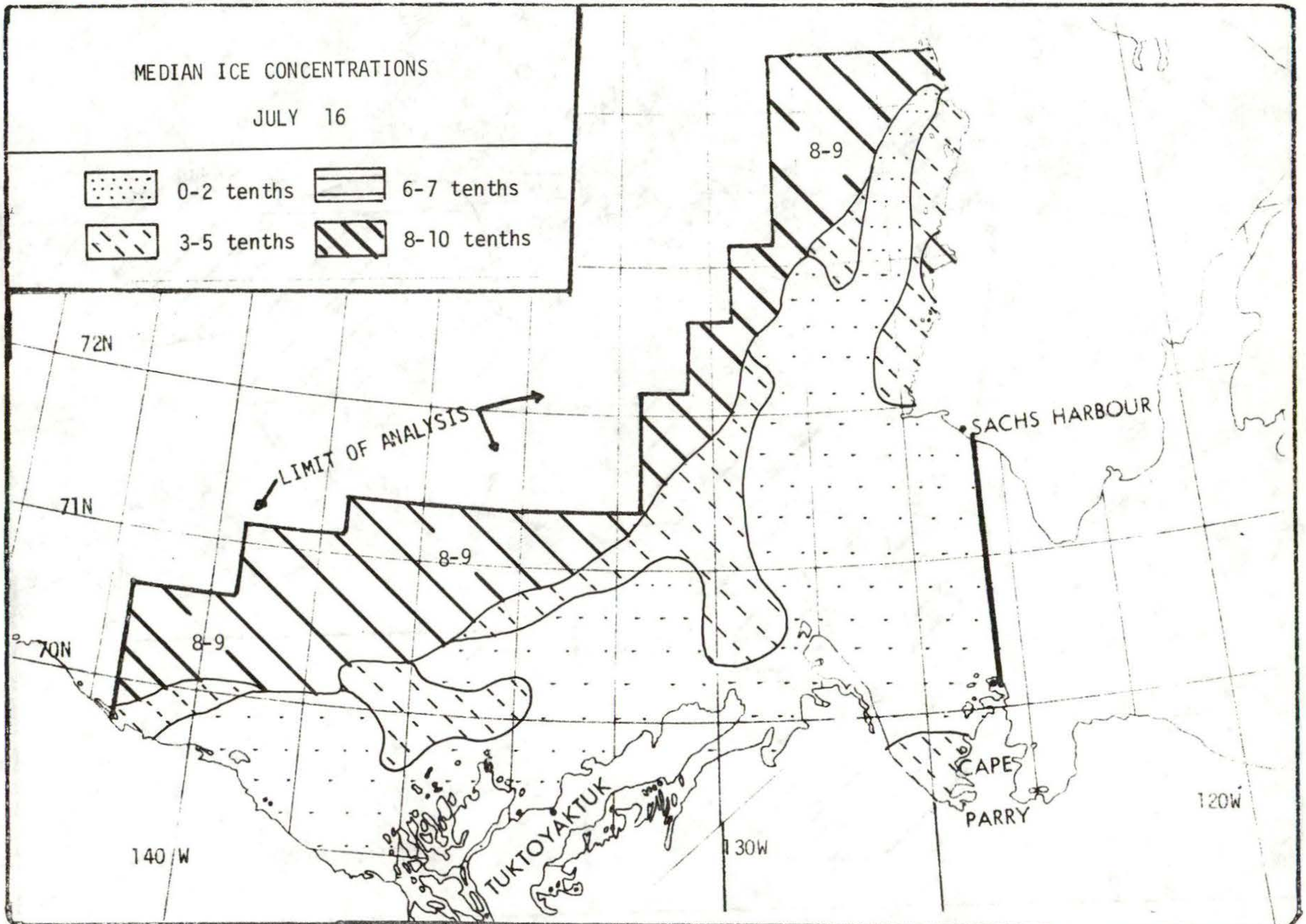

MEDIAN ICE CONCENTRATIONS
JUNE 11
72N
71N
70N
LIMIT OF ANALYSIS
7 - 8
8 - 9
10
10
8
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W


MEDIAN ICE CONCENTRATIONS
JUNE 18
0-2 tenths
6-7 tenths
3-5 tenths
8-10 tenths
72N
71N
70N
LIMIT OF ANALYSIS
7 - 8
8 - 9
10
10
10
SACHS HARBOUR
TUKTOYAKTUK
CAPE
PARRY
140 W
130W
120W

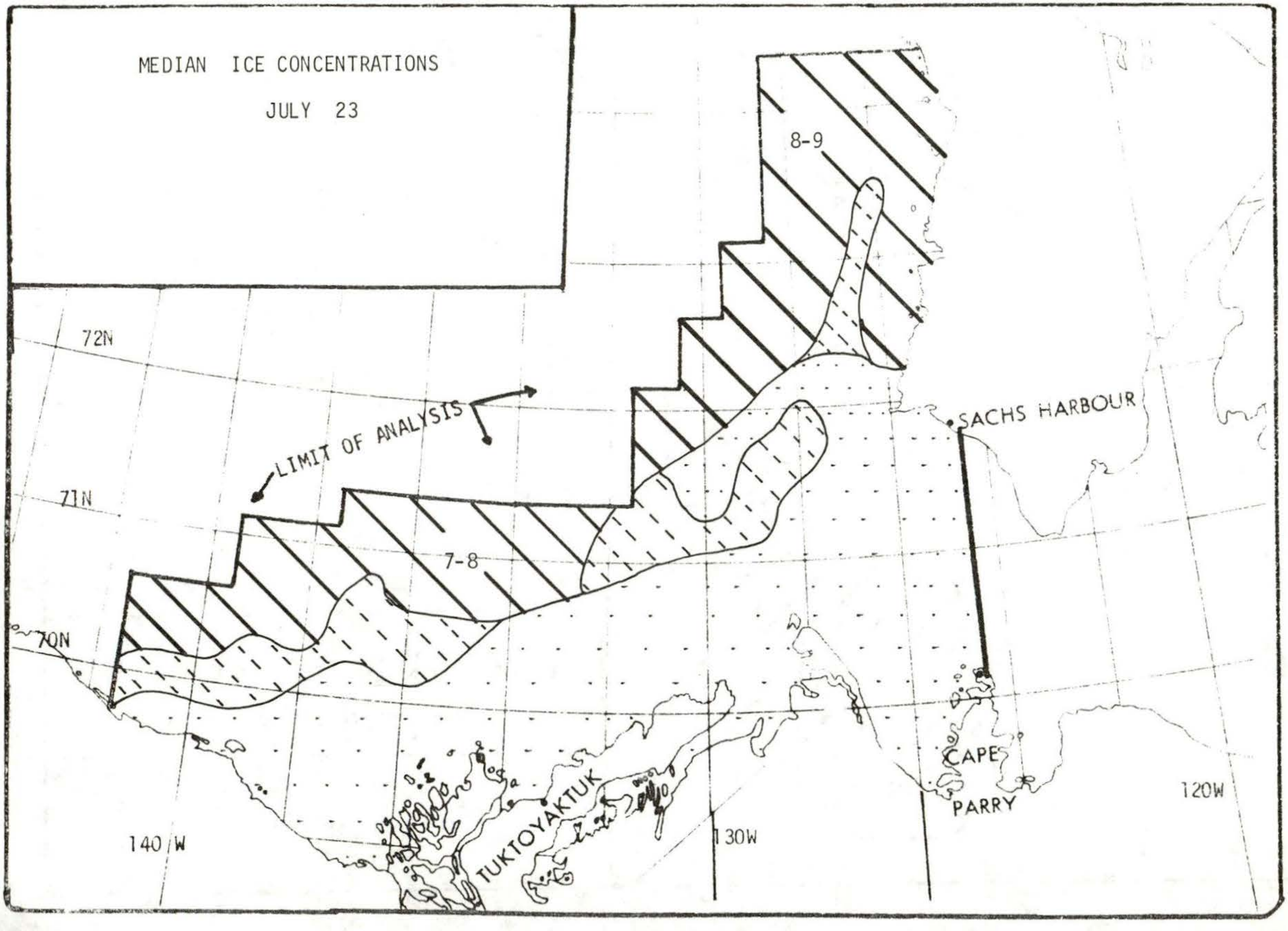

MEDIAN ICE CONCENTRATIONS
JUNE 25
LIMIT OF ANALYSIS
SACHS HARBOUR
TUKTOYAKTUK
CAPE
PARRY
72N
71N
70N
140 W
130W
120W
8
8
8
9
10

