STUDIES OF CLIMATE AND ICE CONDITIONS IN EASTERN BAFFIN ISLAND, 1971-73

J. D. Jacobs, R. G. Barry,

R. S. Bradley and R. L. Weaver

REPORT

to the

OFFICE OF POLAR PROGRAMS

NATIONAL SCIENCE FOUNDATION

NSF GV-28218

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Occasional Paper No. 9

INSTITUTE OF ARCTIC AND ALPINE RESEARCH . UNIVERSITY OF COLORADO

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PREFACE

Climatological investigations by the Institute of Arctic and Alpine Research (INSTAAR) in eastern Baffin Island began in 1970. Since 1971 the program has focussed particularly on ice conditions in western Davis Strait - Baffin Bay in relation to weather and climate but, in addition, a variety of other related climatic studies have been carried out. These investigations complement the specific field measurements of energy budgets in relation to fast-ice breakup processes.

This report is one of a planned series which presents preliminary results of some of these projects and documents data, and information on field activities not appropriate for regular journal publication.

R. G. Barry and J. D. Jacobs

Broughton Island, early July, 1971. The airstrip and settlement lie in the foreground adjacent to Broughton Harbor with 1000 m summits of the coastal highlands of Baffin Island visible to the northwest. Unbroken fast ice to the north and low stratiform clouds are characteristic of the mid-summer period.

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Acknowledgements

The authors wish to acknowledge the assistance and cooperation of the following: M. Anderson, J. Dudley, and R. McKnight, who provided assistance in the field; Pauloosee and Mosesee Audlakiak of Broughton Island, who gave us their valuable experience in traveling and working on the ice; John Pearson, Jeanette Deyell, and T. B. Rose, cooperative observers at Broughton Island; James Deyell, Hudson's Bay Company store manager at Broughton Island, for useful discussions and assistance in a variety of ways; and to the people of Broughton Island, who have accepted our presence and cooperated with us in the course of this work.

We also wish to acknowledge the assistance and cooperation of members of the Atmospheric Environment Service of Canada, both at the Headquarters and in the field, particularly in the provision of necessary data and maps.

Climatology is at least in part concerned with "endless statistics about dead weather," and in the analysis of these masses of data, the imaginative assistance of Mrs. Margaret Eccles, INSTAAR, in computer programming has been an indispensable asset.

Finally, we acknowledge the support of the Office of Polar Programs, National Science Foundation, who continue to provide support for the Baffin Island climatological program under grant number GV-28218.

1. Research Activities during 1973

J. D. Jacobs

Field Program

Field activities based at Broughton Island, N. W. T. (Fig. 1.1) in connection with the synoptic energy budget (NSF GV 28218) were continued during 1973. A limited program of measurements had been conducted during the 1972-73 winter with the assistance of cooperative observers at Broughton, and intensive observations began in May with the arrival of the field team. In the following, the nature and duration of particular parts of the program are presented in some detail. Aspects of the ongoing analysis and results are described in separate sections of this report.

The 1973 field season consisted of a more intensive summer period (mid-May to mid-August) and a fall and early winter period, ending in the first week of January, 1974. Field personnel included J. Jacobs, project leader; R. Weaver, fast ice measurements; Y. Jacobs, data reduction and logistics; J. Deyell and T. Rose, cooperative observers; and M. Audlakiak, guide.

Climatological Station

Twice-daily maximum and minimum temperatures and estimates of precipitation continued to be taken by a cooperative observer at the Stevenson screen located about 50 m east of the Hudson's Bay store. With the exception of April - May 1972, a complete temperature record for "Broughton Village" exists since June, 1971. Atmospheric Environment Service, Canada, have provided calibrated thermometer pairs for this station and, in turn, receive copies of the monthly climatological report which later appear in the official _Monthly Record of Meteorological Observations in Canada_. The Broughton climatological record will also appear in a separate Occasional Paper in preparation.

The original purpose for establishing a station at the village site was to obtain a record more representative of conditions near sea level than is that from the "Broughton" synoptic station, located 8 km SE and 600 m above the village at a Distant Early Warning (DEW-line) site. Substantial differences are found to exist between the two records, largely due to the effects of the regional surface inversion (Jacobs, 1973). The village record has also proved useful in a study of climate in relation to the economy of Broughton Island (Jacobs, 1974 in press).

Broughton "Base" Operations

A small building acquired at Broughton Island in 1972 serves as base for field activities and a variety of meteorological measurements. Further details concerning this station are given in Appendix 1. A basic record of wind, pressure, temperature, and humidity is maintained continuously at the station, with other more intensive observations being done on a short-term basis (Table 1.1). Sensors are located on a 10 m mast west of the house and on the roof of the house.

In addition to the conventional parameters given above, both global solar and net radiation have been measured during the summer periods at Broughton Island since 1971. Some radiation data were also obtained for the winter months in 1972 and 1973.

A principal feature of the 1973 effort was the expansion of instrumentation to provide the basis for accurate estimates of regional surface energy budgets. The installation of a digital datalogger (Esterline-Angus D2020) greatly enhanced this capability by permitting accurate, simultaneous sampling of the various sensor outputs. The 10 m level temperature and wind and the hygrothermograph record supplemented by psychrometry provided the basis for turbulent flux estimates.

Net radiation was measured continuously over a natural surface of known albedo to complete the basic input side of the energy balance equation.

In addition to the aforementioned observations, other measurements were conducted in relation to the radiation regime. These included the use of a normal incidence spectral pyrheliometer for atmospheric transmissivity studies, determination of atmospheric longwave flux from combined pyranometer and pyrgeometer measurements, and measurements of cloudbase thermal fluxes using a precision radiation thermometer. The radiation and energy budget studies will be described in a subsequent report.

Ice Station

Meteorological observations were carried out on the fast ice during the 1973 summer season from 17 June through 5 August at two successive locations (Figure 1.2). The first site, in the middle of Broughton Harbor, was abandoned on 2 July due to locally thin ice. This first site was characterized by first-year ice initially of 70 cm thickness overlain by 45 cm of largely saturated snow. The second location, north of the settlement, was on mixed first and second-year ice of 115 - 120 cm thickness with some 21 cm snowcover. Surface relief in both areas was of the order of 10 to 20 cm before major ablation commenced.

The continuous record of observations made at Broughton "Base" is intended to apply to the local fast ice as well; therefore, observations on the ice were confined to those parameters which are not represented by the land station record. These included continuous records of net radiation, wind, temperature, and relative humidity, as well as frequent measurements of albedo, englacial and sea water temperatures, ice and water salinities, special measurements relating to the energy budgets of meltwater pools, and observations of changes in ice surface morphology. Analysis of these data is still in progress.

In addition to the work described above for the ice station locations, surveys of ice thickness, depth of snow cover on the ice as well as ocean temperature and salinity were conducted regularly in the Broughton vicinity throughout the field season (May 1973 - January, 1974). The areas covered included the immediate vicinity of Broughton Island, Kingnelling Fiord, which is immediately SW of Broughton (see map, Fig. 1.2) and the North Pangnirtung Fiord - Canso Channel area to the south. A general discussion of the fast ice regime based on this research is to be published elsewhere (Jacobs, Barry and Weaver, in press).

Boas Glacier survey

Visits were made to the Boas Glacier (67° 35' N, 65° 16' W) for the purpose of determining winter accumulation and summer ablation, continuing the record begun in 1969 (Andrews, Barry, and others, 1972). The June visit was made traveling over the fast ice from Broughton Island with access to the glacier area from the head of Quajon Fiord. An interesting feature of that trip was the success of one of the Eskimo guides in driving a snowmobile up the Quajon headwall and into Sirmilling Valley, pointing to the possibility of using this method for late spring visits to the glacier. The somewhat above normal snowpack (1.2 m on the glacier) certainly aided this effort.

The August visit was brief and made by small turbine helicopter (Hughes 500) from Broughton Island. In some two hours on the ground, it was possible only to read ablation stakes at mid-to-upper glacier and examine and photograph the ice surface. Ablation in early August was strong, and the 1972-73 budget year seems to have been slightly negative. Detailed results are reported in Part 2 of this report.

Fall and winter programs

After the summer season, field activities were largely confined to the immediate vicinity of Broughton Island. Freeze-up, ice growth, and snow accumulation were monitored, and measurements of radiation and other energy budget parameters continued. Large amounts of old ice in the harbor area until just before freeze-up made salinity and temperature measurements by boat difficult, and, apart from work during an excursion to North Pangnirtung Fiord to assist National Parks wardens stranded by an ice jam, wide-ranging surveys were avoided.

In addition to routine duties associated with the observational program, fall and winter work at Broughton Island consisted mainly of data reduction and analysis and equipment maintenance. The intensive measurements program was ended on 1 January, and the house and basic observations were left with cooperative observers.

Other Activities

Because the 1973 season was an extended one (8 months), the greater part of that year was spent in measurements and primary data reduction. Further analysis of these data and data accumulated over past seasons is the main concern during the 1974 grant extension period.

Progress was made during 1973 in relation to the synoptic climatology of the Baffin Island region through continued analysis of conventional synoptic data in relation to synoptic types. These results are described in Section 3 of this report and, more generally, in a paper presented elsewhere (Barry, Bradley, and Jacobs, 1973). This work is continuing with the acquisition of additional synoptic and upper air data in collaboration with the POLEX data bank efforts of the National Center for Atmospheric Research.

The last two years have seen vast improvements in the quality and resolution of satellite imagery, particularly for ice and snow study purposes. Both ERTS-1 and NOAA-2 imagery are being used in the present study, as reported in Section 5. Collaboration with the Canadian Center for Remote Sensing is being furthered in this regard.

The 1974 field season, to begin in May, involves a limited program of observations on the fast ice east of Broughton Island. This summer's work is expected to complete this phase of the field program begun in 1971. During the 1974 funding period, analysis and study of the accumulated data and results will be aimed at clarifying the synoptic energy budget regime of eastern Baffin Island-Davis Strait in the context of the marginal seas aspect of POLEX.

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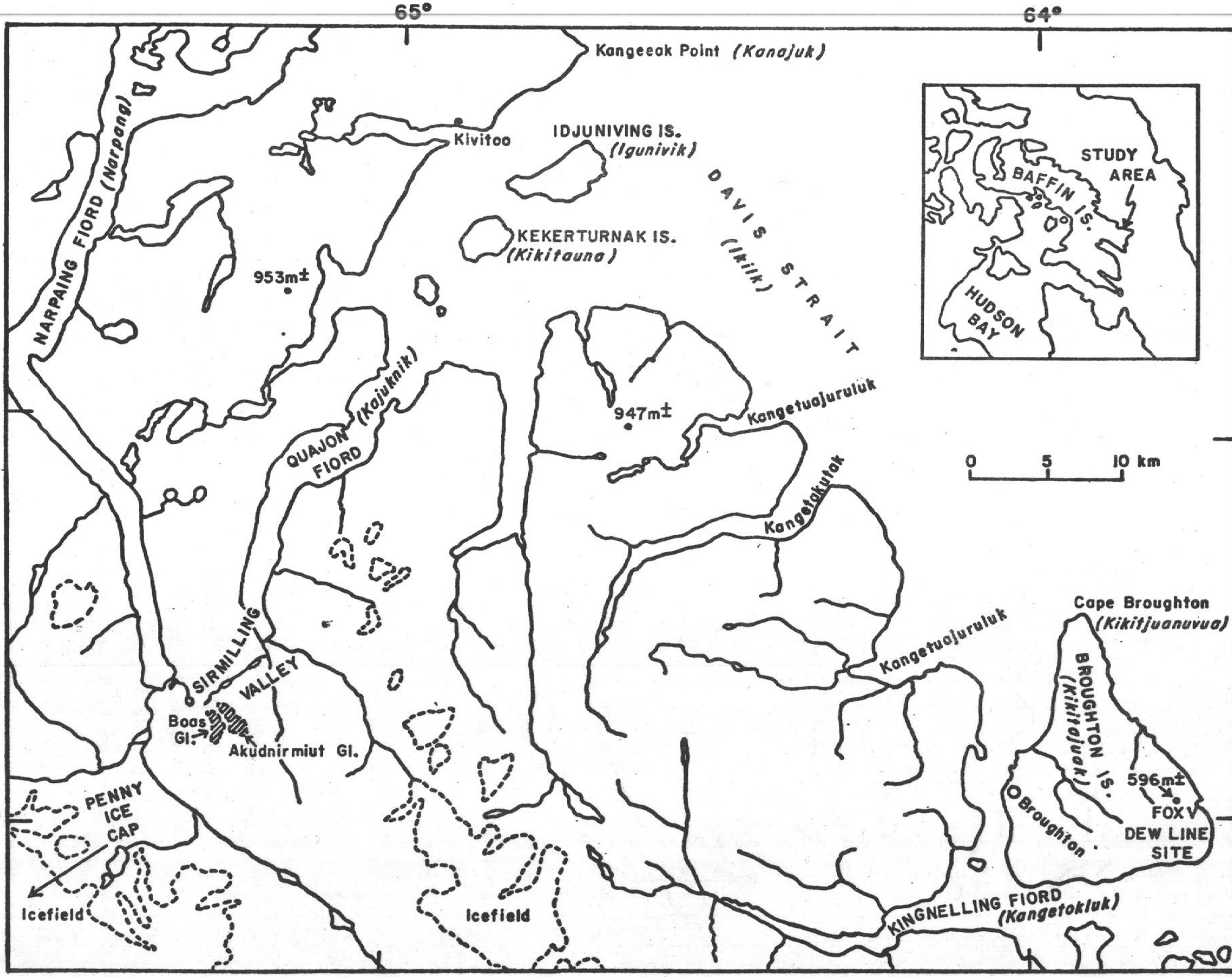
Table 1.1 Measurements and Observations at Broughton Island, N.W.T. during 1973 Field Season

Kind of Observation	Frequency
1. Climatological station maximum and minimum temperatures and precipitation	Twice daily
2. Temperature and relative humidity (hygro-thermograph) at 2 m level	Continuous
3. Windspeed and temperature at 10 m level	Continuous
4. Windspeed, temperature, and humidity at 2 m - Ice Station	Continuous (June - Aug.)
5. Global solar radiation (precision pyranometer)	Continuous
6. Direct solar component (normal incidence pyrheliometer)	Clear days only
7. Net radiation-land station (Fritschen net radiometer)	Continuous
8. Net radiation-ice station (CSIRO net radiometer)	Continuous (June - Aug.)
9. Atmospheric radiation, downward component (CSIRO net radiometer and reference blackbody)	Continuous (Sept. - Dec.)
10. Albedo-ice station (portable albedometer)	Regularly (June - Aug.)
11. Cloudbase thermal radiation (PRT-5 radiation thermometer)	Overcast days
12. Soil temperatures-permafrost site (40 and 80 cm)	Monthly
13. Fast ice thickness-Broughton Harbor and Kingnelling Fiord	Weekly
14. Seawater temperature and salinity-Broughton Harbor	Daily to weekly
15. Mass budget survey-Boas Glacier	June and August

Figure 1.1. The main INSTAAR study area is eastern Baffin Island. Place names given in italics are according to local Innuit usage.