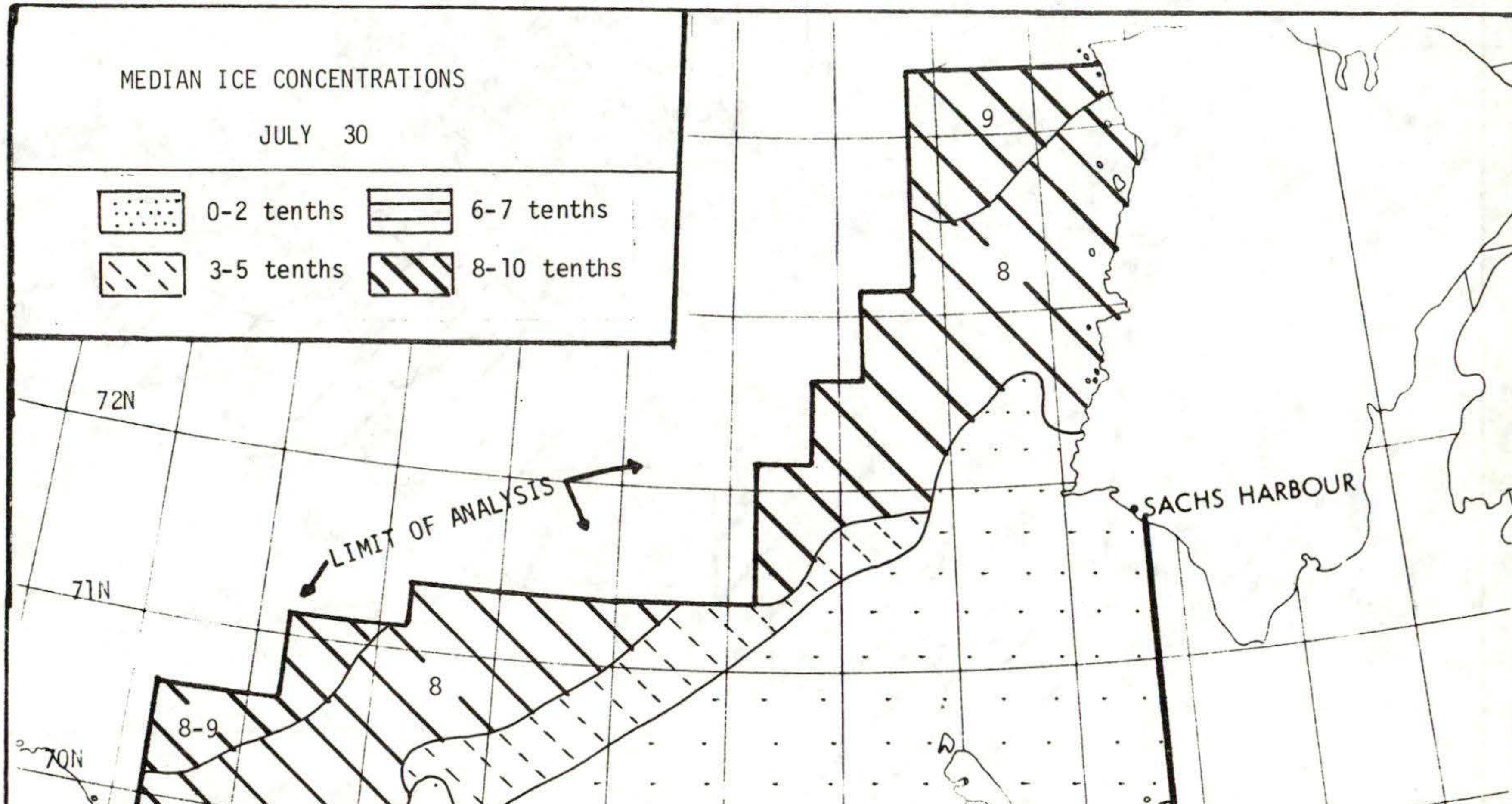

MEDIAN ICE CONCENTRATIONS
JULY 2
0-2 tenths
6-7 tenths
3-5 tenths
8-10 tenths
72N
71N
70N
LIMIT OF ANALYSIS
7 - 8
8
8-9
7-8
8
8-9
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W

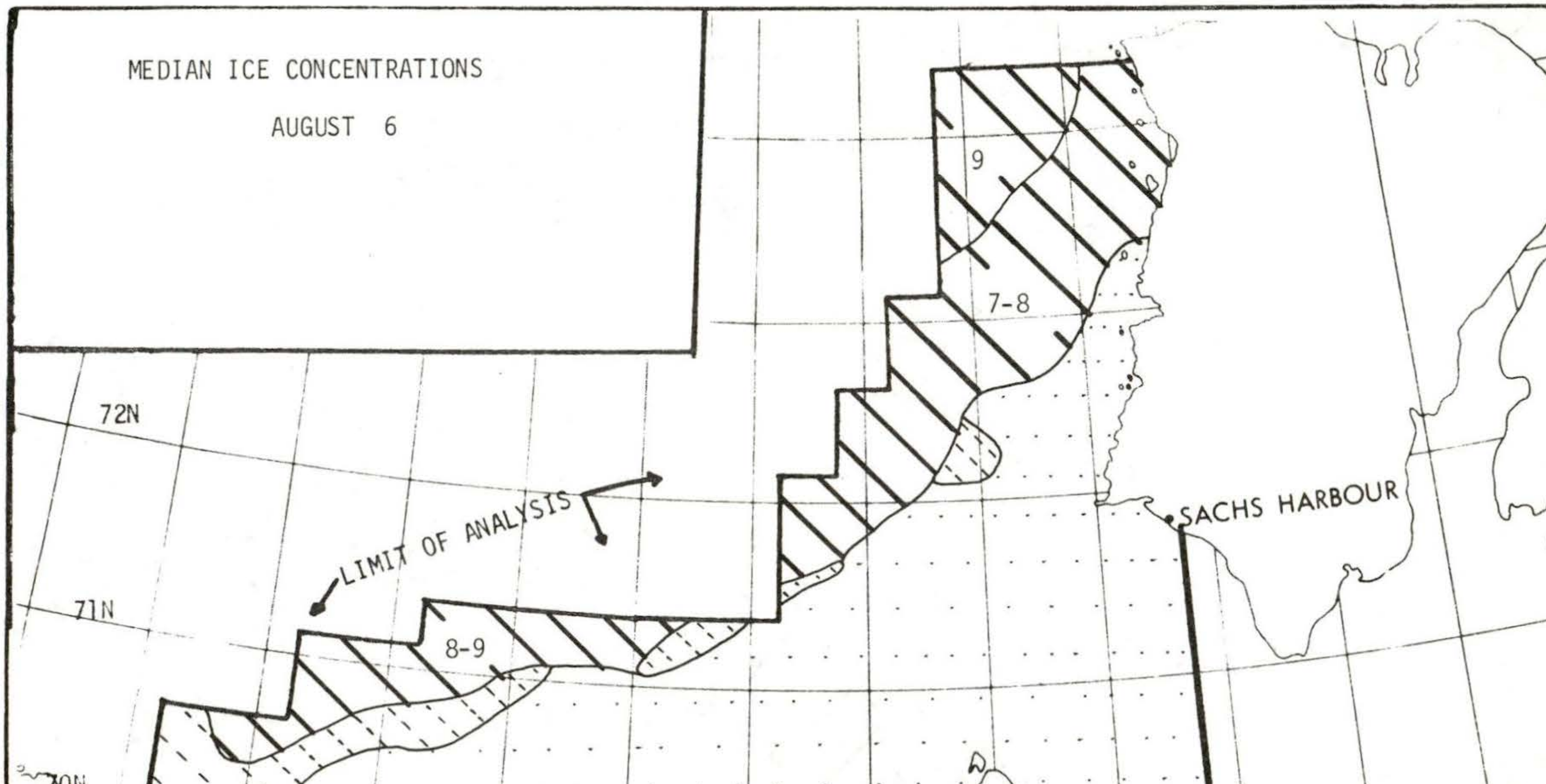

MEDIAN ICE CONCENTRATIONS
JULY 9
72N
71N
70N
LIMIT OF ANALYSIS
8
6
8-9
6
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W