65°
64°
67°45'
67° 30'
Kangeeak Point (Kanajuk)
Kivitoo
IDJUNIVING IS.
(Igunivik)
KEKERTURNAK IS.
(Kikitauna)
DAVIS STRAIT
(Ikilik)
NARPAING FIORD (Narpang)
953m±
947m±
QUAJON FIORD
(Kajuknik)
Kangetuajuruluk
Kangetokutak
Kangetuajuruluk
SIRMILLING VALLEY
Boas Gl.
Akudnirmiut Gl.
PENNY ICE CAP
Icefield
Icefield
KINGNELLING FIORD
(Kangetokluk)
Cape Broughton
(Kikitjuanuvua)
BROUGHTON IS.
(Kikitajuak)
Broughton
596m±
FOX V
DEW LINE
SITE
0
5
10 km
STUDY
AREA
BAFFIN IS.
HUDSON
BAY

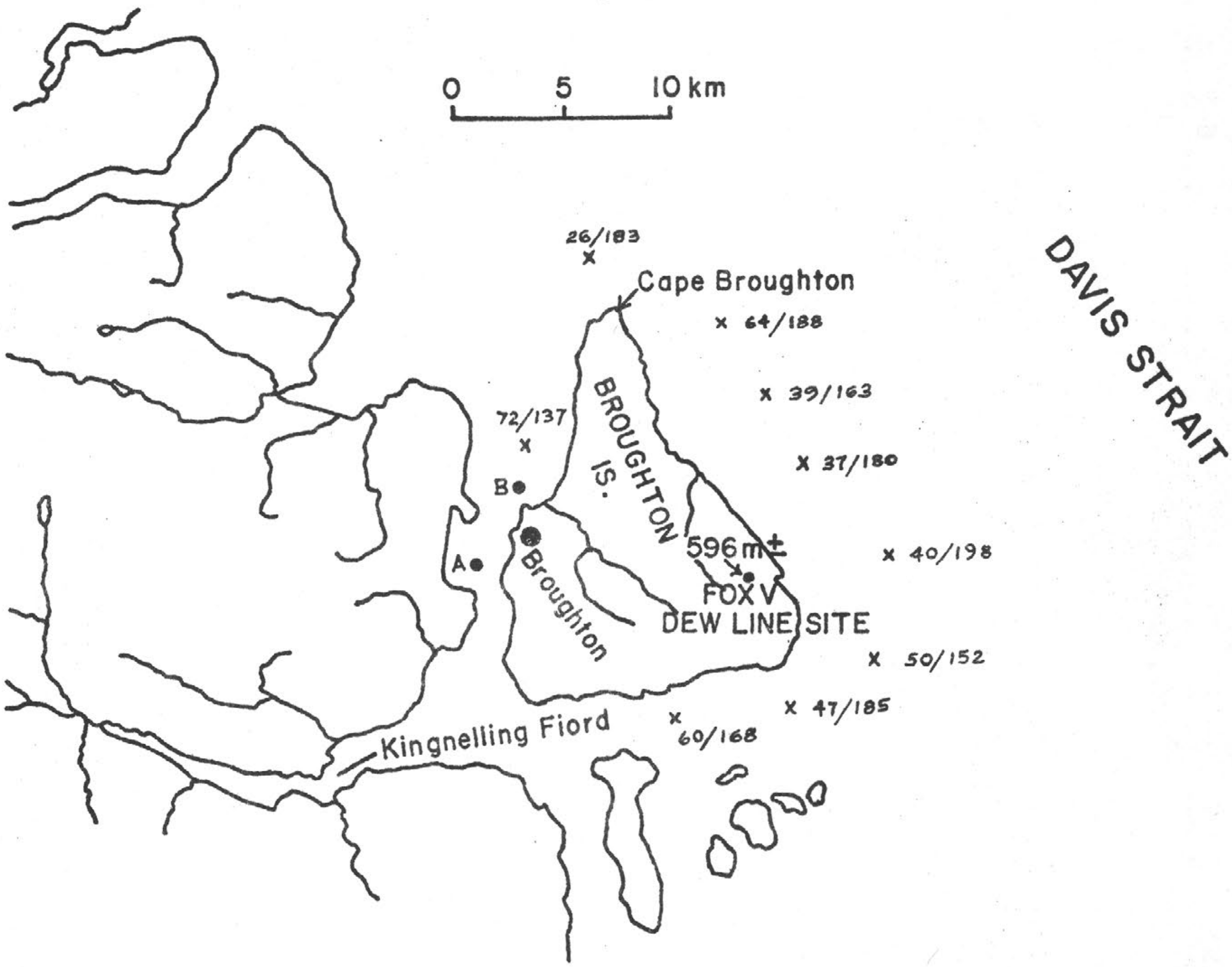


Figure 1.2. Broughton Island and vincinity showing locations of ice stations (A) and (B) during the summer of 1973. Snowdepths and fast ice thicknesses (cm) for early June are also shown.

2. Boas Glacier Mass Balance for the 1971-72 and 1972-73 Budget Years compared with the Previous Two Years of Record

R. L. Weaver

Introduction

The mass balance of the Boas Glacier (Fig. 1), located on Cumberland Peninsula, Baffin Island N. W. T., (67° 35' N, 65° 16' W) has been measured each year by Institute of Arctic and Alpine Research field personnel since 1970. This glacier [1], numbered 46204J68 in the Canadian Glacier Inventory, has an area of 1.42 km^2 and is located between the heads of Narpaing and Kajuknik (Quajon) fiords in the northeastern sector of the Baffin Island National Park. Further descriptive information and results of past mass balance studies may be found in Andrews and Barry et. al. (1972a and 1972b), Jacobs et. al. (1972). This paper presents estimates of specific winter, summer and net balances for the 1971-72 and 1972-73 budget years and summarized the glacier's net balance for the period of observations. Nomenclature used here follows the UNESCO/IASH (1970) terms for mass balance studies.

Winter Accumulation

The 1972-73 winter accumulation (and the 1971-72 net balance) calculations are based on four snow pits and 157 snow depths measurements collected on 10 and 11 June 1973. Field techniques developed during the summer of 1970 were followed and summarized in Andrews and Barry (1972a).

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[1] The name "Boas" has been suggested but not yet officially adopted for this glacier.

In all four pits refrozen snow was encountered between 1 and 1.3 meters below the surface. The snow above this layer is interpreted as the 1972-73 winter accumulation while the firn below is thought to be the non-superimposed ice portion of the 1971-72 net balance. It is not known how much of the relatively clean superimposed ice found below the firn was formed during the 1971-72 budget year.

The specific winter accumulation ($\bar{b}_w$) (see tables 1 and 2) was calculated by multiplying the average density (.279 gcm^{-3}) by the average probed snow depth (1.20 m). Despite heavy late spring snowfall the winter accumulation of 0.32 m H_2O is moderate when compared to the heavy 1969-70 (.391 m H_2O) or the light 1970-71 (.244 m H_2O) accumulations. The two Hoinkes type storage precipitation gauges, one located at the base of the glacier's terminal moraine and the other positioned 1.6 km to the south in Smirling Valley measured .234 m and .373 m H_2O respectively. These agree reasonably well with the winter accumulation figure reported above even though the measurement period, June 1972-June 1973, includes the summer 1972 precipitation in the gauge totals. The lower reading in the gauge located on the moraine is most probably due to wind deflection of the precipitation catch.

Summer Ablation

The summer ablation calculations are based on a cursory two hour helicopter survey of the upper portion of the main Boas Glacier on 20 August. The June-August surface lowering was quite evident and, from eight actual stake measurements, it averaged 1.48 m ablation (standard deviation = 0.16). The August 1973 surface was below the August 1970 surface and the glacier's 1969-73 net specific balance ($\bar{b}_n$) was .40 $\pm$ m H_2O.

The computed approximate summer mass loss was - .42 $\pm$ m H_2O and is on the same order as the heavy ablation of the 1971 season (- .444 m H_2O).

Several patches of dirty superimposed ice or possibly glacial ice were visible on the lower one-third of the glacier, but were not viewed close-up.

<u>Review of the Four Years of Record</u>

Table 4 and Figure 2 summarize the winter, summer, and net specific mass balances of the glacier over the past four years. A cyclical two year pattern of net balance is evident from both the data and graph. It is principally controlled by large variations in summer ablation.

Parametric statistical tests could not be directly applied to the hybrid variable "water equivalent" (We = density x probed depth) since paired density and probe readings were not taken. This analysis assumes that the snow density's variance is small and shows no year to year variation which is statistically discernible from within year variations. Therefore, the average density for each 150 m altitude increment was used and the variance of the We is really just that of the probed depth. These approximations limit stringent interpretation of the analysis of variance tests but, at least permit data evaluation in a more quantitative manner.

Winter accumulation no doubt contributes to the mass balance fluctuations. However, when the water equivalence data are grouped by 150 m altitude increments and analysis of variance tests applied to the between and within year variances, it was concluded that the variation in We by itself cannot explain the large net balance changes. The F statistic for rejection of the hypothesis of equal yearly We means was significant at the .5 probability level and thus the test was indeterminant. A similar analysis comparing the We data derived for each stake line (n = 13) in 1970 and 1971 more strongly rejects the hypothesis which was significant at the p = .025 level.

The summer ablation, on the other hand, clearly shows a statistically significant difference in mean values for the 1970 and 1971 summers--the two seasons with adequate data for statistical analysis. The F statistic test allowed rejection of the null hypothesis assuming equal We means at the p = .001 level. The nature of the data for the remaining two years does not allow statistical testing. However, it seems reasonable to expect the variance in We to be on the same order as 1970-71 making the 1972-73 estimates significantly different by assuming variances of similar magnitude.

By adding the four net budget figures, it is concluded that the glacier has accumulated .38 ± m H_2O since 1969. This figure is of the same order as the specific net budget $< \overline{b}_n >$ .40 (σ = .1, n = 9) independently calculated from August ablation stake readings taken in 1970 and 1973 in the area above 1000 meters. This extrapolation is justified by a similar comparison in 1970-71 which indicated that the total glacier response is reasonably approximated by the ablation stake readings above 1000 m.

Acknowledgements

This research was supported initially by the United States Army Research Office, Durham, (1969-70-71) and subsequently by the Office of Polar Programs, National Science Foundation under Grant Number GV28218 (1972-73). The author expresses his gratitude to the Canadian Parks Service for providing helicopter support in August 1973, and to A. Dyke and D. Squires for assistance in the field.

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Table 1

Average Snow Densities from Pit Studies, June 10 - 11, 1973

Altitude Intervals	Average (gcm^{-3}) density	Number of Samples	Standard Deviation
750 - 900	No Data	-	-
900 - 1050	.246	4	.020
1050 - 1200	.310	5	.041
1200 - 1350	.289	4	.061
1200 - 1350 East Bowl	.243	3	.026
Average of all measurements	.279	(n = 16)	.047

Table 2

Probed Snow Depths, June 10, 1973.

Altitude Intervals	Average Depth (M) to Estimated 1972 end-of-summer Surface	Number of Samples	Standard Deviation
750 - 900 M	1.44	19	.18
900 - 1050 M	1.31	33	.11
1050 - 1200 M	1.21	24	.16
1200 - 1350	1.03	33	.05
1200 - 1350 East Bowl	1.03	48	.13
Average all probes	1.20	(n = 157)	.16

Table 3

Net Specific ($\bar{b}_n$) and Net Winter Balance (B_w), Boas Glacier 1973.

Altitude Interval	$\bar{b}_n$ (mWe)	Area $10^6 M^2$	B_w ($10^6 M^3$)
750 - 900 (density from 900-1050 area)	.354	.13	.046
900 - 1050	.321	.194	.062
1050 - 1200	.376	.405	.152
1200 - 1350	.297	.307	.090
1200 - 1350 East Bowl	.251	.414	.104
Average meters water equivalent	.320		
Total Winter balance			.454

Table 4

Specific winter, summer, and net balances (mH_2O) for the four years of record.[1]

Year	$\bar{b}_w$	$\hat{\sigma}_w$	$\bar{b}_s$	$\hat{\sigma}_s$	$\bar{b}_n$	$\hat{\sigma}_n = \hat{\sigma}_w + \hat{\sigma}_s$
1969-1970	.399	.042	-.088	.076	.404	.118
1970-1971	.345	.078	-.474	.06	-.129(R)	.113
1971-1972	.342	.018	-.13±(R)[2]	-	.21±	-
1972-1973	.344	.047	-.42±	-	-.10±(R)	-

[1]note: The totals presented above vary from those in the text because modified calculation techniques were used to accommodate the statistical analysis

[2](R) indicates this value was calculated as a residual

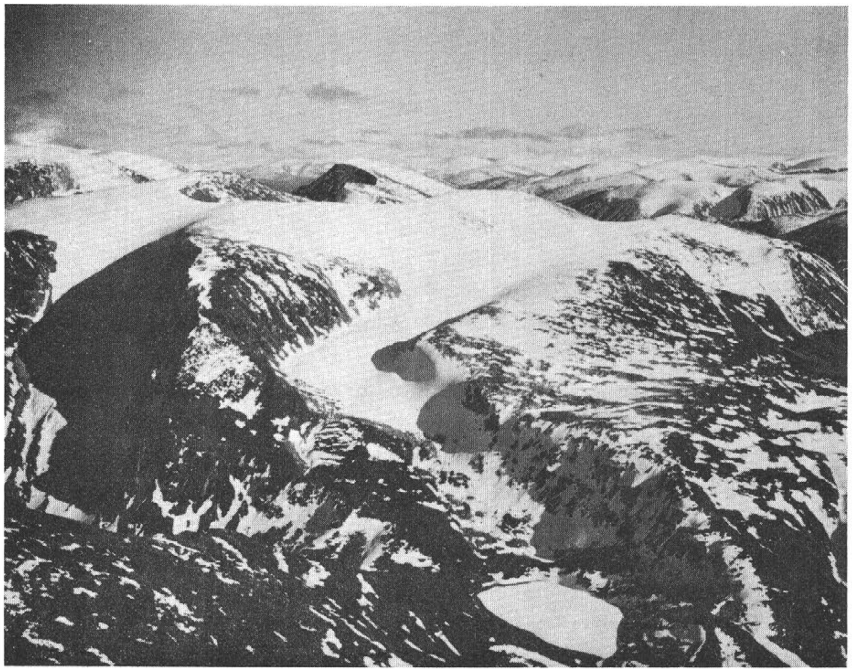

Figure 2.1. Boas Glacier viewed from the north, early August, 1970.

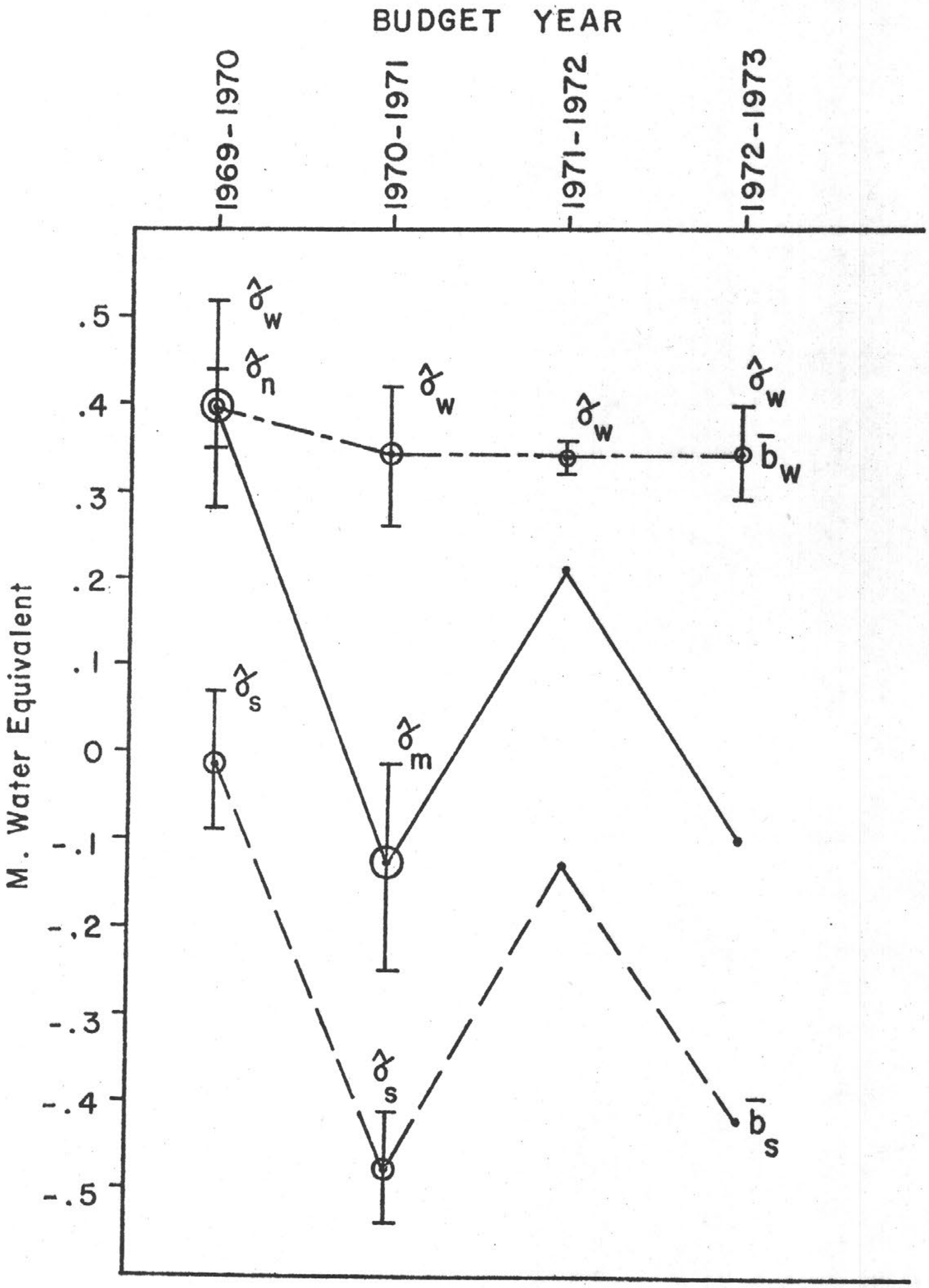

Figure 2.2. Boas Glacier mass balance for the period 1967-1973 (see text for explanation of symbols.

3. Climatic Conditions in Eastern Baffin Island in Relation to Synoptic Pressure Patterns

R. S. Bradley[1]

Climatic conditions at four stations on the eastern coast of Baffin Island have been examined in relation to a classification of synoptic types. Details of the classification scheme have been discussed elsewhere (Barry, 1972, 1974). The typing relates to the static pressure field over an area bounded by latitudes 55° and 80°N, and meridians 50° and 100°W (Figure 3.1). The following months have been classified: January, February, April, September and October 1961-65, and July and August 1961-70. Forty types were identified (Barry, 1972), but in order to simplify the classification scheme, and to increase the sample sizes in each category, 12 major groupings of the 40 types are used in the following analyses. These "type-groups" (six cyclonic, C1-C6 and six anticyclonic A1-A6) are shown in Figs. 3.2 and 3.3 and in Table 3.1. The frequencies of occurrence of these 12 type-groups are given in Table 3.2. Clearly, at different times of the year, the relative frequencies of the types vary. Of particular interest is the relatively rare C6 type-group (inverted low) which occurs only in winter months in the period of study.

In the following section, various meteorological parameters at Cape Dyer, Broughton Island, Cape Hooper and Clyde are examined in relation to the synoptic type-groups.

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Precipitation

Before discussing the contribution of particular type-groups to monthly precipitation totals, it is important to note the relative importance of the months under consideration to the annual totals of precipitation (Table 3.2). Approximately half of the yearly precipitation at Broughton Island and Cape Hooper falls during July through October whereas at Clyde this figure is almost two-thirds and at Cape Dyer it is only one third. At all stations, the months of September and October contribute more precipitation to the annual total than the other months classified.

Figure 3.4 shows the percentage of monthly precipitation associated with each type-group, plotted in the form of cumulative percentages.

The following features are apparent:

January/February: Type C1 with a central low pressure is important to precipitation totals at all stations in these mid-winter months. At Broughton Island and Cape Hooper, types C6, C5 and C2 are also important. Types C1, C2, C6 and C5 together account for approximately 81% of January/February precipitation. It should be noted, however, that on average only 7% of the total annual precipitation falls in these months (Table 3.2).

April: This month accounts for very little of the annual precipitation total -- an average of less than 5%. As a result, the importance of any one type-group to the monthly total precipitation varies widely between stations. In general, the anticyclonic types are the principal contributors to precipitation in April though this simply reflects the higher frequency of these types at this time of year (Table 3.1).

July/August: Types C1 (central low) and C2 (low in Davis Strait) account for between 45 and 50% of the monthly precipitation totals at all four stations. Type group C1 is the major contributor although it is also the most frequent type in these months. Other types also of importance at most stations are types C4 and C5 (with a low to the southwest).

September/October: As mentioned above, these months are the most important (of those examined) for precipitation totals. Types C1, C2, C3 and A6 are of importance at all stations though they are also the four most frequent types in these months, occurring on 56% of days. These types contribute between 60% (at Broughton Island) and 80% (at Cape Dyer) of the monthly precipitation totals.

In summary types C1, C2, C3 and to some extent A6 are the most important type-groups for precipitation on the eastern Baffin Island coast, during the months examined. The percentage of total monthly precipitation resulting from cyclonic types (C1 to C6) is shown in Table 3.3. Although the actual percentages vary from station to station and from month to month it is clear that a major proportion of the annual precipitation amounts on eastern Baffin result from cyclonic types, particularly in the months of July to October (Tables 3.2 and 3.3).

Relative Proportions of Precipitation Falling as Rain or Snow

The relative proportions of precipitation falling as rain or snow during July through October are shown in Table 3.4. It is not possible to stratify this information further on the basis of synoptic types as precipitation may occur in both forms during a climatological day. However, Table 3.4 gives an approximate indication of the relative amounts of rain and snow (water equivalent) in these mid-summer to autumn months. Snowfall accounts for between one third and one fifth of July-August precipitation, depending on latitude and elevation of the station. It is interesting to note that at Broughton Island (lat. 67°33'N, elevation 581 m a.s.l.) almost 38% of precipitation at this critical period in the ablation season is in the form of snow. In September-October snowfall accounts for over 80% of the precipitation water equivalent with a maximum of 97% at Broughton Island.

Temperature

Tables 3.5(a) to 3.8(a) show the mean temperatures associated with the 12 synoptic type groups in each month examined. The lower part of these tables (Tables 3.5(b) to 3.8(b)) show the ranking of the types by mean temperature, coldest (rank 1) to warmest (rank 11 or 12).

January-February: (Table 3.5) At all stations type A6 (ridge with N-NW flow), occurring on 14% of days, has the lowest mean temperature with an average as low as -29.8°C at Clyde. Types C3, A5 and A2 are also consistently amongst the coldest types at all stations. The extreme cold associated with types A5, A6 and A2 may be related to the development of a strong inversion layer at the surface associated with these relatively stable anticyclone conditions. It is of interest in this regard that at all four stations, from Clyde at 3 m a.s.l. to Broughton Island at 591 m a.s.l., type A6 is the coldest type suggesting that any inversions associated with this type are probably of considerable vertical thickness.

The warmest winter conditions occur with type C6 (the inverted low) which occurs on only 4% of days. Type C6 is considerably warmer than any of the other types; at Cape Dyer type C6 days are at least 8°C warmer than days with any other type.

April: (Table 3.6) In most cases the four coldest types are types C2, C3, A3 and A6 which are associated with predominantly northerly or northwesterly airflow. The warmest types are generally types C5 and A5, which are from 4°C to 8°C warmer than the coldest types at each station. It is of interest that type A6, the coldest type at Cape Dyer and Clyde is the most frequent type at this period of the year.

July-August: (Table 3.7) All types are associated with above zero temperatures in July and August. Type C2 (Davis Strait Low) is the coldest at all stations (mean temperature of 0.5°C at Cape Hooper). Type C1 is also one of the coldest types at all stations (except Broughton Island) and both these types (C1 and C2) are associated with considerable precipitation during this period as noted above. During 1961-70, these types occurred on 25% of days. The warmest type at all stations is type A4 (high in the east), followed by types A2 and A1. These are anticyclonic types generally associated with little precipitation (a maximum of 21% of July/August precipitation for all anticyclonic types at Clyde).

September-October: (Table 3.8) All types are associated with below-zero temperatures, though the warmest type, type C1, is only slightly below the freezing point (-1.6°C at Clyde to -3.1°C at Cape Hooper). The three coldest types, A5, A6 and A2 occur on 26% of days, while the warmest type is itself the most frequent individual type. It is interesting to note that type C1 is of importance at all stations in terms of precipitation associated with this type. However, at Broughton Island type A6, the coldest type-group, is the single most important type for precipitation at this time of the year.

Wind Direction

In order to investigate the mean wind direction associated with the synoptic type groups, daily data for 1900 L.S.T. (00 GMT) were examined from Broughton Island (581 m a.s.l.). This station is located in an exposed situation on a hill summit and therefore presumably gives a good indication of the general airflow over the area. Wind directions have been noted on a 16 point basis for the months classified; the results are shown in Figures 3.5(a) and 3.5(b) for winter and summer, respectively. Although in many cases the sample size is insufficient to determine the principal wind direction associated with particular synoptic types (particularly due to the large proportion of days with no wind), it has been possible in some cases to determine the predominant wind direction and these are shown as shaded segments in the figures. It is of interest to examine the wind directions in relation to the temperature and precipitation data outlined above. However, it should be carefully noted that even though a particular type may be associated predominantly with a particular air flow direction, the precipitation associated with the type may occur on days when the air flow is not from that predominant direction.

January-February: (Figure 3.5) Major precipitation types are not associated with southerly or south easterly flow as might be expected, but with northerly and north westerly air flow. The coldest type (A6) is associated with air flow in the west to north quadrant on 70% of non-calm days. The warmest type (C6) appears to be associated with southerly or westerly air flow, though the sample is very small.

April: (not shown) The coldest types were found to be associated with air flow in the quadrant west to north. However, type A5 generally one of the warmest types, also has a marked northwesterly component.

July-August: (Figure 3.5(b)) Type C1, which is of major importance to precipitation totals at this time of the year has air flow predominantly in the south through east quadrant. However, type C2, the second most important type for precipitation in July/August has air flow predominantly in the quadrant west through north. This sheds light on the fact that it is the coldest type during this period, though type C1 with southeasterly flow is also one of the coldest types. By contrast, type A4 also with predominantly southeasterly flow, is the warmest type at all four stations. Types A2 and A1 which are also relatively warm, are associated with northwesterly flow. In short, the simple concept of warm air coming from the southeast and cold air from the northwest in summer months is untenable. The situation is considerably more complex than this and can only be resolved by considering in more detail the ultimate source of the air, perhaps using streamline analysis.

September-October: (not shown) The warmest type (C1) is associated with south or southeasterly air flow, and much precipitation also results from this type. The three coldest types, A5, A6 and C6, are all associated with northwesterly or northerly airflow. Other types, important for precipitation, also have predominantly northwesterly air flow.

In summary, considering the principal wind directions for the summer-early autumn period (July-October) for the synoptic type-groups, seven of the 12 types have a predominantly westerly through northerly air flow (C2, C3, A3, A5, A6, A2, A1). Only three types (C1, C4, A4) have clearly dominant air flow from the south and east. Type C5 has approximately equal frequencies of northwesterly and southeasterly air flow. However, it should be noted once more that between 35 and 50% of days in the period July-October were classified as "calm", therefore the air flow characteristics discussed here are based at best on only two-thirds of the available synoptic type days.

Synoptic Aspects of Climatic Change on Eastern Baffin Island

It is clear from the foregoing discussion that by stratifying days on the basis of synoptic types it is possible to evaluate the relative importance of each type to the overall seasonal climatic characteristics of the region. The importance of this to glaciological studies is obvious (cf. Barry, 1972). By evaluating the relative influence of each type on glacial mass balance in the area, the effect of changing frequencies of the synoptic types can be assessed. In this regard, it is of interest to note that the circulation over the Canadian Arctic archipelago has changed markedly over the past 20 years with eastern Baffin Island dominated by a ridge in the 1960's compared to its position beneath a weak trough in the 1950's (Figures 3.6 and 3.7). This suggests a higher frequency of northerly and northeasterly air flow over the area, although an examination of wind data from Broughton Island for the 1960's (Table 3.9) does not show any clear trend in this direction. Northerly flow at Broughton Island increased between 1961-65 and 1966-70 but southerly flow showed a similar increase. Westerly flow also increased while easterly flow declined. Such a pattern is hard to reconcile with the overall near surface circulation patterns for the 1960's (Figure 3.7) but it may reflect a weakening of that circulation regime in the latter half of the 1960's. A consideration of changing frequencies of synoptic type-groups themselves (Table 3.1), indicates that anticyclonic conditions have increased in the latter part of the 1960's, as one would expect from the circulation shown in Figure 3.7.

References

Barry, R.G., 1972. Chapter 3 in J.T. Andrews and R.G. Barry, Present and Paleo-climatic Influences on the Glacierization and Deglacierization of Cumberland Peninsula, Baffin Island, N.W.T., Canada. Occas. Pap. No. 2. Inst. of Arctic and Alpine Res., University of Colorado, Boulder.

Barry, R.G., 1974. Further climatological Studies of Baffin Island. Inland Waters Directorate, Tech. Res. Bull. No. 65. Ottawa, (In press).

TABLE 3.1. FREQUENCY OF TYPE-GROUPS (PERCENT) 1961-65

TYPE-GROUP	JAN-FEB	APRIL	JULY-AUG(1961-70)	SEP-OCT
Cyclonic				
C1. Central Low	11	7	16	15
C2. Davis St. Low	10	4	9	14
C3. Baffin Bay Low	19	9	5	13
C4. SW Low	4	6	10	6
C5. SW Low & Others	5	2	9	9
C6. Inverted Low	4	-	-	-
	53	28	49	57
Anticyclonic				
A1. Anticyclone	7	17	10	8
A2. Ridge	10	5	8	6
A3. Ridge, Low to S.	2	7	10	3
A4. High in E, Low to W.	3	5	10	7
A5. Ridge, Baffin Bay Low (NE Flow)	11	11	4	5
A6. Ridge, Baffin Bay Low (N-NW Flow)	14	27	9	14
	47	72	51	43

TABLE 3.2

Precipitation as a Percentage of the Annual Total (for periods specified).

	Clyde	C. Hooper	Broughton Is.	C. Dyer	Mean
Jan./Feb.(1961-65)	7.3	3.5	6.4	10.8	7.0
April (1961-65)	1.9	7.2	3.8	3.8	4.2
July/Aug.(1961-70)	24.9	15.5	12.5	12.4	13.8
Sept./Oct.(1961-65)	39.7	31.3	39.5	22.4	33.2
	73.8	57.5	62.2	49.4	

TABLE 3.3

Percentage of total monthly precipitation resulting from "cyclonic"type-groups (C1 - C6) 1961-65*

	Cape Dyer	Broughton Island	Cape Hooper	Clyde
Jan/Feb	79.9	83.4	91.5	56.3
April	37.7	52.6	28.4	40.4
July/Aug*	71.6	78.4	69.9	69.9
Sept/Oct.	80.8	53.9	77.6	81.4

* July/Aug.: 1961-70

TABLE 3.4

Relative contribution of Rain and Snow to mean monthly precipitation totals:

	elevation(m)	July/Aug. 1961-70		Sept./Oct. 1961-65	
		% rain	% snow(cm w.e.)	% rain	% snow (cm w.e.)
Cape Dyer	376	79.5	20.5	19.0	81.0
Broughton Island	581	62.5	37.5	3.0	97.0
Cape Hooper	401	67.9	32.1	16.0	84.0
Clyde	3	70.0	30.0	17.0	83.0

TABLE 3.5

a) Mean Temperatue (°C): Jan./Feb. (1961-65); by type-groups

Type-Group	Frequency(%)	C. Dyer	Broughton Is.	C. Hooper	Clyde
C1	11	-17.3	-19.8	-22.3	-23.2
C2	10	-21.2	-25.5	-25.4	-26.8
C3	19	-24.5	-25.8	-26.8	-28.3
C4	4	-22.3	-23.3	-24.6	-28.1
C5	5	-23.7	-23.8	-24.6	-23.5
C6	4	- 7.8	-13.1	-19.5	-18.6
A1	7	-22.4	-23.9	-25.2	-28.8
A2	10	-24.1	-25.7	-26.4	-29.5
A3	2	-16.1	-23.5	-24.6	-27.8
A4	3	-20.6	-19.9	-21.6	-22.8
A5	11	-22.6	-26.7	-27.0	-28.7
A6	14	-26.4	-27.1	-28.3	-29.8

b) Ranking of type-groups by temperature: coldest (1) to warmest (12)

Rank	C. Dyer	Broughton Is.	C. Hooper	Clyde
1	A6	A6	A6	A6
2	C3	A5	A5	A2
3	A2	C3	C3	A1
4	C5	A2	A2	A5
5	A5	C2	A1	C3
6	A1	A1	C2	C4
7	C4	C6	C4	A3
8	C2	A3	C5	C2
9	A4	C4	A3	C5
10	C1	A4	C1	C1
11	A3	C1	A4	A4
12	C6	C5	C6	C6

TABLE 3.6

a) Mean temperature (°C): April (1961-65); by type-groups

Type-Group	Frequency(%)	C. Dyer	Broughton Is.	C. Hooper	Clyde
C1	7	-13.8	-14.6	-16.0	-17.1
C2	4	-15.3	-18.7	-20.3	-19.2
C3	9	-15.8	-18.2	-18.1	-18.8
C4	6	-16.1	-15.4	-15.9	-19.3
C5	2	-10.6	- 9.9	-10.8	-16.0
C6	0				
A1	17	-11.5	-14.1	-14.6	-17.6
A2	5	-13.3	-15.7	-16.5	-19.2
A3	7	-15.3	-16.3	-17.2	-19.6
A4	5	-12.8	-12.6	-15.4	-16.4
A5	11	-10.4	-13.2	-14.6	-15.1
A6	27	-16.1	-17.7	-17.7	-19.9

b) Ranking of type-groups by temperature: coldest (1) to warmest (11)