MEDIAN ICE CONCENTRATIONS
JULY 16
0-2 tenths
3-5 tenths
6-7 tenths
8-10 tenths
8-9
8-9
8-9
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W

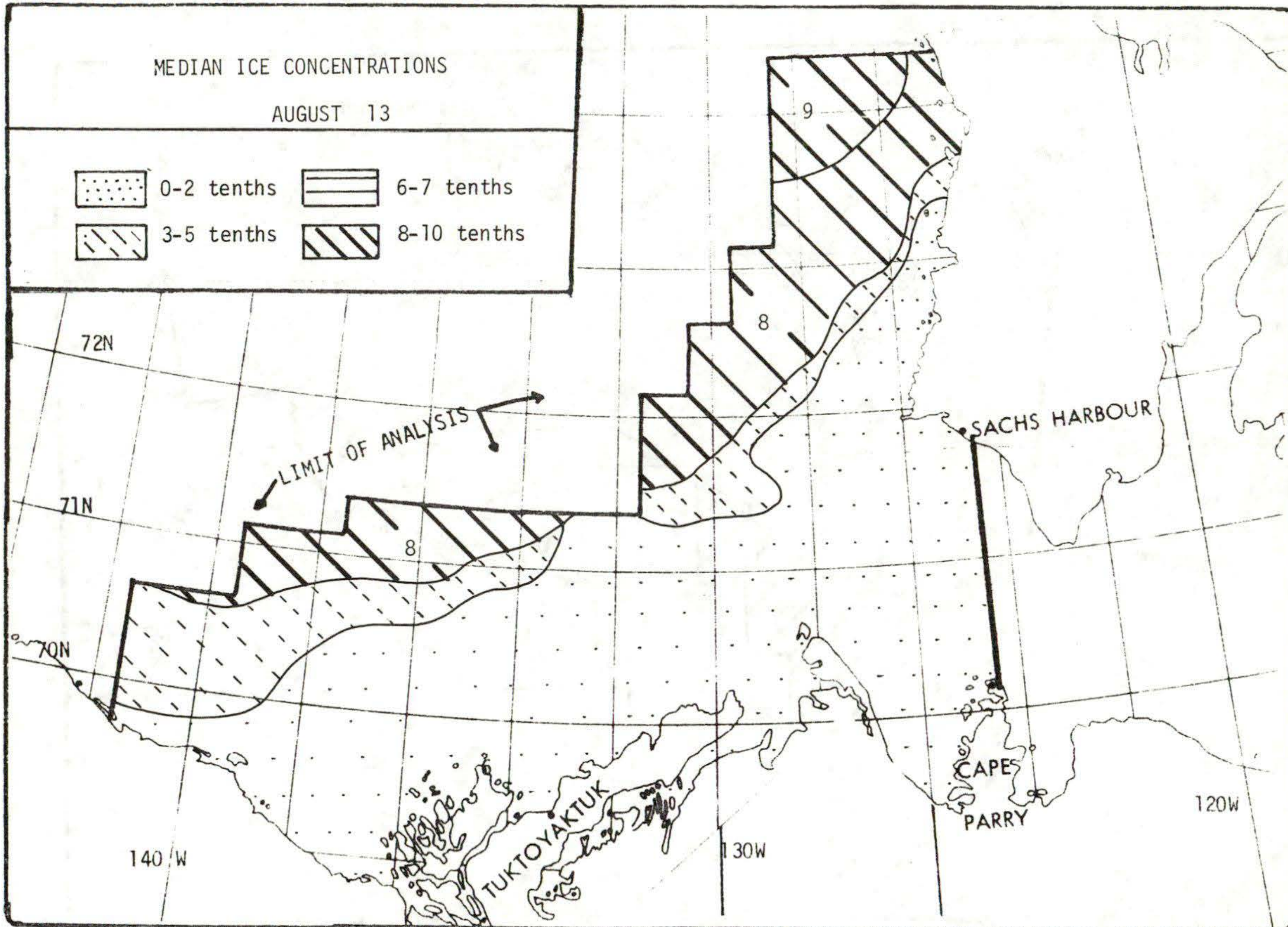

MEDIAN ICE CONCENTRATIONS
JULY 23
8-9
7-8
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W

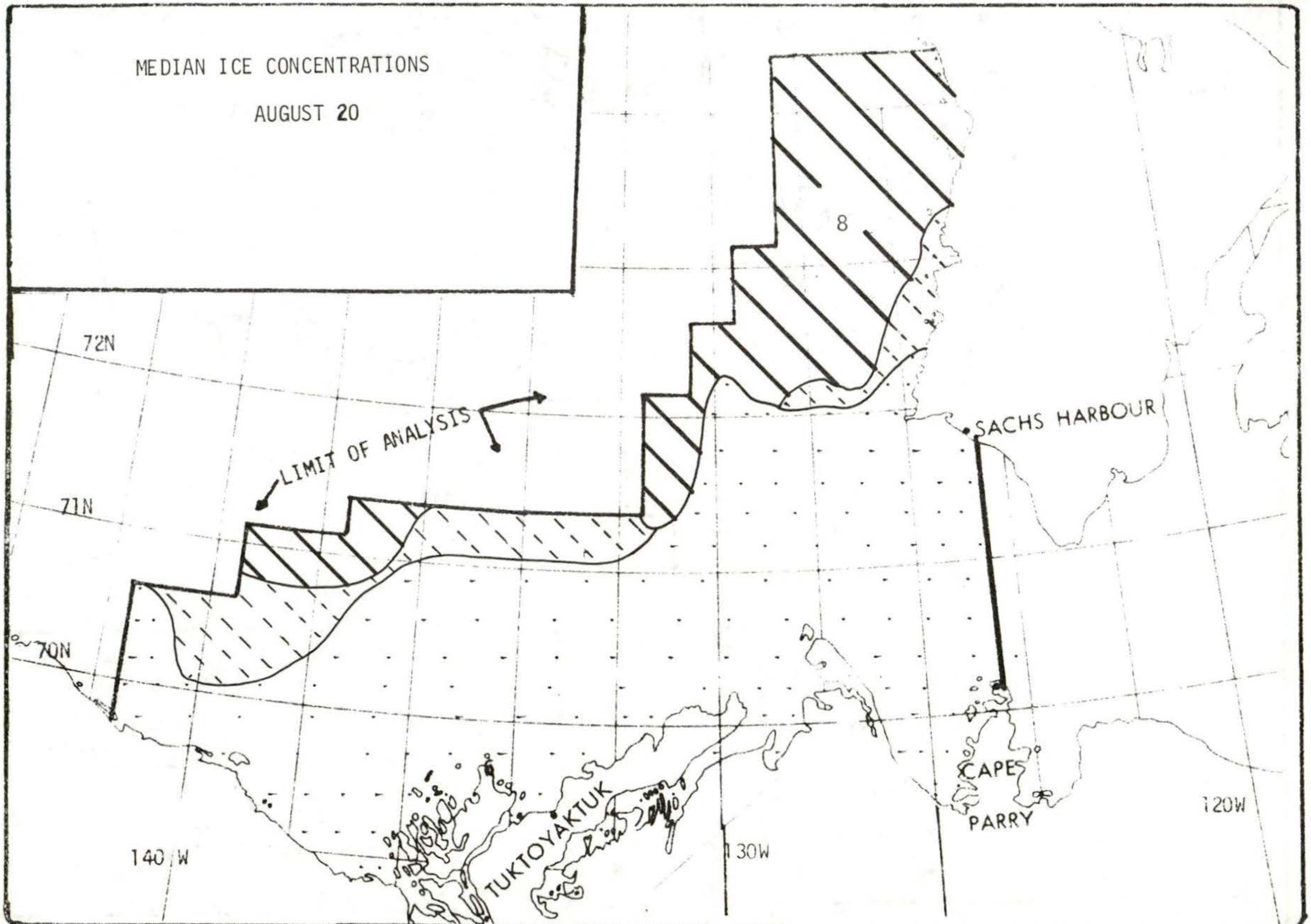

MEDIAN ICE CONCENTRATIONS
JULY 30
0-2 tenths
3-5 tenths
6-7 tenths
8-10 tenths
72N
71N
70N
LIMIT OF ANALYSIS
9
8
8
8-9
SACHS HARBOUR
TUKTOYAKTUK
CAPE
PARRY
140 W
130W
120W

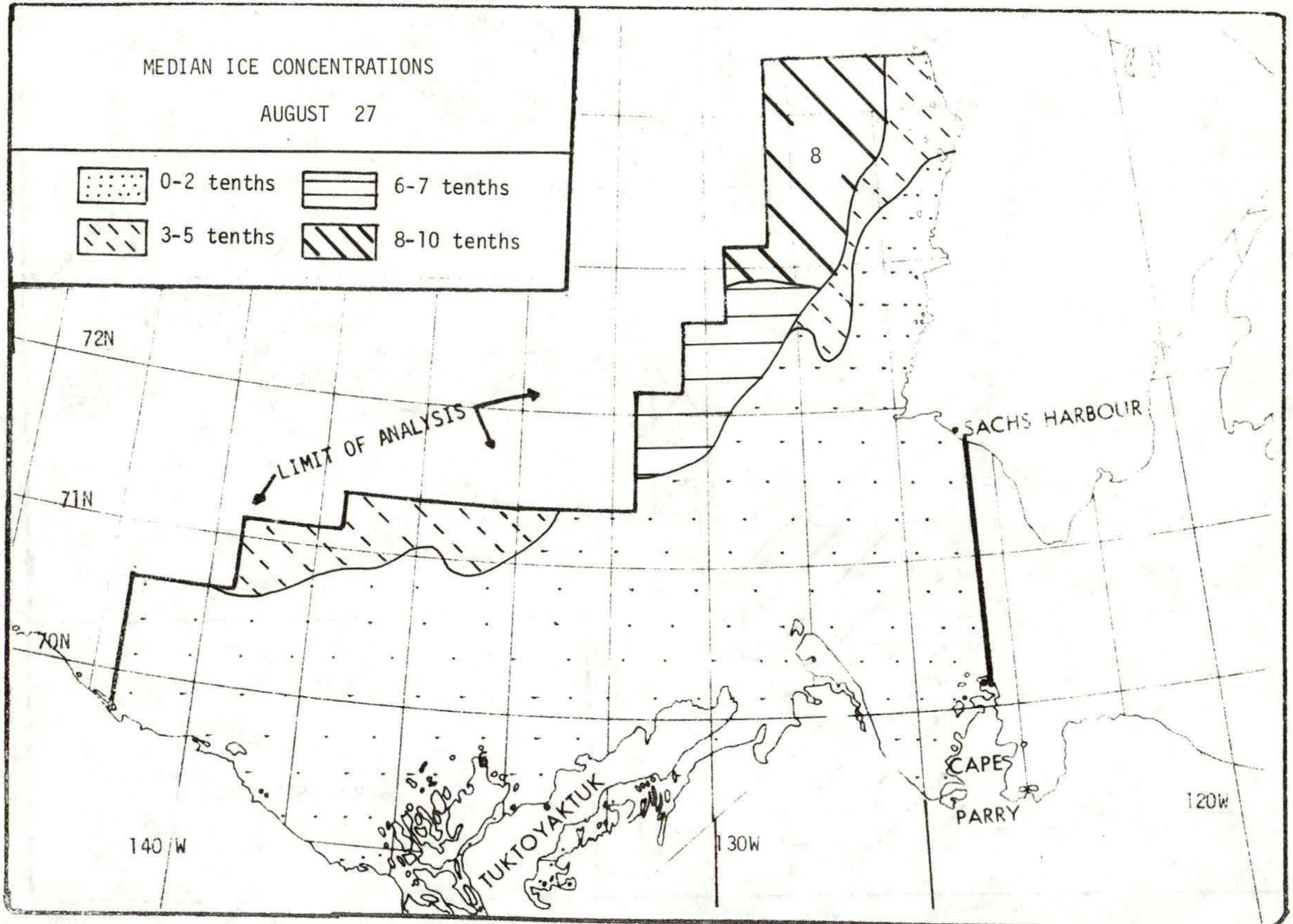


MEDIAN ICE CONCENTRATIONS

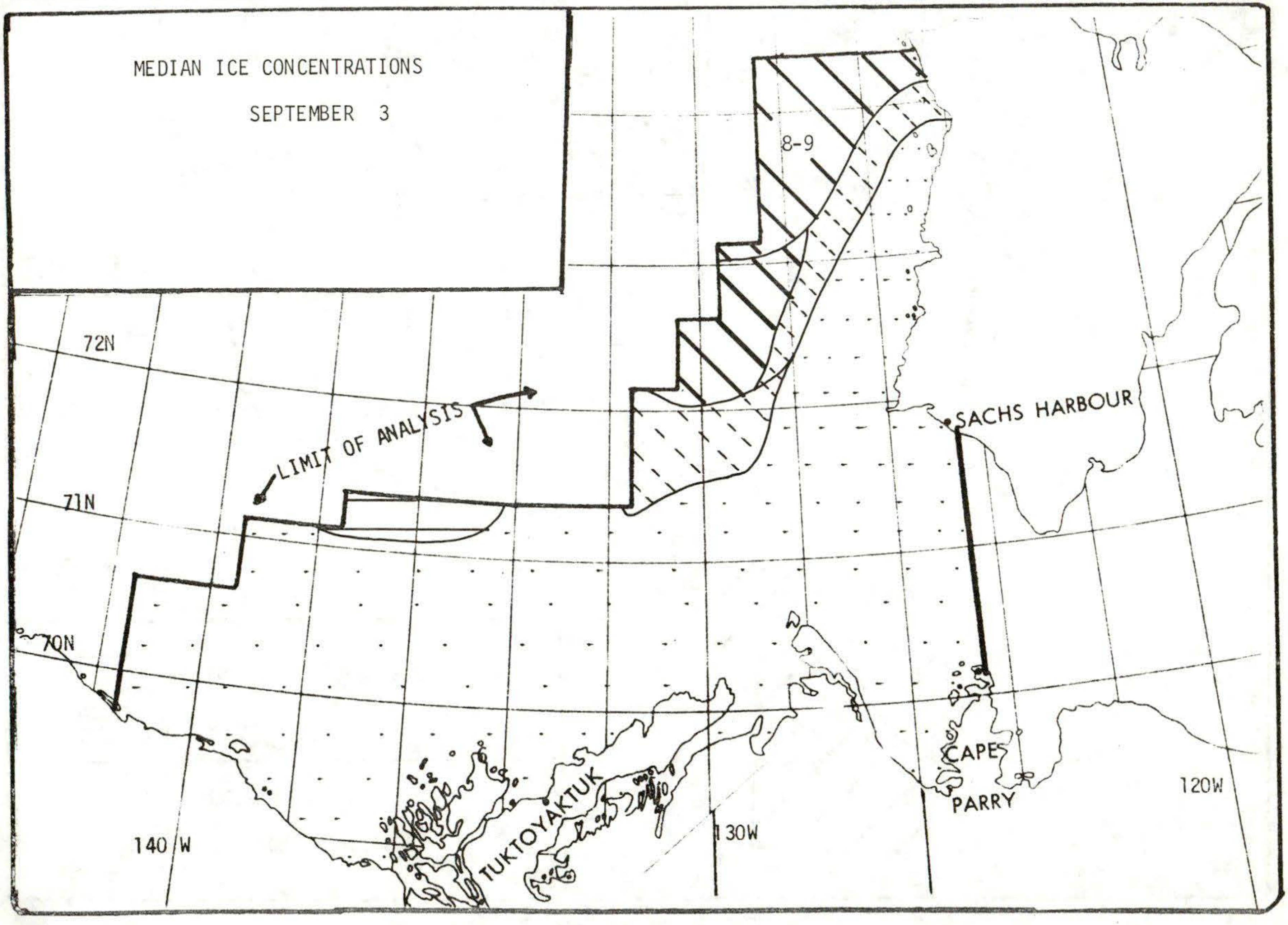
AUGUST 6

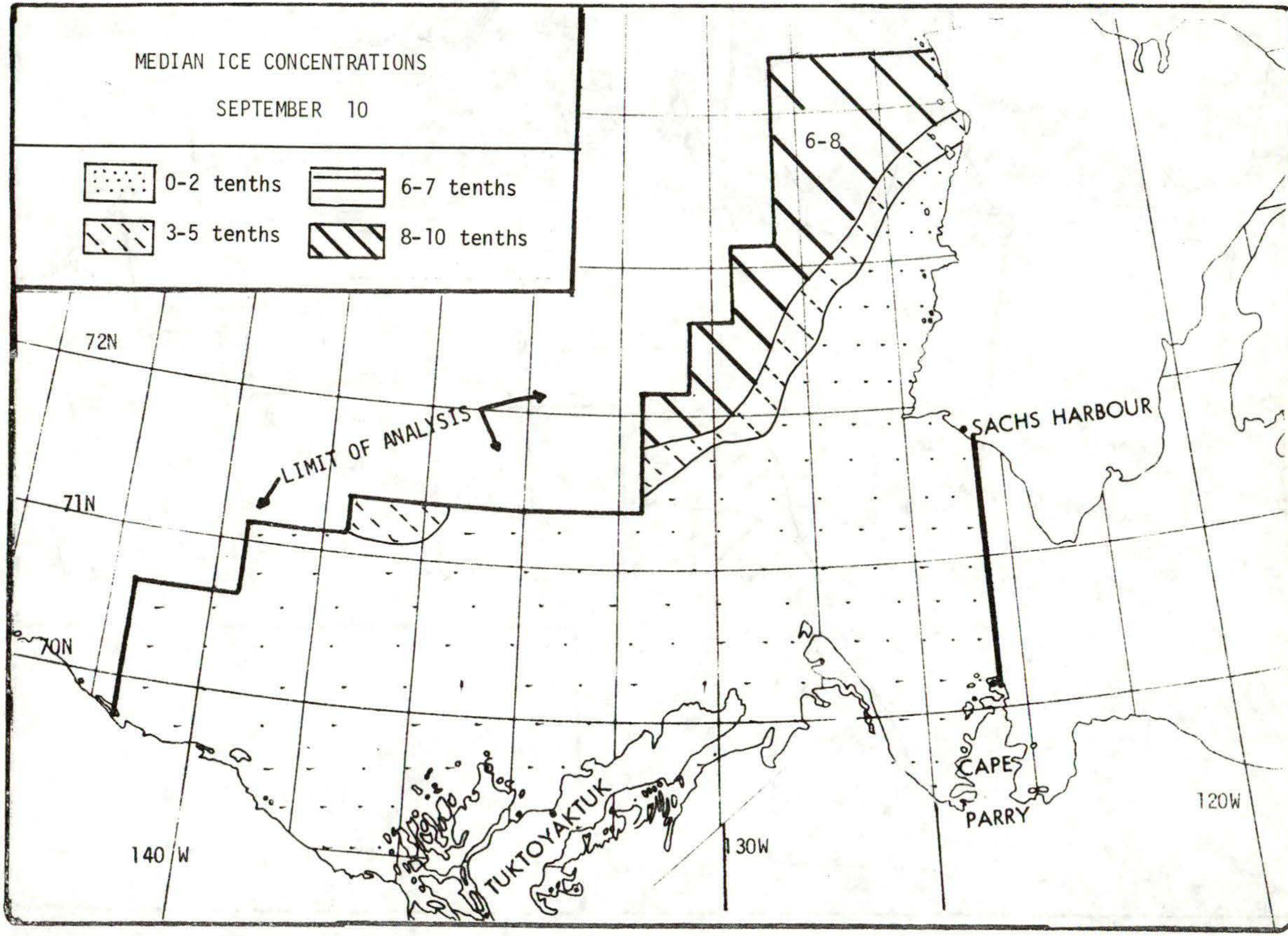

MEDIAN ICE CONCENTRATIONS
AUGUST 13
0-2 tenths
3-5 tenths
6-7 tenths
8-10 tenths
LIMIT OF ANALYSIS
9
8
8
72N
71N
70N
SACHS HARBOUR
CAPE PARRY
TUKTOYAKTUK
140 W
130W
120W