Rank	C. Dyer	Broughton Is.	C. Hooper	Clyde
1	A6	C2	C2	A6
2	C4	C3	C3	A3
3	C3	A6	A6	C4
4	C2	A3	A3	A2
5	A3	A2	A2	C2
6	C1	C4	C1	C3
7	A2	C1	C4	A1
8	A4	A1	A4	C1
9	A1	A5	A5	A4
10	C5	A4	A1	C5
11	A5	C5	C5	A5

TABLE 3.7

a) Mean temperature (°C): July/August (1961-70); by type-groups

Type-Group	Frequency(%)	C. Dyer	Broughton Is.	C. Hooper	Clyde
C1	16	4.1	3.9	3.0	3.5
C2	9	3.6	1.6	0.5	2.7
C3	5	4.6	3.2	3.6	3.7
C4	10	4.8	4.3	3.0	3.8
C5	9	4.6	3.8	3.5	3.9
C6	0				
A1	10	5.3	4.3	5.3	5.2
A2	8	5.1	4.4	4.7	4.7
A3	10	4.9	3.7	2.5	3.4
A4	10	6.8	7.1	7.1	5.9
A5	4	4.5	2.4	3.2	3.6
A6	9	5.0	3.4	4.1	4.1

b) Ranking of type-groups by temperature: coldest (1) to warmest (11)

Rank	C. Dyer	Broughton Is.	C. Hooper	Clyde
1	C2	C2	C2	C2
2	C1	A5	A3	A3
3	A5	C3	C1	C1
4	C5	A6	C4	A5
5	C3	A3	A5	C3
6	C4	C5	C5	C4
7	A3	C1	C3	C5
8	A6	C4	A6	A6
9	A2	A1	A2	A2
10	A1	A2	A1	A1
11	A4	A4	A4	A4

TABLE 3.8

a) Mean temperature (°C): September/October (1961-65); by type-groups

Type-Group	Frequency(%)	C. Dyer	Broughton Is.	C. Hooper	Clyde
C1	15	-2.5	-2.8	-3.1	-1.6
C2	14	-4.3	-6.1	-5.6	-4.1
C3	13	-4.1	-5.6	-5.6	-2.9
C4	6	-5.0	-5.4	-5.1	-3.8
C5	9	-4.8	-5.2	-5.4	-4.0
C6	0				
A1	8	-4.6	-6.1	-6.1	-5.1
A2	7	-5.9	-6.8	-6.6	-5.9
A3	3	-4.5	-5.1	-4.9	-4.2
A4	7	-4.1	-4.3	-4.4	-3.9
A5	5	-5.6	-6.9	-6.5	-4.9
A6	14	-7.2	-8.5	-8.4	-7.4

b) Ranking of type-groups by temperature: coldest (1) to warmest (11).

Rank	C. Dyer	Broughton Is.	C. Hooper	Clyde
1	A6	A6	A6	A6
2	A2	A5	A2	A2
3	A5	A2	A5	A1
4	C4	A1	A1	A5
5	C5	C2	C2	A3
6	A1	C3	C3	C2
7	A3	C4	C5	C5
8	C2	C5	C4	A4
9	C3	A3	A3	C4
10	A4	A4	A4	C3
11	C1	C1	C1	C1

TABLE 3.9

Frequency of wind directions at Broughton Island, July, 1961-70 (4 observations per day)

	S	SSE	SE	ESE	E	ENE	NE	NNE	N	NNW	NW	SWNW	W	WSW	SW	SSW	CALM
a) 1961-65	74	40	49	10	41	2	11	9	28	10	23	6	17	2	12	14	272
b) 1966-70	91	57	36	17	9	1	8	11	39	20	18	19	20	4	9	14	247
(b) - (a)	+17	+17	-13	+7	-32	-1	-3	+2	+11	+10	-5	+13	+3	+2	-3	0	-25

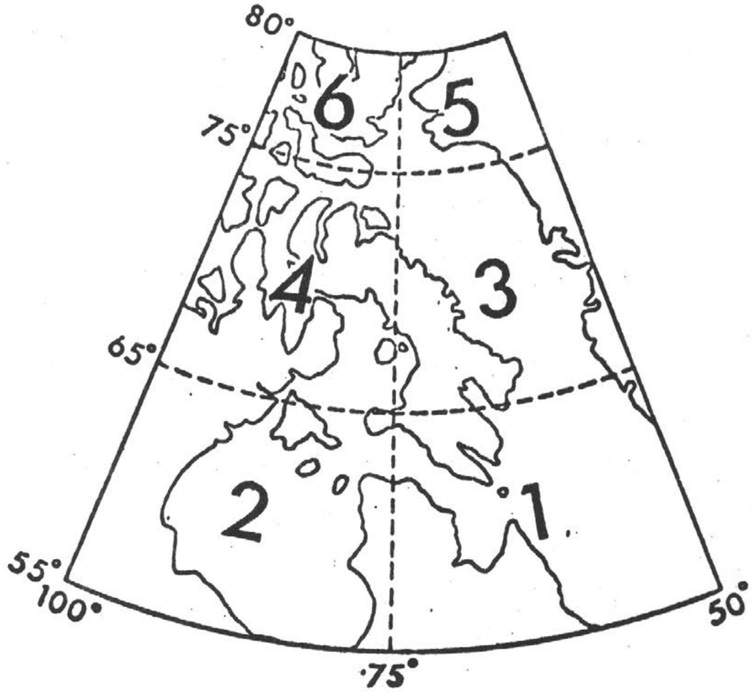


Figure 3.1 Area covered by synoptic classification scheme of Barry (1972)

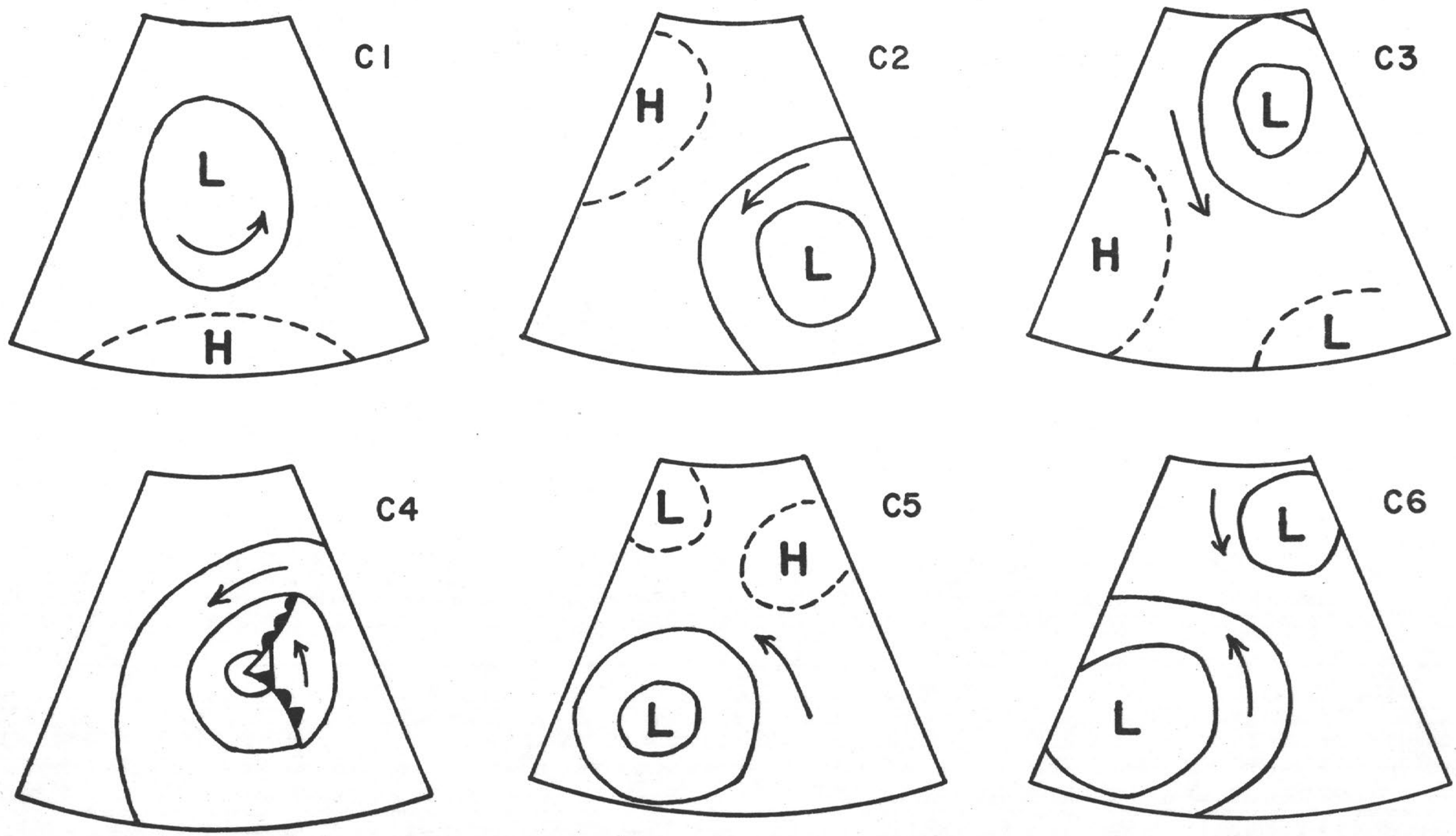


Figure 3.2. Cyclonic type-groups after Barry (1972) for area shown in Figure 3.1

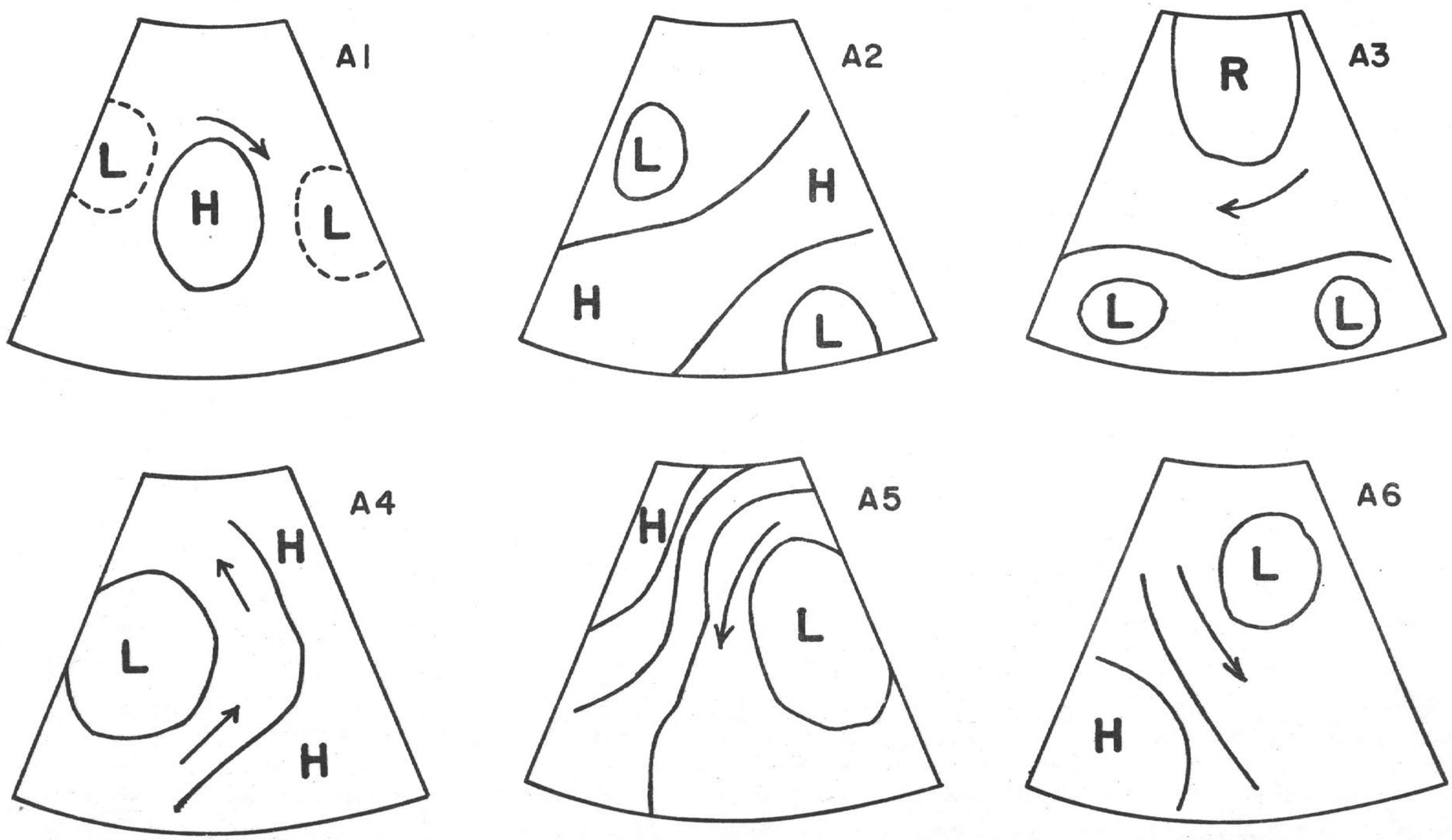
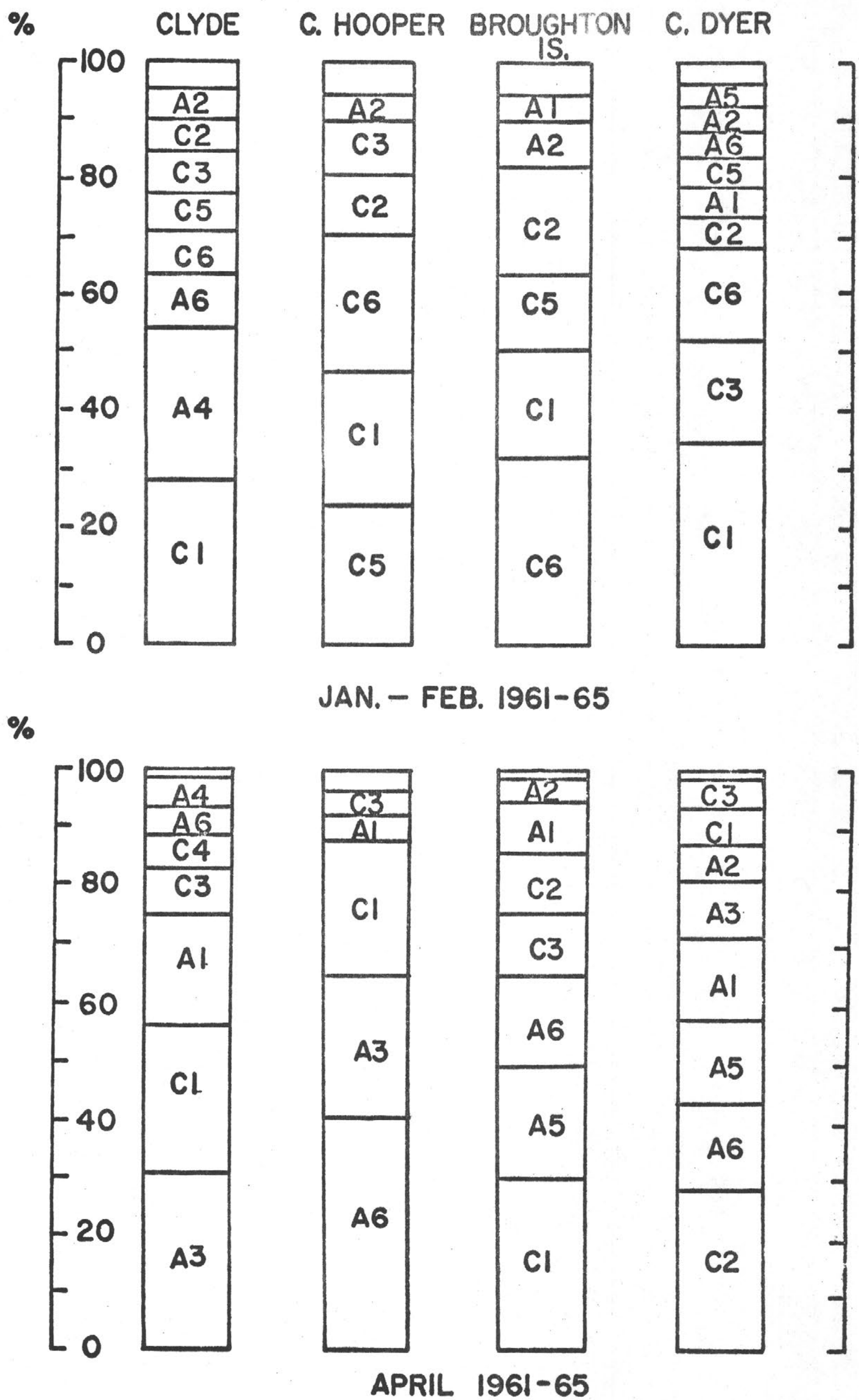


Figure 3.3 Anticyclonic type-groups after Barry (1972)

Figure 3.4 (a, b) Precipitation at eastern Baffin Island stations by synoptic type group and season.



%
CLYDE
C. HOOPER
BROUGHTON IS.
C. DYER
100
80
60
40
20
0
A2
C2
C3
C5
C6
A6
A4
C1
A2
C3
C2
C6
C1
C5
A1
A2
C2
C5
C1
C6
A5
A2
A6
C5
A1
C2
C6
C3
C1
JAN. – FEB. 1961-65
%
100
80
60
40
20
0
A4
A6
C4
C3
A1
C1
A3
C3
A1
C1
A3
A6
A2
A1
C2
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A5
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C1
A2
A3
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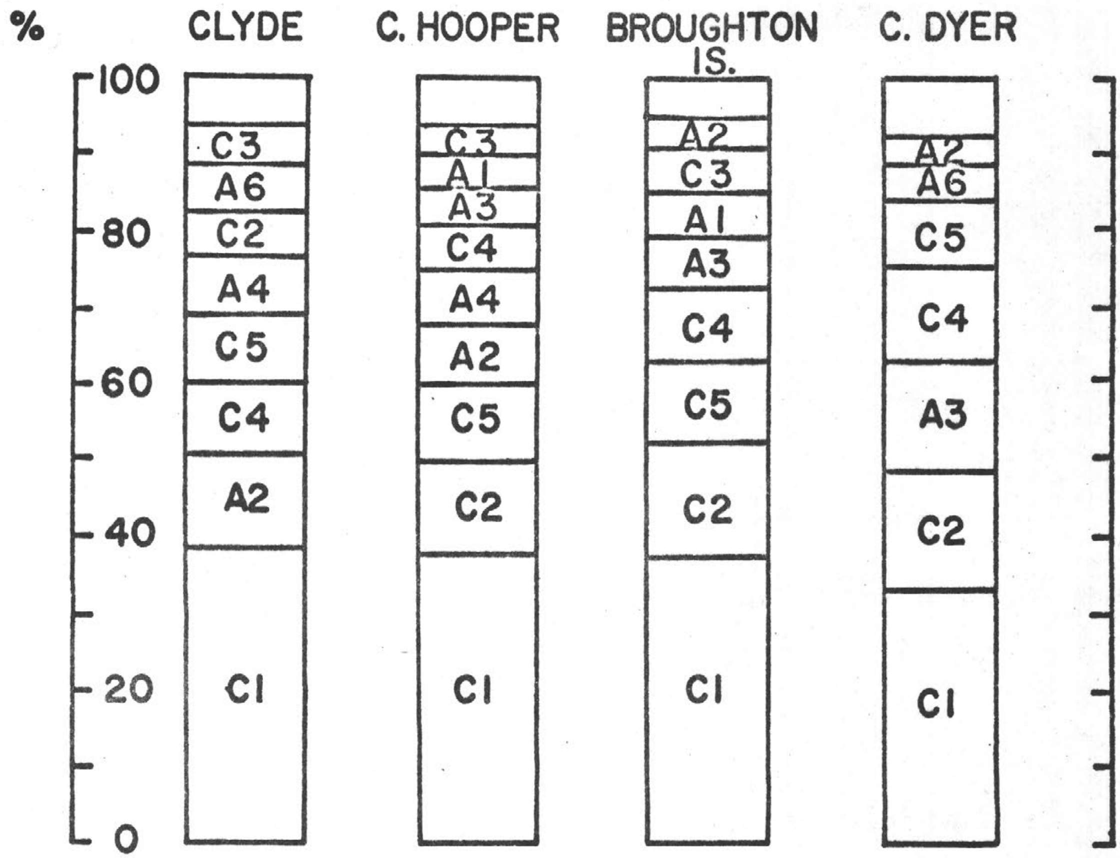
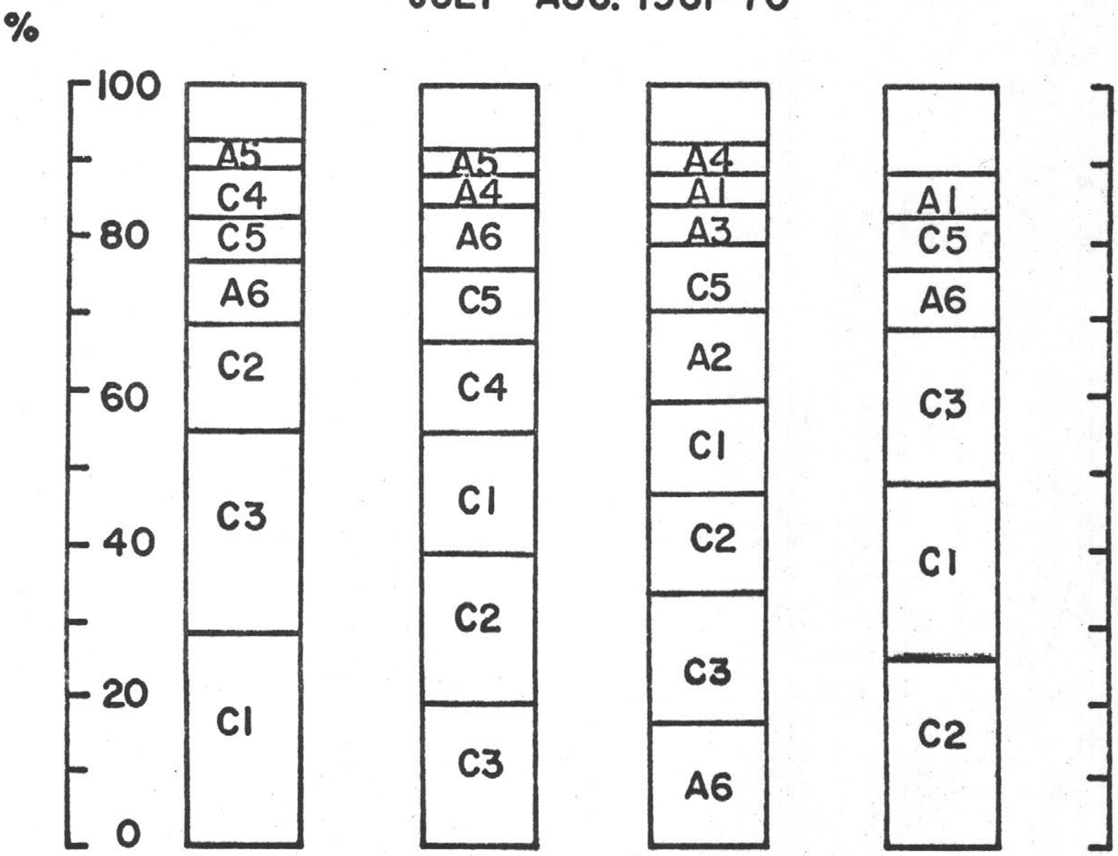
A6
C2
APRIL 1961-65



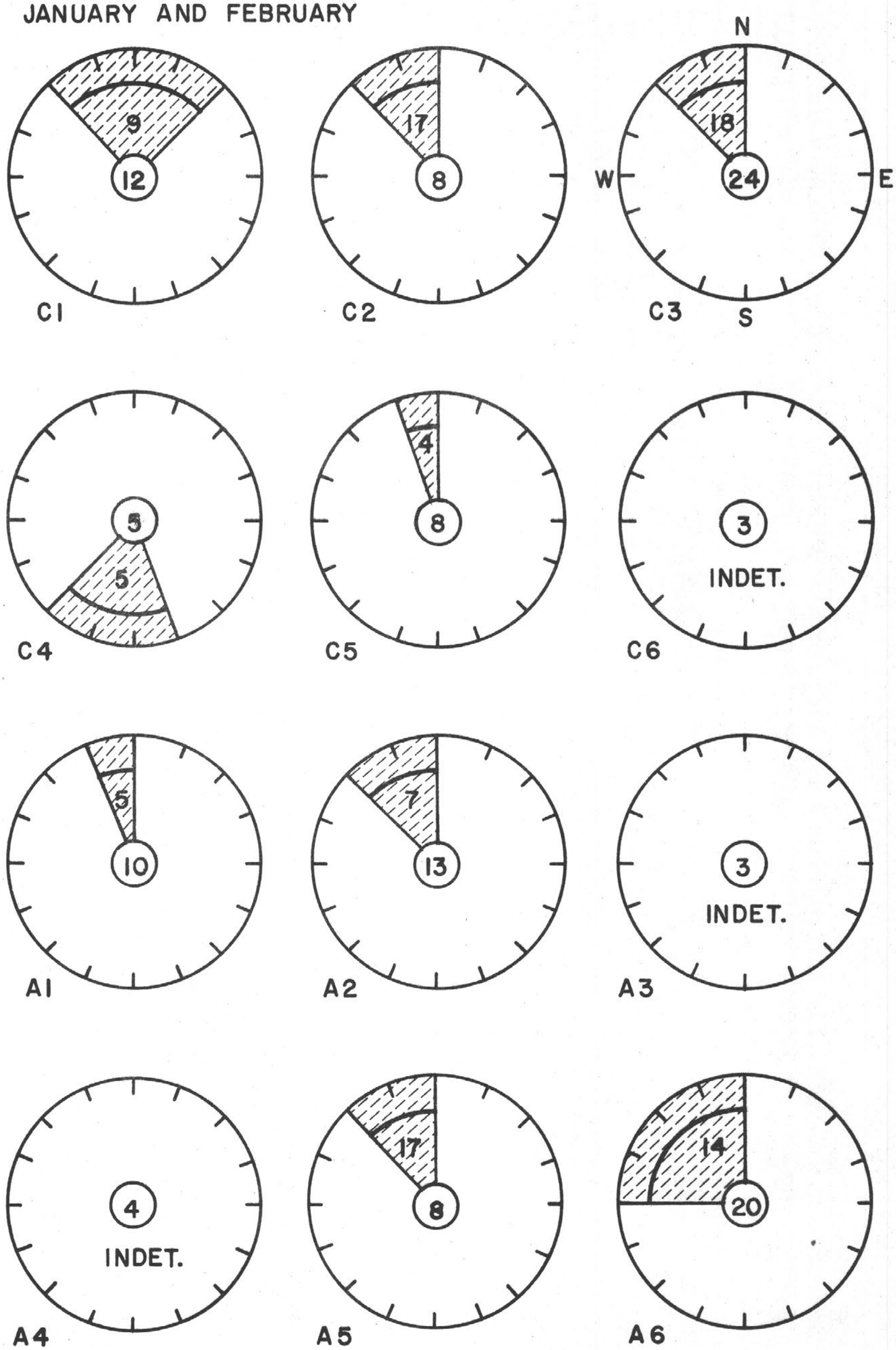
JULY – AUG. 1961-70

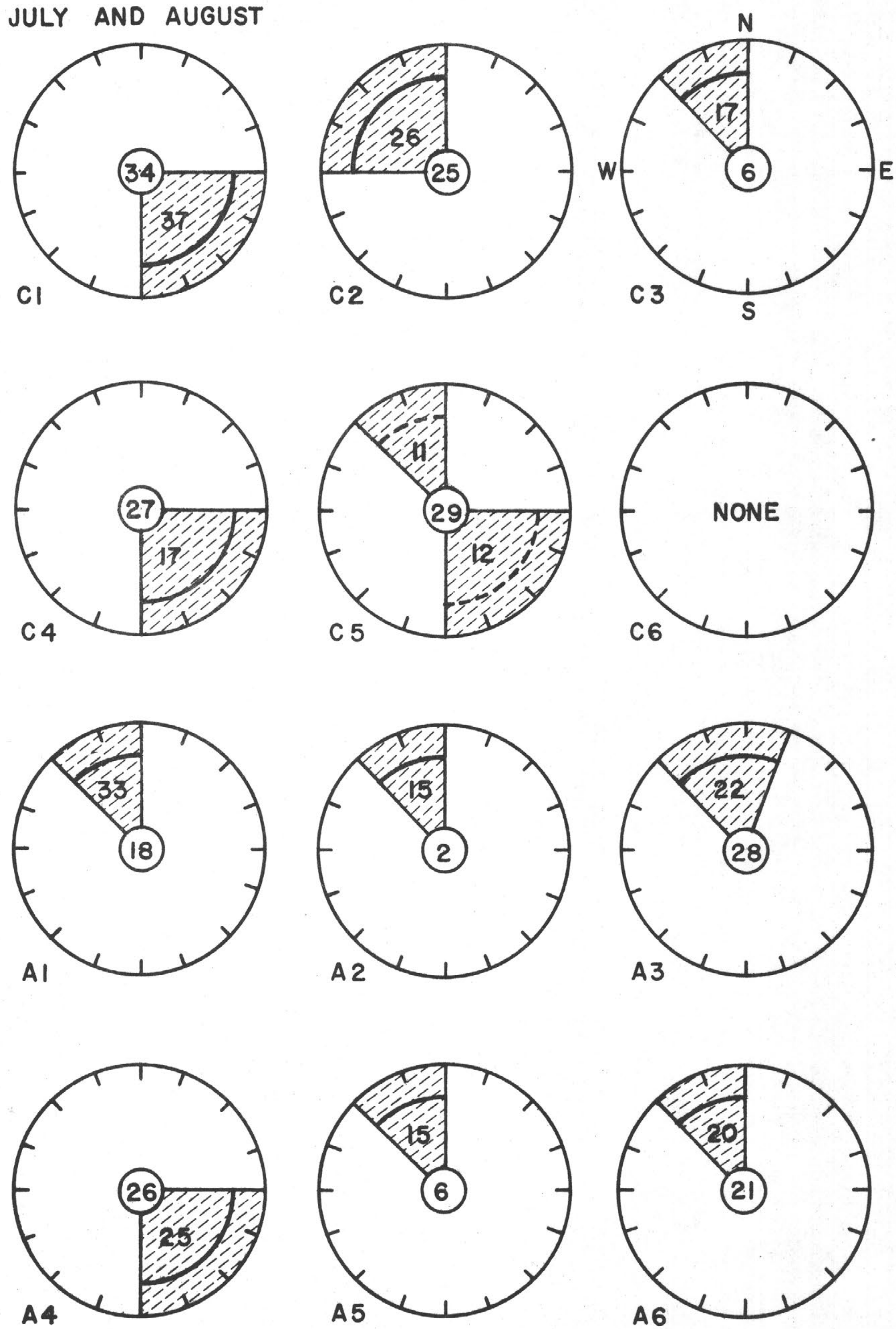


SEP. – OCT. 1961-65

Figure 3.5 Wind roses at Broughton Island (a) Jan.-Feb., (b) July-Aug.