MEDIAN ICE CONCENTRATIONS
AUGUST 20
72N
71N
70N
8
LIMIT OF ANALYSIS
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W



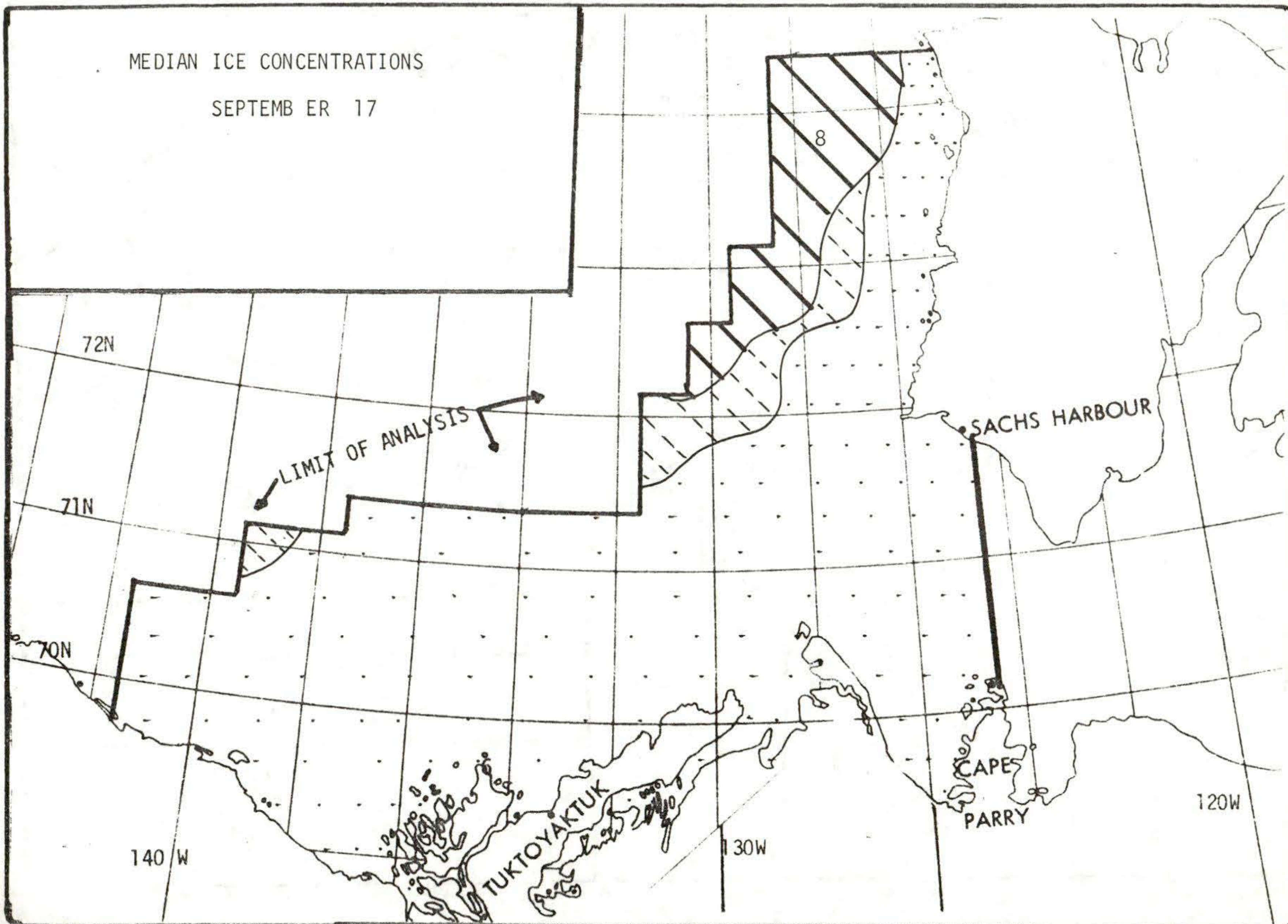
MEDIAN ICE CONCENTRATIONS
AUGUST 27
0-2 tenths
3-5 tenths
6-7 tenths
8-10 tenths
8
LIMIT OF ANALYSIS
72N
71N
70N
SACHS HARBOUR
TUKTOYAKTUK
CAPE
PARRY
140 W
130W
120W

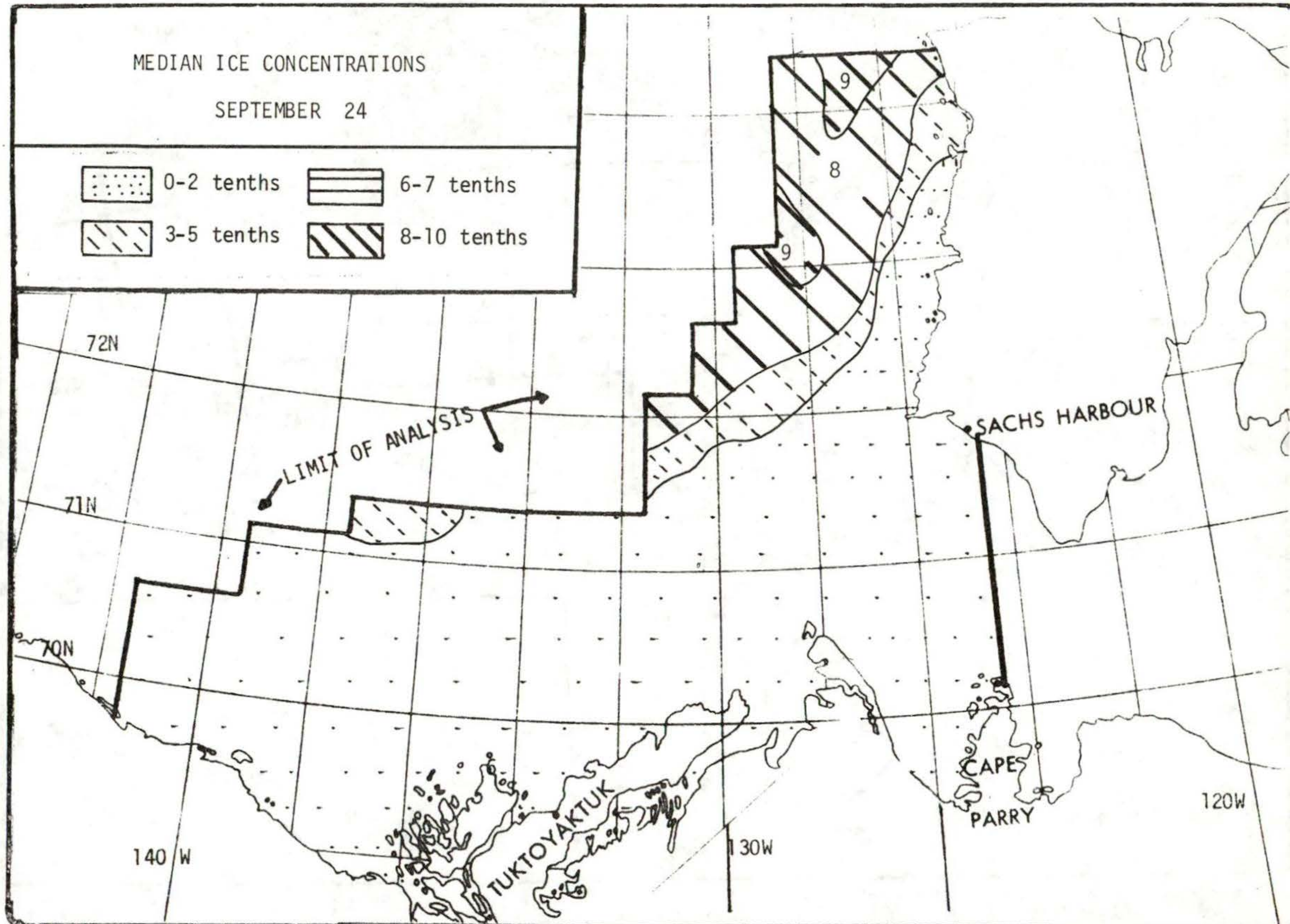

MEDIAN ICE CONCENTRATIONS
SEPTEMBER 3
8-9
LIMIT OF ANALYSIS
72N
71N
70N
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W

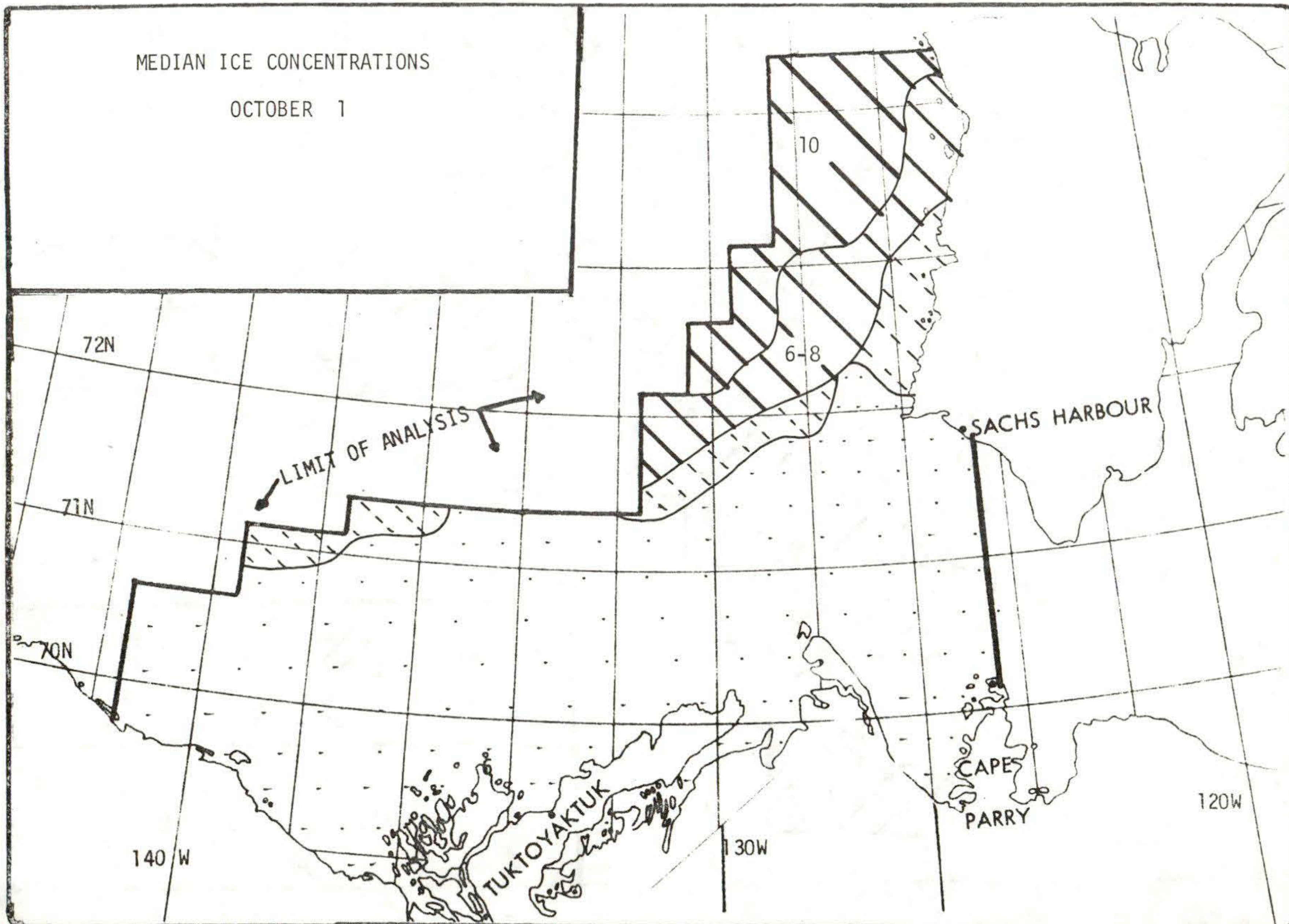

MEDIAN ICE CONCENTRATIONS
SEPTEMBER 10
0-2 tenths
3-5 tenths
6-7 tenths
8-10 tenths
6-8
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
TUKTOYAKTUK
CAPE
PARRY
140 W
130W
120W