JANUARY AND FEBRUARY




JULY AND AUGUST
N
W
E
S
34
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C1
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C2
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C5
NONE
C6
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A5
21
20
A6

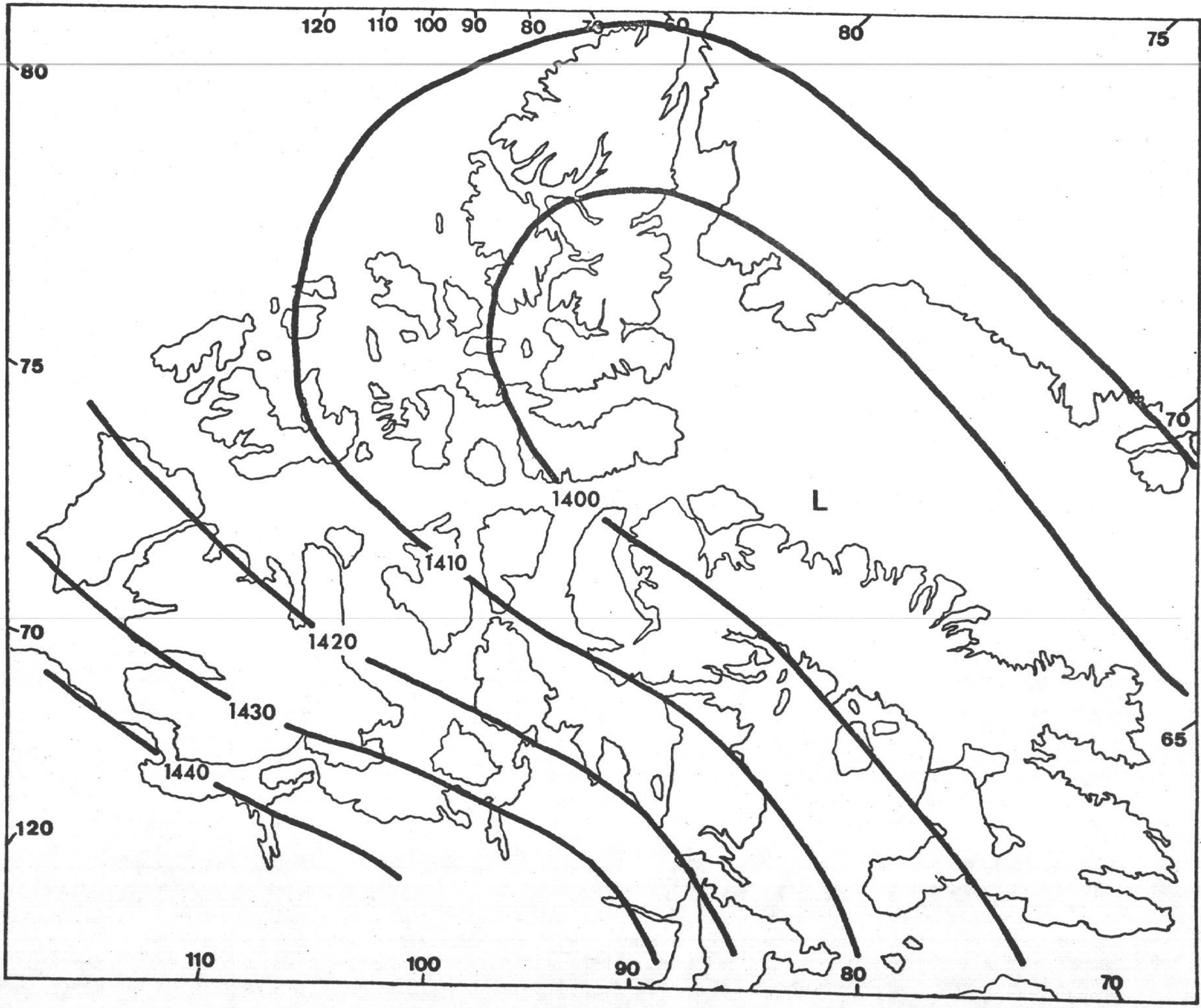

Figure 3.6 Mean 850 mb topography (gpm) for July, 1951-1960

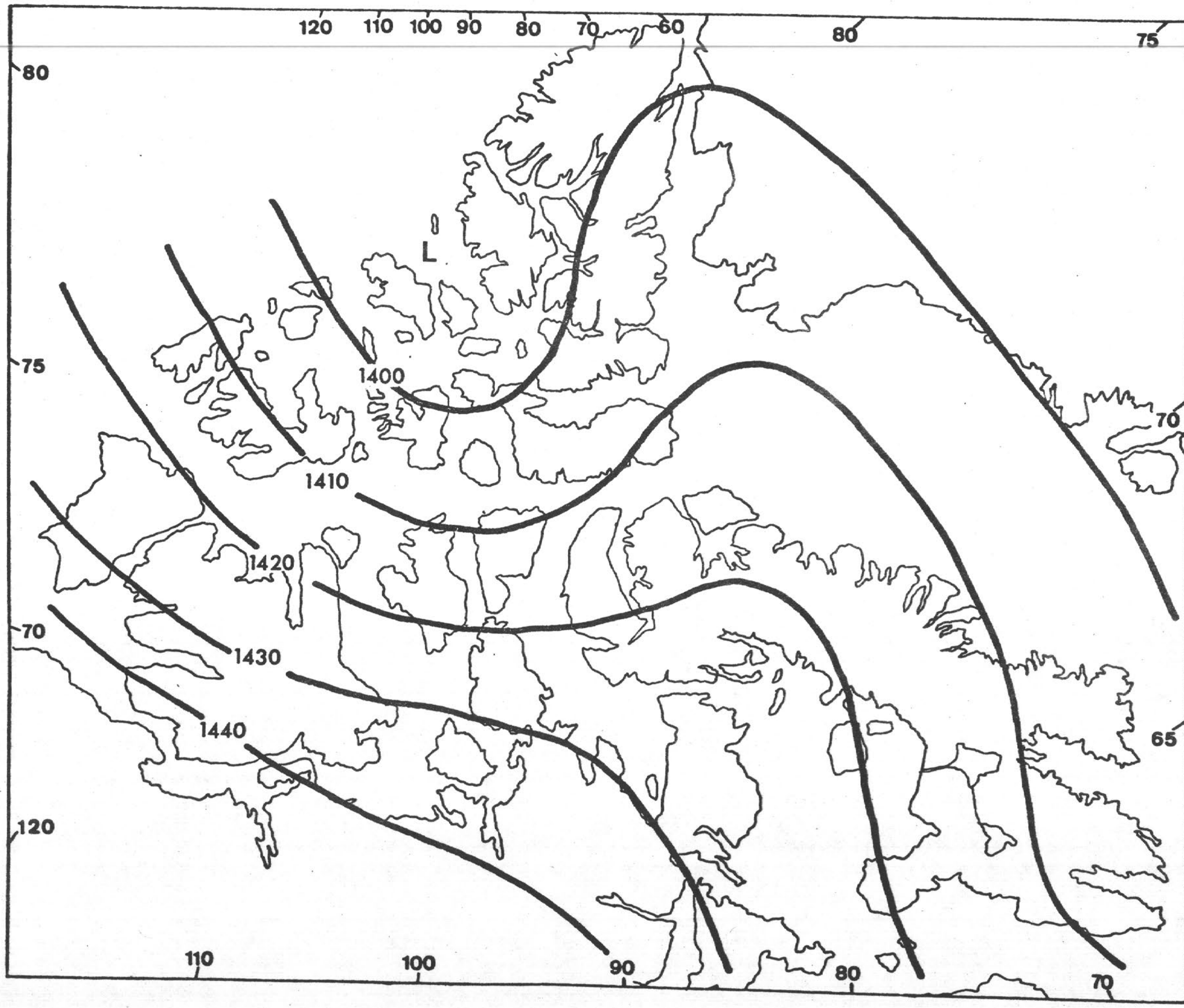

Figure 3.7 Mean 850 mb topography (gpm) for July, 1961-1970.

4. A Growth Equation for Fast Ice

J. D. Jacobs

Introduction

In Arctic coastal waters, freeze-up occurs when the temperature of the upper few meters reaches the freezing point and the air temperature drops below that point. Once the sea surface has become frozen, continued cooling of the surface means that heat flows from the relatively warm water, through the ice, and into the atmosphere. The result is continued accretion of ice at the lower boundary. The problem of sea ice growth is therefore one of heat transfer through a quasi-solid substance under certain varying conditions at the atmosphere and ocean boundaries.

In practice, two general approaches to ice growth problems are encountered; one is based upon the theory of heat transfer and the other on empirical considerations. The works of Untersteiner (1961) and Doronin (1969) are examples of the former approach. Difficulties in applying the theoretical method arise in the uncertainty of most of the physical parameters actually encountered in nature. The result is a complicated set of differential equations which must be solved numerically and are valid for a limited range of boundary conditions (e.g., Maykut and Untersteiner, 1969). Doronin (ibid.) argues that such exact solutions are usually less accurate in describing actual conditions than are any of a number of empirical formulas.

Among empirical treatments, that of Bilello (1961) is probably the most advanced. In that work, data from five stations in the Canadian Archipelago were used to derive formulas for freeze-up and break-up dates as well as growth rates. Ice thicknes, Z, is correlated with accumulated degree-days, B, (screen temperatures) below the freezing point (- 1.8°C) and snow cover h, and a regression formula obtained of the form:

$$dB = dZ\, k_1\ (Z + k_2 h) \qquad (4.1)$$

Bilello's results permit calculation of growth rates over relatively small (for the high Arctic) increments--on the order of 20 cm. However, the applicability of the formulas (not the method) is restricted to the localities studied, since each has particular values for the coefficients k_1 and k_2 in the formula. Wide use of the method is further discouraged by the fact that a number of years' observations, including frequent ice thickness measurements, are required for individual stations. Since, as Bilello points out, the causes of ice regime variations among different localities are meteorological and oceanographic in nature, it would seem that further attention to those aspects of the problem might lead to the development of a more general method.

For the fast ice along the eastern Baffin Island coast, the brevity of ice growth observations discourages the use of a strictly empirical approach. Also, since concern here is with processes on a regional scale, such an approach is of questionable value, as indicated above. Hence, an attempt has been made to deduce a simple model from consideration of heat transfer theory which is consistent with the limited observational data. Such a model should lend itself to continuous refinement as more measurements are made. Also, the model is intended to be compatible with regional energy budget calculations.

<u>Derivation of the Equation</u>

The heat flux within a plane slab and normal to its upper and lower boundaries is given by

$$F = -k \frac{\partial T}{\partial z} \qquad (4.2)$$

where T, temperature, is a function of distance z, and time t, and k is a conductivity coefficient.

The difference in the fluxes across the upper and lower boundaries, respectively, is the change in the amount of heat stored in the slab or

$$\frac{\partial F}{\partial z} = \rho c \frac{\partial T}{\partial t} \qquad (4.3)$$

where ρ is the density of the substance and c its specific heat.

Equation 4.2 is adequate to describe the instantaneous flux provided T(z,t) is known. While the function T is usually not known, its derivatives in t and z can often be found experimentally. An expression in terms of these derivatives is obtained by combining equations 4.3 and 4.4. Thus

$$\frac{\partial T}{\partial t} = - \frac{k}{\rho c} \frac{\partial^2 T}{\partial z^2} \qquad (4.4)$$

which is the general form of the heat equation in one dimension.

Application of the heat equation to the sea ice problem is the basis for the more-or-less exact solutions of Doronin and others mentioned previously. In the present case, a much simpler and therefore restricted solution is desired. A two-layered slab is considered in which a homogeneous, uniform sheet of ice is overlain by a layer of snow. Simplifying assumptions are (1) the conductivity, density, and specific heat of each layer are constant, and (2) within the time span of interest, the incremental change in ice thickness ΔZ is negligible in relation to the total thickness.

Depending upon conditions at the two or more boundaries, specifically, the temperature gradient through the slab, the ice sheet may either be growing static, or ablating. The static case ($\Delta Z = 0$) may be viewed as the limiting case of a growing ice sheet. Thus, we are concerned with either a growing or ablating ice sheet.

The growing ice sheet may be treated incrementally as a steady state problem; i.e., the temperature distribution is constant with time within the interval considered. The heat equation is then

$$\frac{\partial^2 T}{\partial z^2} = 0 \qquad (4.5)$$

The boundary conditions for (4.5) are:

$$\begin{aligned} \text{At} \quad z &= 0 \qquad T = T_o \\ z &= h \qquad T = T_h \\ z &= Z \qquad T = T_w \end{aligned}$$

For the steady state, the fluxes in the respective layers are equal. Solving (4.5) for the snow layer gives

$$T(z)_s = T_o + \left(\frac{T_h - T_o}{h}\right) z \qquad (4.6)$$

and for the ice layer

$$T(z)_I = T_h + \left(\frac{T_w - T_h}{Z}\right) z \qquad (4.7)$$

The corresponding fluxes (per unit area) are obtained by applying equation 4.2 to equations 4.6 and 4.7. Thus

$$F_s = - k_s \left(\frac{T_h - T_o}{h}\right) \qquad (4.8)$$

and

$$F_I = - k_I \left(\frac{T_w - T_h}{Z}\right) \qquad (4.9)$$

By solving (4.8) and (4.9) for the temperature differences and adding the two, T_h is eliminated. The final form becomes

$$F = \frac{T_A - T_w}{(Z/k_I + h/k_s)} \qquad (4.10)$$

where only the temperatures at the upper and lower boundaries appear. It is evident that the slab may be divided into any number of layers with a similar form resulting; that is, with only the temperatures of the upper and lower boundaries of the slab appearing.

The flux across the lower boundary consists of two parts: the latent heat released in the formation of added increments of ice F_L and a turbulent flux from the moving water, F_w. The former is given by

$$F_L = L\rho_I \frac{\Delta Z}{\Delta t} + F_w \qquad (4.11)$$

where L and ρ_I are respectively the latent heat of fusion and density of the ice. The turbulent term F_w is unknown and in the present study is obtained as a residual.

The flux across the upper boundary is therefore

$$F_A = F_L + F_w$$

$$= L\rho_I \frac{\Delta Z}{\Delta t} + F_w \qquad (4.12)$$

Additional terms due to phase changes within the brine are assumed to be negligible.

The simple solution to the heat transfer equation developed in the foregoing was made possible by assuming that the temperature distribution within the slab remains constant with time, i.e.,

$$\frac{\partial T(z,t)}{\partial z} = 0$$

Over intervals of several days, the time scale of synoptic events, changes in surface temperature may be large--as much as 20°C. An estimate of the change in heat content (enthalpy) of the ice due to such variations in temperature can be made using an approximation due to Untersteiner (1964), that is

$$Q_I = 0.9\ (T_2 - T_1)\ (0.5 + \frac{4.1S}{T_1\ T_2}) \qquad (4.13)$$

Where T_1 and T_2 are initial and final average temperatures through the slab, S the average salinity (g/kg) and Q_I the change in heat content per unit volume (cal/cm^3). For example, consider an ice sheet of average salinity 10 g/kg and initial temperature -15°C. For a temperature increase of 5°C, the change in heat content will be 3.5 cal/cm^3. For an ice sheet of, say, 50 cm thickness, this means a total increase in heat content of 175 cal. While this is a somewhat extreme example, it nonetheless suggests that the term Q_I is important.

It is helpful in this context to consider the experimental work of Lewis (1967) at Cambridge Bay, N.W.T. Arrays of thermistors were embedded at several levels within a growing ice sheet over 100 cm thick. Hourly temperature readings provided information on heat diffusion rates. Air temperature fluctuations of $\pm$ 10°C occurred over periods of several days (some 100 hours) and a characteristic temperature wave was recognized. In our terminology, this wave period corresponds to a synoptic event. Such waves showed a linear rate of propagation with a propagation time of some 50 hours to a depth of some 90 cm, where they were effectively damped out. Measuring a mean growth rate of 0.03 cm per hour, and estimating a turbulent flux at the lower boundary of about 10 percent of the latent heat term, Lewis concluded that the change in heat content was about 25 per cent of the amount of heat released due to the observed ice growth.

It must be concluded that on the time scale of interest here, Q_I must be included in the calculations, as must some estimate of F_w. The latter can probably be considered constant for a particular location. Including these terms in equation 4.12 yields

$$F_A = L\rho \frac{\Delta Z}{\Delta t} + Q_I Z + F_w \qquad (4.14)$$

where Q_I may be obtained from equation 4.13.

Finally, solving 4.14 for the rate of growth of the ice sheet, we have

$$\frac{\Delta Z}{\Delta t} = \frac{1}{L\rho_I}\left(F_A - Q_I Z - F_w \right)$$

$$= \frac{1}{L\rho_I}\left[\left(\frac{T_A - T_w}{Z/k_I + h/k_s}\right)\right] - Q_I Z - F_w \qquad (4.15)$$

Figure 4.1 depicts growth rate curves calculated from equation 4.15 with Q_I and F_w assumed to be zero. The importance of snow cover is apparent from the figure.

The final working equation (4.15) is admittedly crude, particularly when Q_I must be approximated. However, it does appear to lend itself to ice growth calculations on the time-scale of synoptic events, as will be shown in the following section.

Application to Fast Ice Growth

Broughton Island was visited in mid-December, 1971, for the purpose of measuring fast ice growth rates in relation to thermal and meteorological variables. A program of daily observations had been continued by a cooperative observer since the preceding summer, and it was hoped that these data in conjunction with intensive mid-winter field work would provide information on synoptic processes in relation to sea ice formation and growth.