MEDIAN ICE CONCENTRATIONS

SEPTEMB ER 17

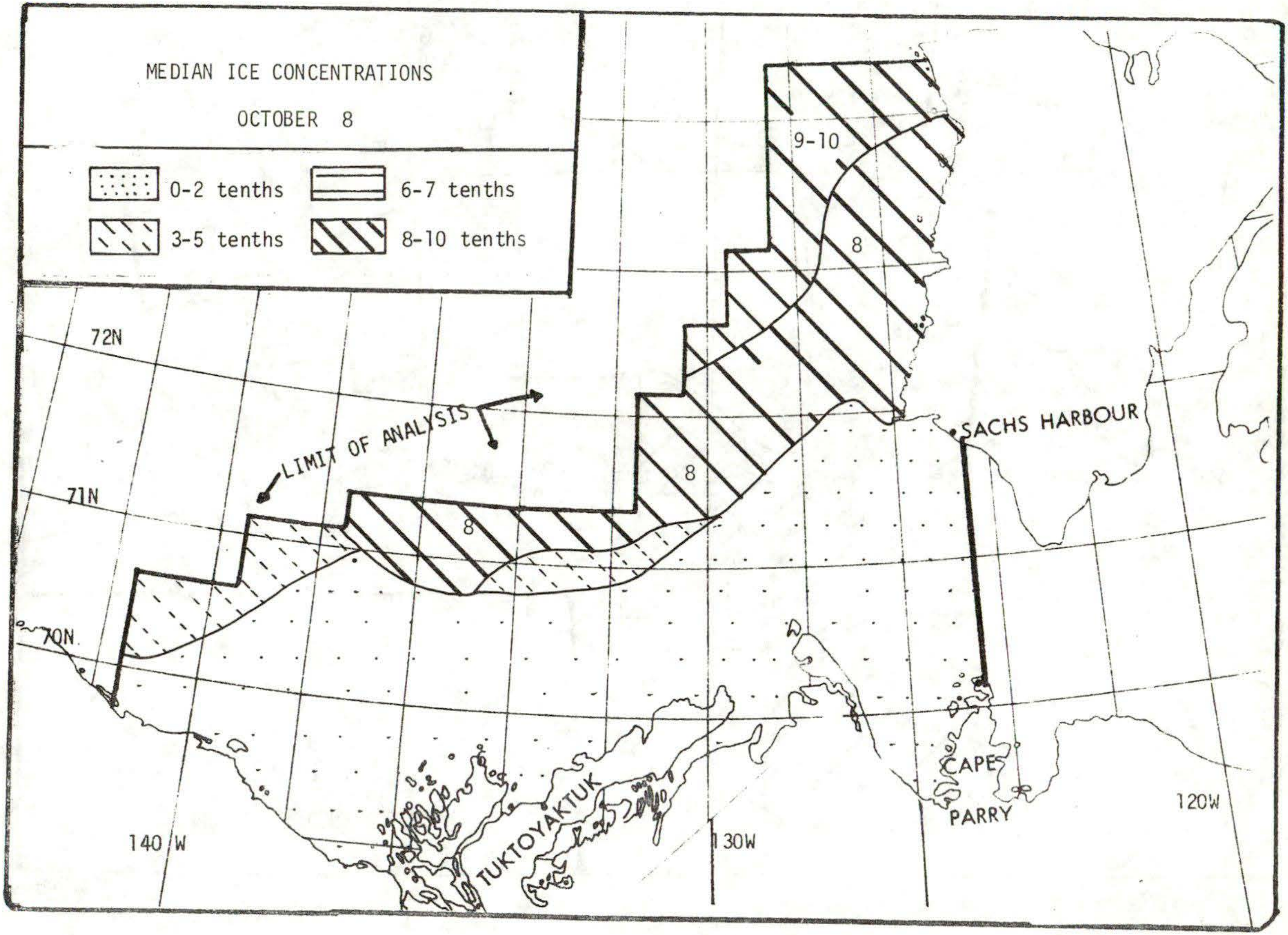


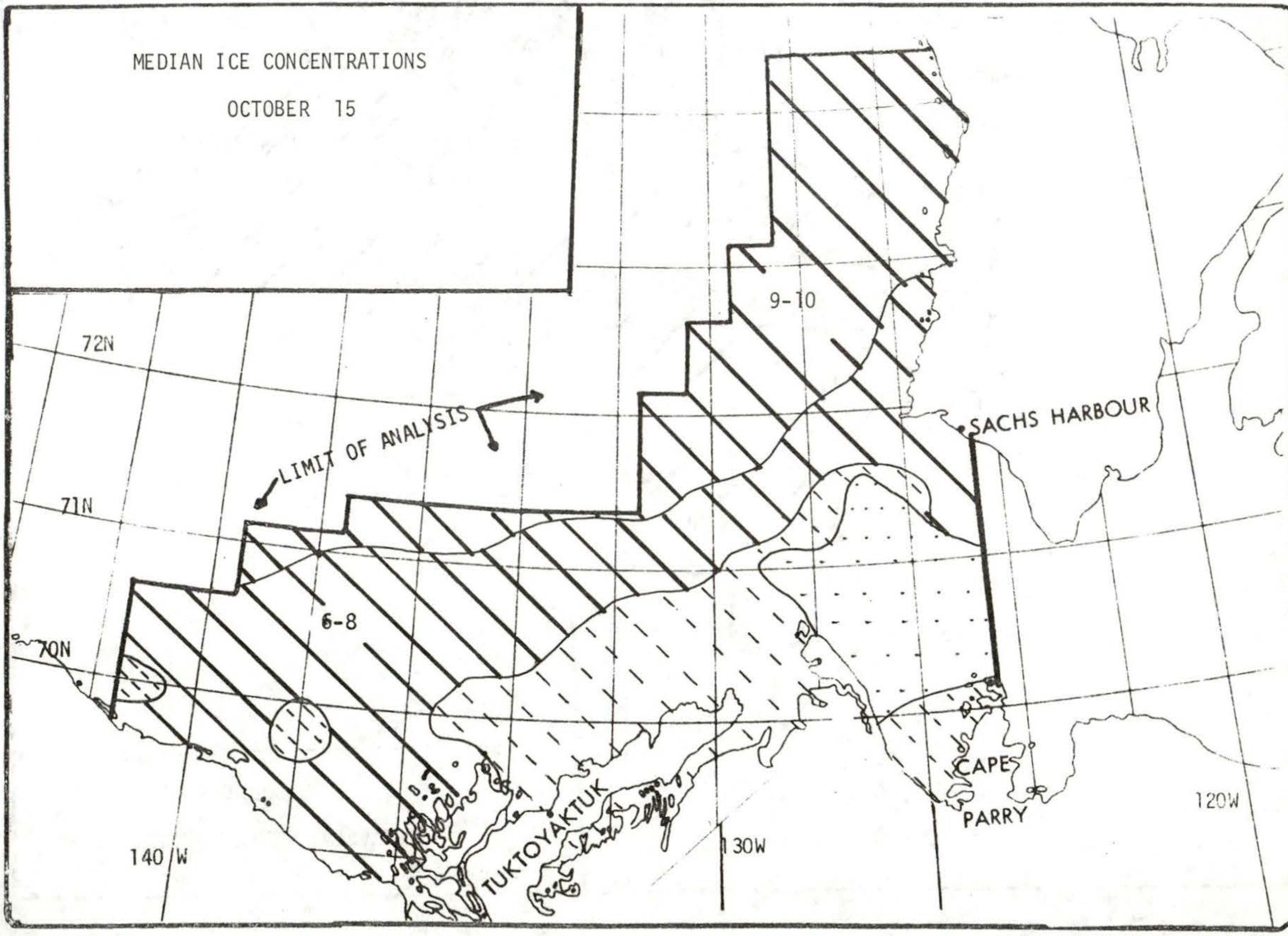

MEDIAN ICE CONCENTRATIONS
SEPTEMBER 24
0-2 tenths
3-5 tenths
6-7 tenths
8-10 tenths
9
8
9
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
CAPE PARRY
TUKTOYAKTUK
140 W
130W
120W