Weather conditions during the field period (15 December - 18 January) were considerably varied, and included one major storm and a record low temperature of - 42.8°C on the day of departure (19 January). A relatively uniform snow cover of about 7-8 cm was initially measured on the ice in Broughton Harbor, with 10-20 cm depths estimated for the adjacent land. Snowfall data from the Broughton DEW-line site were about normal for October and November. The harbor ice was found to be very smooth and contained few old floes, bergy bits or bergs. Travel over the ice some 80 km to the south showed similar conditions inshore of the islands. To the north of Cape Broughton and on the east side of Broughton Island, the unsheltered waters of Davis Strait bore a considerably rougher cover, with minor pressure ridges (1 to 3 m high) and recently opened and refrozen areas estimated at 10 to 20 per cent of the total area (Figure 4.2).

Ice thickness measurements were made during traverses around the island and to the north and south, and regularly in Broughton Harbor. These measurements, presented in Figure 4.3, showed a fairly uniform regional ice thickness of about 100 cm for mid-winter. A series of holes drilled among the islands in the vicinity of Padloping Island (80 km south of Broughton) showed considerable variation of ice thickness with snow depth and situation. For example, in open areas some 3-5 km from the nearest shore, the snow cover was 8-10 cm and the ice 90 cm thick.

However, in the narrower (1-2 km) straits among the islands snow depths tended to be 15 to 20 cm and ice thickness 50 to 70 cm. A "potential" ice thickness of 90 cm was assumed for unsheltered areas and a 10 cm snow cover. This corresponds to measurements in exposed areas north of Broughton Island which are taken to be representative for purposes of ice growth calculations.

For convenience of access, a restricted area in the middle of Broughton Harbor was chosen for regular ice thickness and temperature measurements. Initial measurements as well as a transect northward showed the ice thickness in mid-harbor to be less than the regional average. The "harbor" is actually a narrow strait separating Broughton Island from Baffin Island, and tidal currents of some 1-2 m/sec were observed there in the preceding summer. The turbulent flux beneath the ice must therefore be large, although fairly constant. Thus, all other factors affecting ice growth rates were assumed to be the same between the mid-harbor site and the more open areas.

The 1971 freeze-up of Broughton Harbor occurred on October 31, and by November 16, the ice was sufficiently thick to support foot and snowmobile travel (J. Pearson, pers. comm.). Climatological records from the Broughton Village station show a total of 63.5 deg-days below - 1.8°C through freeze-up. A week of relatively heavy snowfall occurred immediately following freeze-up, and by mid-November a 5-10 cm snow-cover had accumulated.

On December 18, 45 cm of ice at the harbor site was measured using a 2 cm diameter auger. Measurements throughout the subsequent 31-day period indicated nearly linear growth at an average rate of 0.95 cm per day. The spatial variation of ice thickness in the immediate study area was tested on a single occasion by boring four holes within a 500 m radius, resulting in a range of thickness of 7 cm. Thereafter, a single hole was assumed to be representative of the area. Temperature profiles were obtained for each hole at 5 to 10 cm increments by placing a rapid-response thermistor in firm contact with the bottom of the hole. On one occasion, a larger hole was made with a chisel and ice samples taken for salinity measurements. Sample temperature profiles and a salinity profile are shown in Figure 4.4.

In addition to the salinity profile established by the "pit" method, an effort was made to recover most of the auger parings for some of the bored holes in order to determine the average salinity of the ice sheet. On one occasion this gave an average of 10.0 g/kg $\pm$ 2.0 for five holes, which suggests this more rapid technique to be practicable.

The almost linear form of the measured temperature profiles (Figure 4.4) suggested the applicability of a simple ice growth model of the form given in Equation 4.15. Using the reported freeze-up date and assuming an ice thickness of 25 cm when "travel" began, a regional ice growth curve was derived. Five-day intervals were considered and mean screen temperatures substituted for T_A. This latter practice seems justified by experimental comparisons of screen and ice surface temperatures reported by Doronin (1969) for winter ice.

In the initial solution, Q_I and F_W were disregarded and, not surprisingly, the calculated growth rates were in excess of those measured. It was then found that the growth rate for each five-day interval could be weighted by the ratio of the measured thickness to that first calculated--a factor of 0.67--resulting in a more realistic growth curve (Figure 4.3).

These results suggest that a reasonably good growth model can be obtained from screen temperatures and snow cover alone among the meteorological variables, where ice salinity is known or assumed. Prediction of ice thickness for a specific date requires additional information: either the freeze-up date or the actual ice thickness at some subsequent date.

The area was revisited in early June, 1972, and a more extensive ice thickness survey made. The results (Figure 4.5) show the same pattern of variations encountered in the winter, with the greatest thicknesses occurring east of the island over depths of several hundred meters. The average of all measurements was 160 cm, while for the deep water areas it was 180 cm. The complete form of Equation 4.15 was applied to the daily temperature and precipitation records from Broughton Village from freeze-up (1 November) to the end of May. This resulted in a calculated thickness of 175 cm, i.e., within 3 per cent of the actual (deepwater) value. In this calculation F_w was disregarded. The close agreement suggests that either that term is negligible in deepwater areas, or some other compensating error is present.

Conclusion

The results described above suggest that a good estimate of the rate of growth of first-year ice can be made using an equation based on one dimensional heat flow through a two-layered slab with daily mean temperatures and daily snowfall increments as independent variables. The exception occurs in shallow or constricted areas, where turbulent exchange of heat results in thinner ice. The advantage of the method presented here over empirical expressions lies in the fact that it can be applied immediately and generally given the climatological data, without the need for a long series of thickness measurements.

References

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Lewis, E. L., 1967. Heat flow through winter ice, Physics of Snow and Ice, H. Oura, ed., Hokaido Univ.: Sapporo, 611-631.

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Untersteiner, N. 1961. On the mass and heat budget of Arctic sea ice., Arch. Met. Geophys. Bioklimat., A., 12, 151-182.

__________. 1964. Calculation of temperature and heat budget of sea ice in the central Arctic. J. Geophys. Res., 69, 4755-4766.

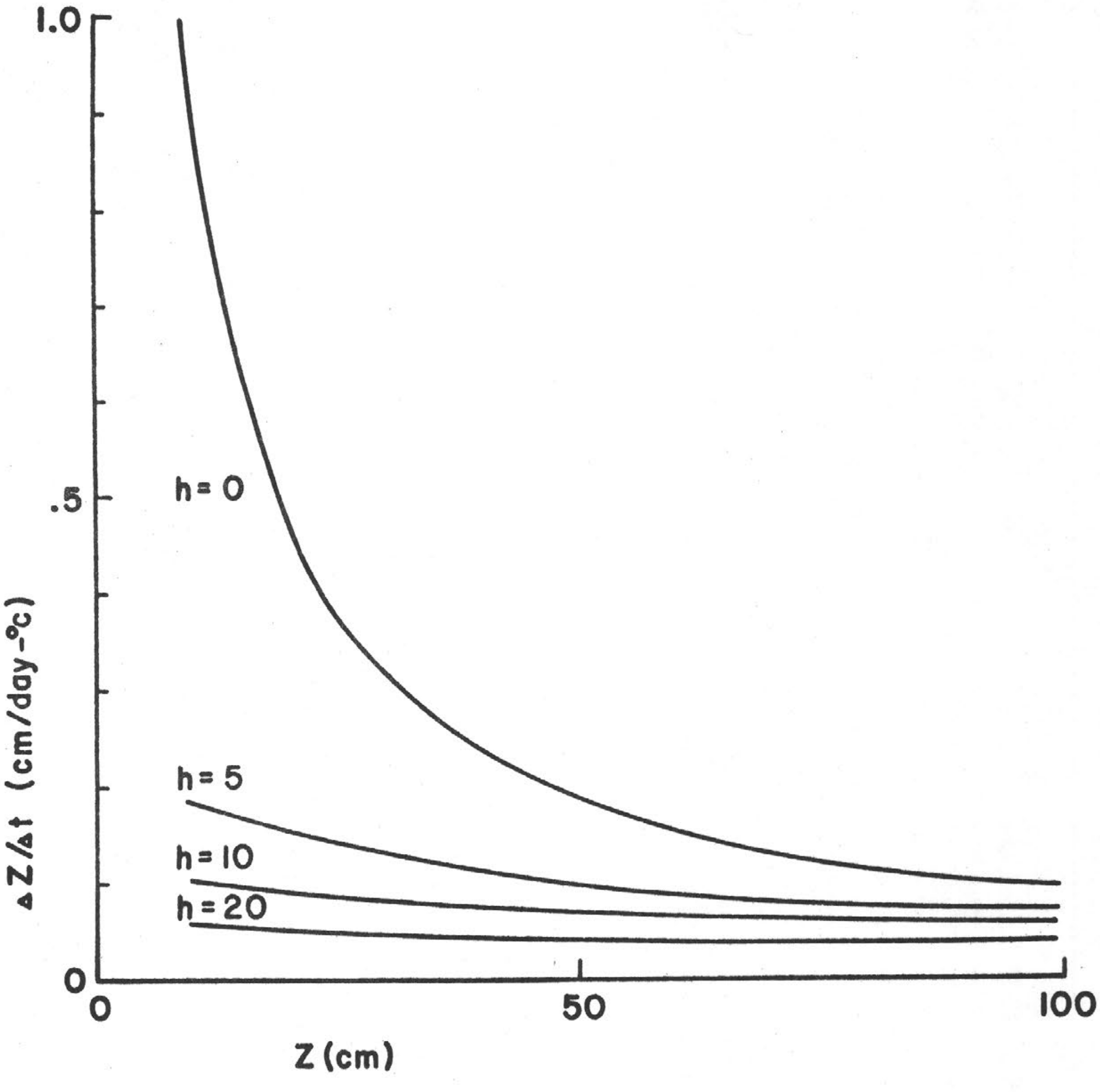


Figure 4.1. Sea Ice Growth Rate as a Function of Thickness for Various Depths of Snow Cover (cm).

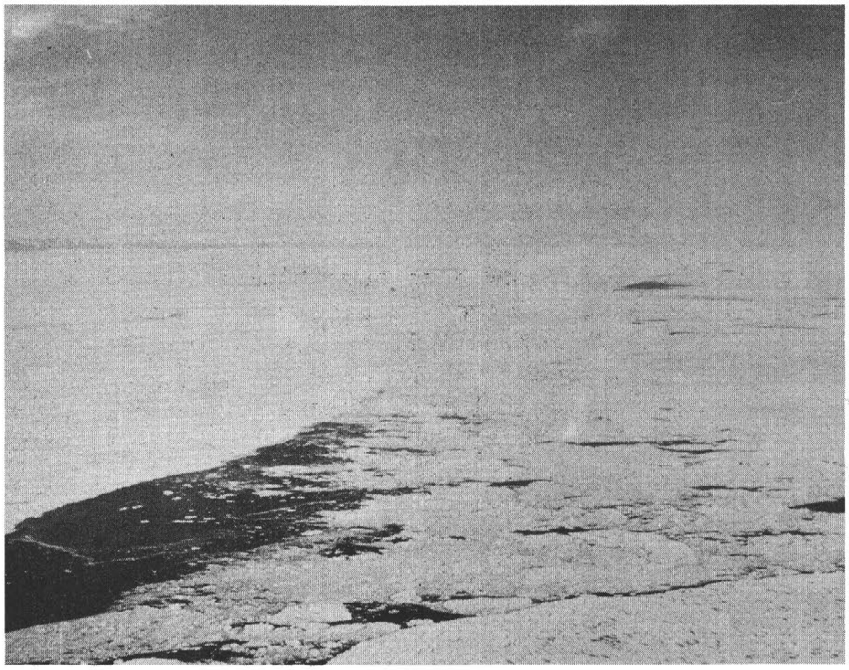
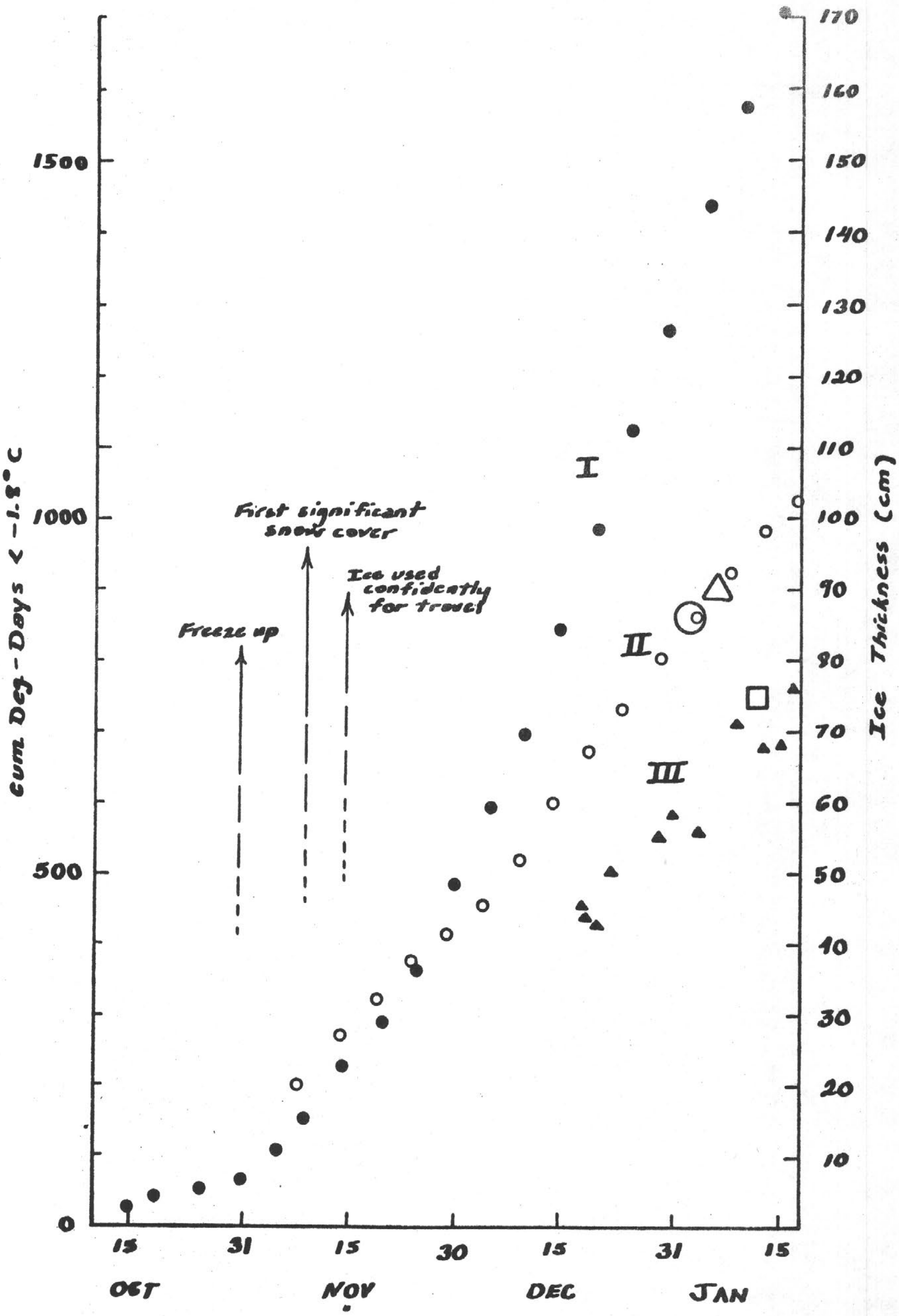


Figure 4.2. Boundary between Unbroken Fast Ice and Pack Ice Looking Northward 17 nmi East of Cape Broughton, Early August, 1972.

Figure 4.3. Fast Ice Growth through Midwinter 1971 - 72 off Broughton Island. Curve I shows Cumulative Degree-Days below - 1.8°C. Curve II is the Calculated Growth from Equation 4.10, and the Circle and Triangle show Measured Values. Curve III shows Measured Values in the Shallow Waters of Broughton Harbor and (Open Square) Delight Harbor, Padloping Island.