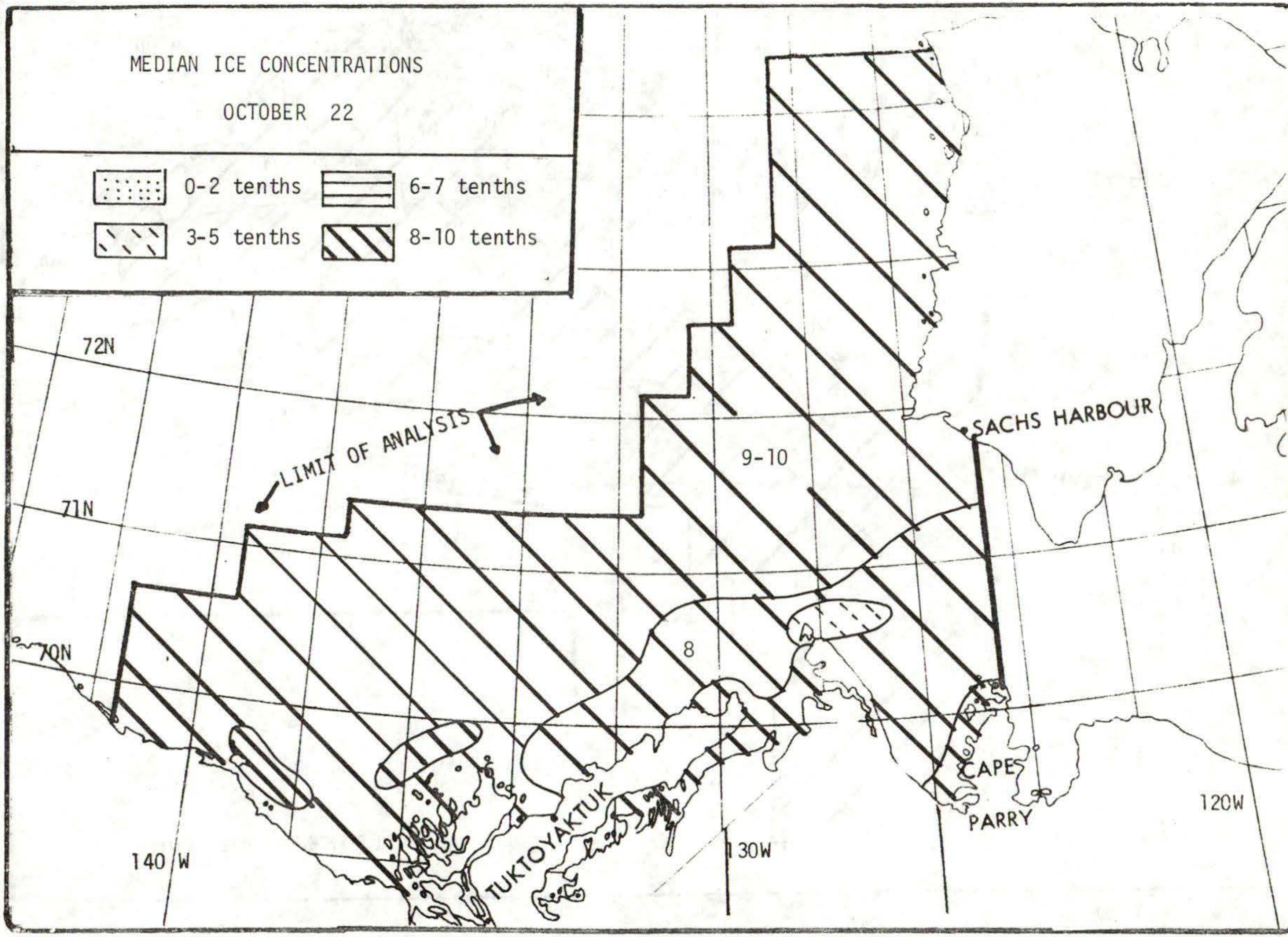


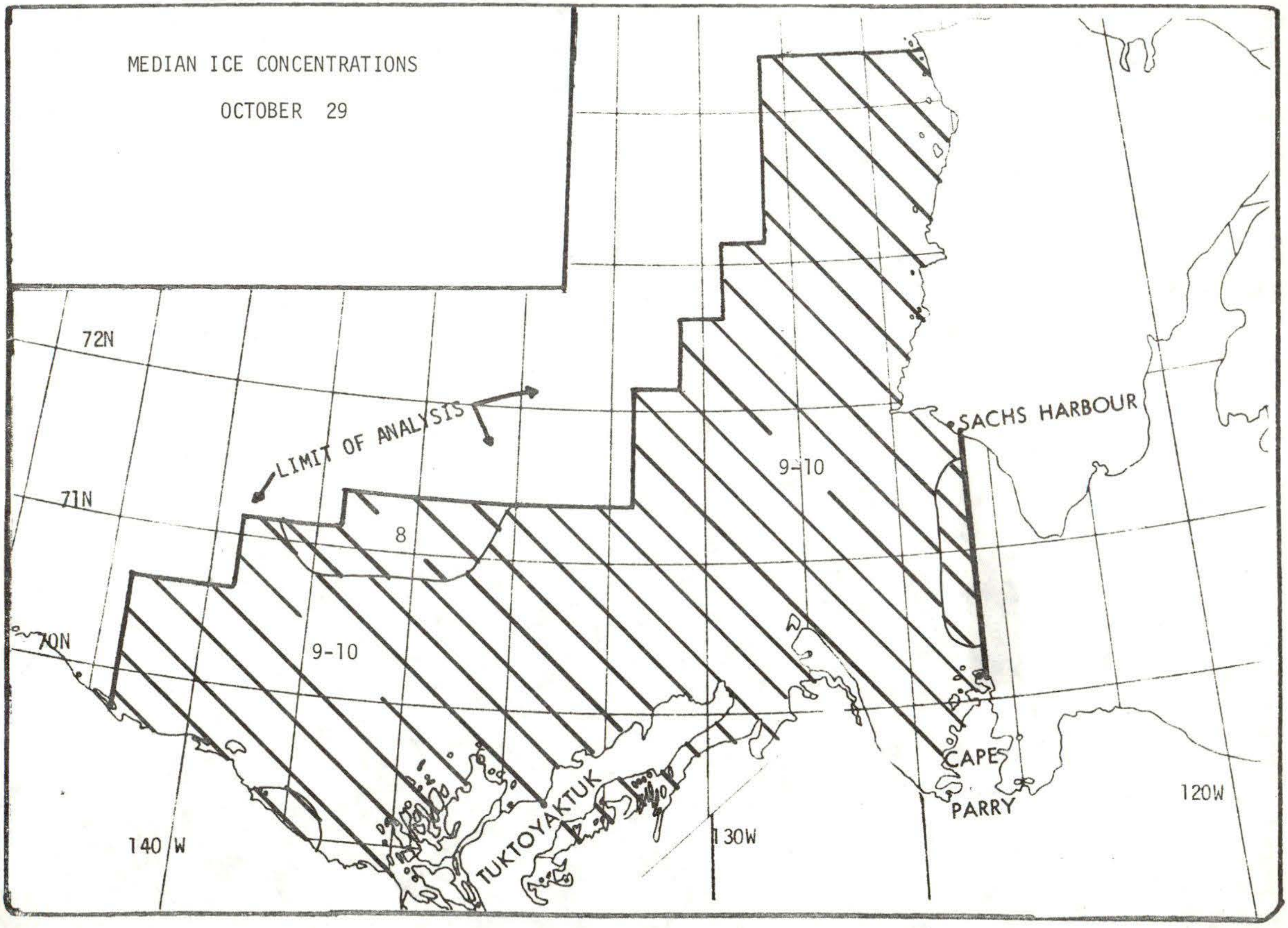
MEDIAN ICE CONCENTRATIONS

OCTOBER 1


MEDIAN ICE CONCENTRATIONS
OCTOBER 8
0-2 tenths
6-7 tenths
3-5 tenths
8-10 tenths
9-10
8
8
8
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
CAPE PARRY
TUKTOYAKTUK
140 W
130W
120W


MEDIAN ICE CONCENTRATIONS
OCTOBER 15
72N
71N
70N
LIMIT OF ANALYSIS
9-10
6-8
SACHS HARBOUR
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W


MEDIAN ICE CONCENTRATIONS
OCTOBER 22
0-2 tenths
6-7 tenths
3-5 tenths
8-10 tenths
72N
71N
70N
LIMIT OF ANALYSIS
9-10
8
SACHS HARBOUR
TUKTOYAKTUK
CAPE
PARRY
140 W
130W
120W


MEDIAN ICE CONCENTRATIONS
OCTOBER 29
72N
71N
70N
LIMIT OF ANALYSIS
SACHS HARBOUR
9-10
8
9-10
CAPE
PARRY
TUKTOYAKTUK
140 W
130W
120W