Cum Deg-Days < -1.8°C
Ice Thickness (cm)
1500
1000
500
0
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
I
II
III
First significant snow cover
Ice used confidently for travel
Freeze up
15
31
15
30
15
31
15
OCT
NOV
DEC
JAN

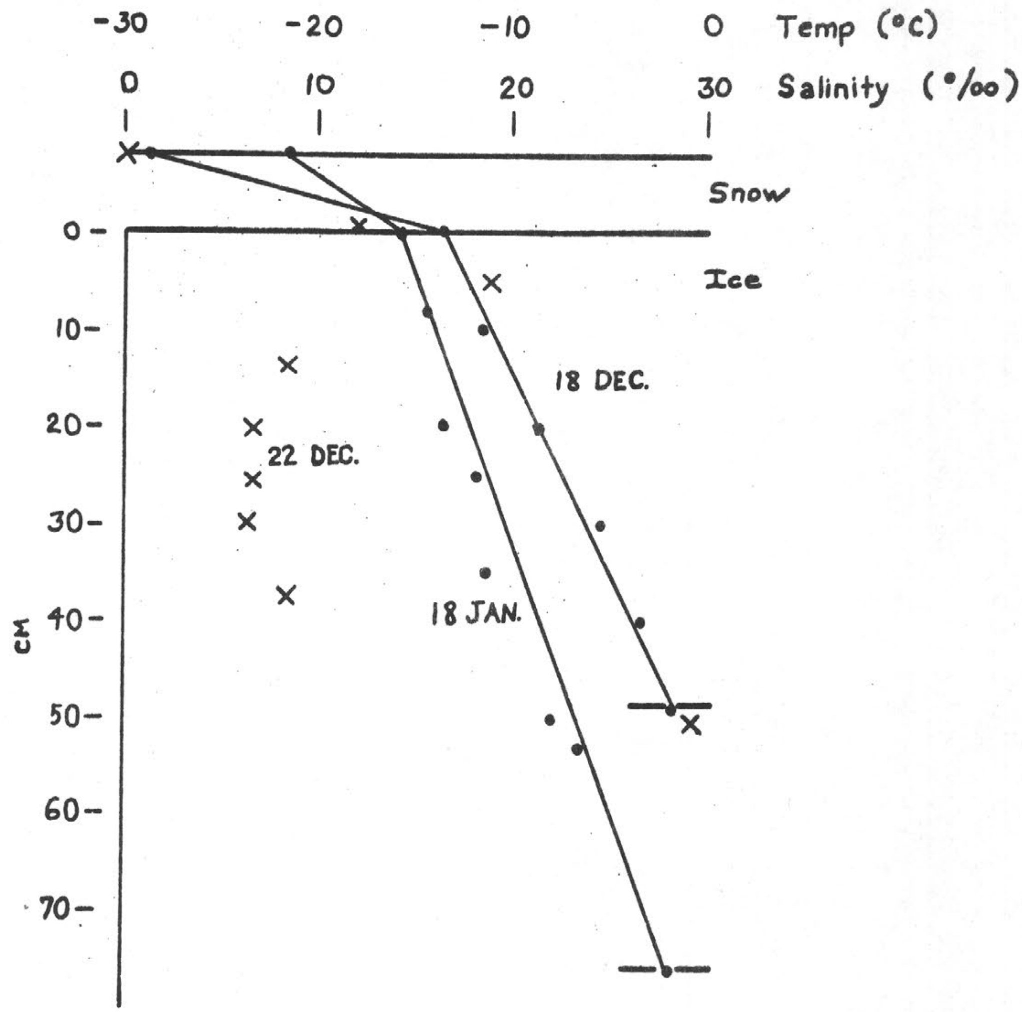


Figure 4.4. Examples of Temperature and Salinity Profiles in Fast Ice, Broughton Harbor, Winter 1971 - 72.

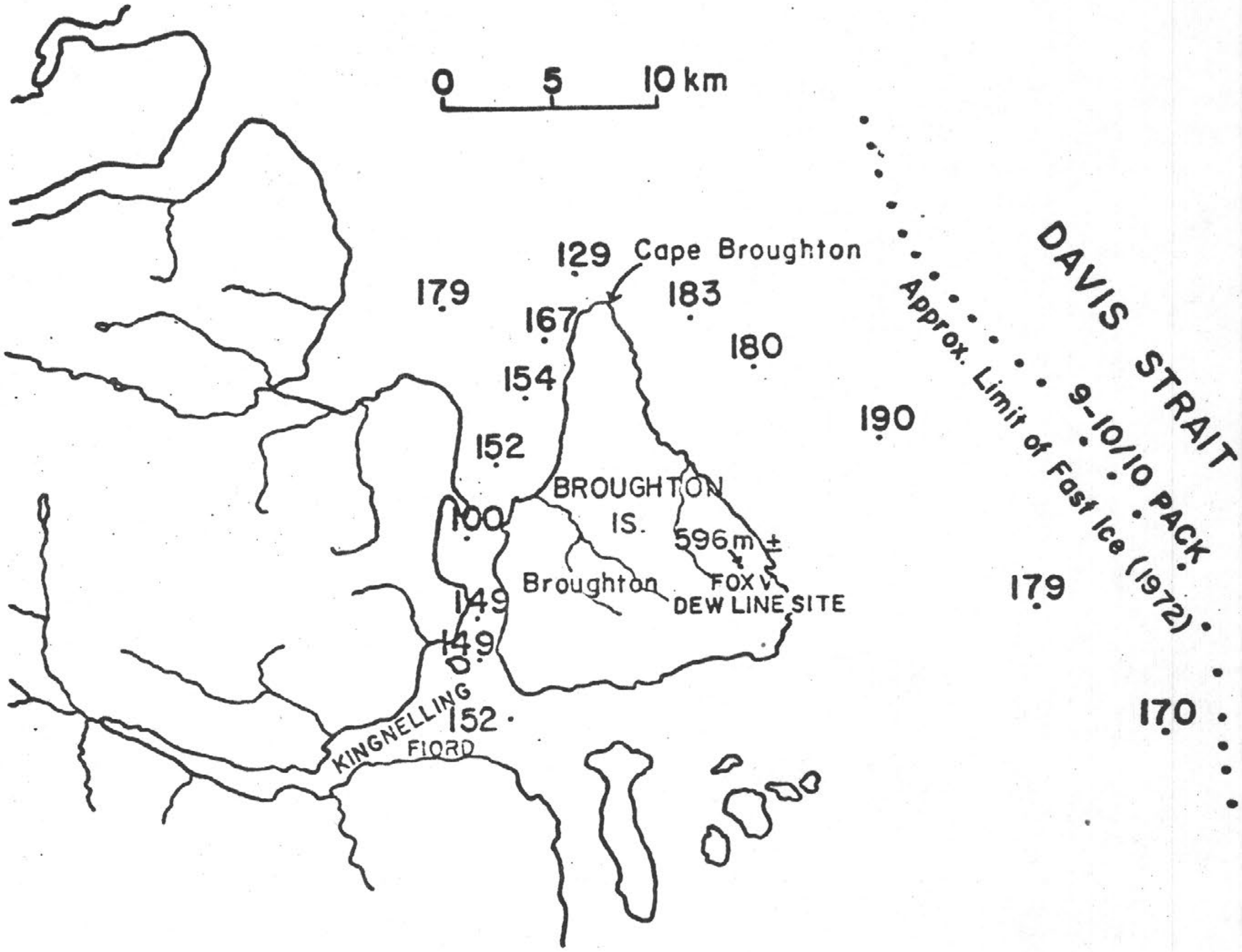


Figure 4.5. Maximum Thickness (cm) of Fast Ice in the Vicinity of Broughton Island during the 1971-72 Winter. Survey made in early June.

5. Mapping Seasonal Changes In The Fast Ice And Pack Using Remote Sensing Data.

R. L. Weaver

Introduction

This section is concerned with results of the analysis of satellite imagery, Canadian Ice Forecast Maps and Side Looking Airborne radar (SLAR) to determine 1) seasonal changes in pack and fast ice extent for the years 1970-73 in the Davis Strait-Baffin Bay region, and 2) regional fast ice composition in the Home Bay-Broughton Island area. A contrast enhancement technique developed in the course of this work for use on the Earth Resources Technology Satellite (ERTS-1) imagery is discussed separately in Section 6. The various data types and sources are described first.

Data Sources

The data were collected from four sources. The weekly Ice Forecast Maps compiled primarily from aircraft observations and published on a scale of 1: 4,000,000 by the Ice Forecast Central, Atmospheric Environment Service (AES), Canada provided the basic information for the maps. The ERTS-1 Multispectral Scanner System (MSS) and the NOAA-2 Very High Resolution Radiometer (VHRR) are the two primary satellite systems used. Visual imagery from the ESSA 9 and ITOS 1 automatic picture transmission systems (APT) were used for spot checks of 1970 and 1971 maps but were not incorporated in the final maps. Orbital and sensor characteristics for the ERTS-1 and NOAA-2 Satellites are summarized in Table 5.1. One strip of SLAR imagery flown on 5 March 1973 over the area immediately east of Broughton Island provided input to the Broughton regional fast ice analysis. The SLAR imagery was provided by Dr. Moira Dunbar, Defense Research Board, Canada.

Pack Ice Maps

Mean monthly maps (Figures 5.1 (a-d)) of pack ice concentrations in excess of four to five tenths were prepared from the AES ice forecast maps, supplemented by satellite data where cloud cover and image availability permitted. The pack ice perimeter from the first and last maps for a given month were traced onto a single monthly summary map. A line drawn midway between these two boundaries was arbitrarily defined as the mean monthly extent. This procedure was followed for each of the months June, July, August, and September for the years 1970-73. The major conclusions are as follows:

a) The average monthly position of the western margin appears stationary during all four years while the north and east margins fluctuate from year to year. The late season (August-September) ice tends to concentrate along the southern part of Davis Strait and the southeast coast of Baffin Island.

b) During 1970 and 1971 the mean August pack lay offshore in the middle of Davis Strait. This contrasts with the 1972 and 1973 seasons when the mean August pack was displaced westward against the east Baffin Coast.

c) The 1972 summer, characterized as a severe fast ice year, showed no major variation in pack ice distribution when compared to the other years. (Caution must be exercised here because a significant change in pack ice distribution may have occurred if areas of less than four tenths cover were considered).

d) The general trend of pack ice concentration follows the pattern established in the severe ice 1960 decade (Dunbar, 1973), rather than the milder 1950's (Figure 5.2.)

Fast Ice Maps

Two areas of persistent fast ice occur in the Davis Strait-Baffin Bay area. They are the east coast of Baffin Island from Pond Inlet to

Cape Dyer and Melville Bay southeast of Thule on the Greenland Coast. The present study is concerned only with the east Coast of Baffin Island.

The fast ice margin was mapped from late May or early June until breakup for the 1970-73 seasons (Figures 5.3 (a-d)). Each week with a significant change was mapped. For the 1973 summer VHRR imagery was analyzed with the aid of a Bausch and Lomb Zoom Transfer Scope to cross-check the ice forecast maps. Inaccuracies in the AES maps in the position of the fast ice edge of some 10-20 km were discovered for certain dates. Therefore, it may be assumed that the accuracy of our early season maps for the first three years is probably of the same order. The depiction in the AES maps of the north-south retreat of the fast ice and the late season margin are most probably more accurate because of the margins's close proximity to recognizable landmarks and thus greater mapping ease for an airborne observer. These reservations must be kept in mind in consideration of the results: a) The distance of the fast ice margin from the coast varies little from year to year in late May-early June. b) The pattern of the breakup of the fast ice shows considerable variability from year to year. Excluding the severe 1972 season, fast ice in the Home Bay - Broughton Island area broke up about the second week of August. The region centered around Royal Society Fiord (north of Cape Adair) usually preceded the southern area by about a week. The Cape Dyer area has persistent pack ice during most of the season but little fast ice. c) In general the breakup of the fast ice is associated with a decrease in pack ice concentration along the fast-pack ice boundary. e) A polynya between the fast ice margin and the pack approximately 40 km southeast of Henry Kater Peninsula, was noted in the satellite imagery in all three years of coverage. This feature persisted for most of June 1971 but in other years was more intermittent. The polynya corresponds to the deep (circa 300 fathoms) water shoreward of the Alexander and Isabella Banks. f) In 1972 the fast ice persisted in the Home Bay area but broke up along the coast north of Cape Adair. Several "flaw leads" and/or polynyas were noted along the fast ice margin in July 1972.

Fast Ice Composition in Home Bay

The ERTS-1 MSS imagery allows for the first time mapping of the fast ice extent and certain characteristics of the ice surface on a nominal scale of 1: 1,000,000. Figure 5.4 is a mosaic of ERTS-1 "Quick-look" [1] prints of the east Baffin Coast from Cape Raper on the north-west to Padloping Island on the southeast. The fast ice margin is clearly visible to the east and the Penny ice cap to the south. The previously mentioned Henry Kater polynya is also visible. Low lying stratus cloud covers the Kivitoo Headland. It should be noted that the individual frames making up the mosaic were not all from the same day, but all are within the period 12-14 July.

Surface reflectance information derived from band 6 imagery (0.7-0.8 μm in the near photo-infrared) was transferred to a 1: 500,000 universal transverse mercator (UTM) map base for satellite passes over Home Bay on 27 June and 13 July (Figure 5.5). The reflectance of the fast ice was arbitrarily divided into three categories--"3" being the lowest reflectance and "1" the highest. More precise division of the grey scale is inappropriate given the subjective manner in which the categories were chosen and the quality of the "Quicklook" prints.

The heavy lines on the highlands of Henry Kater Peninsula (Figure 5.5) are the average snow limit for each date. They indicate a retreat from an elevation near 100 m to approximately 300 m over the 17 day

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[1] "Quicklook" is the trade name given the ERTS-1 imagery product available on a rapid delivery basis (approximately two weeks) from Donald Fisher and Associates, Prince Albert Saskatchewan, the satellite tracking subcontractor.

period.

A generalized lowering of the surface spectral reflectance is evident between 27 June and 13 July. This decrease in albedo, associated with the rapid melting of the snowpack on the ice, was caused in part by air mass advection. The areas designated "2" are most probably large (15-30 m) melt pools on the ice surface, assuming surface observations in the Broughton Island area may be extrapolated northward. The "3" areas correspond to deeper surface water or in some cases open water. The fast ice margin is the solid line to the extreme east side of the map.

By combining our knowledge of 1972 end-of-season conditions with reflectance and lineation analysis we conclude that the "2" area directly east of Cape Henry Kater is second-year ice. Likewise the ice west of the generally north-south trending line from Hiaqurnak Point to Satigsun Island is also ice left from the 1972 season.

The fast ice margin in the northeast corner of the map retreated less than a kilometer during the period between the satellite passes.

Fast Ice composition East of Broughton Island

The area from Kivitoo to Merchants Bay was mapped (Figure 5.6) in a manner similar to the Home Bay fast ice map previously discussed. The ERTS-1 frames from 10 and 11 July were used. These frames were used. These frames were also compared to SLAR imagery collected on 5 March, 1973.

Surface reflectance contrasts, although not as striking as those in the Home Bay area, were none-the-less found in this area. The '2' area east of Kivitoo is thought to be second-year fast ice; however, we do not have confirming evidence from the previous summer as is available for Home Bay.

Comparison of the ERTS-1 and SLAR imagery show striking similarities. We found that many low reflectance and linear features in the ERTS-1 frames were easily located on the SLAR imagery. We conclude that these lineations which generally parallel the fast ice margin are most probably lateral slip fractures which occurred during freeze-up. No apparent motion is detectable along <u>any</u> of the linear features including those within a few kilometers of the fast ice margin, during the four months between the SLAR and ERTS-1 imagery dates. The fast ice margin itself shows very little modification as well.

The composition of the fast ice, at least for the 1972-73 season, was a complex mixture of first and multi-year ice. The SLAR imagery clearly shows a matrix of older floes imbedded in larger floes which in turn were frozen into the fast ice sheet.

Summary

We first generalize our conclusions about the fast and pack ice over the past four years, and second review and evaluate the remote sensing data available to us with emphasis on future analysis.

During the first four years of the 1970's, the pack ice in the Davis Strait continued to follow the trend of severe ice years of the 1960's as reported by Dunbar (1973). We found the maps of the four to five tenths pack ice concentration boundary to be a relatively insensitive indicator of severe ice seasons such as 1972.

The fast ice in the 1973 season was a complex mixture of first and second year and possibly multi-year ice east of Broughton Island and in parts of Home Bay. The fast ice margin was very stable from March to mid July in the Broughton Island Area.

The fast ice margin in the early season Ice Forecast maps was inaccurately mapped but with the aid of satellite imagery we were able to establish that the position of the early season fast ice margin varies little from year-to-year. A persistent polynya was noted southeast of Henry Kater Peninsula.

During 1973, three remote sensing imaging systems accompanied by surface and aerial photography provided data for our analysis. We conclude that no single system can provide all the information needed to describe surface conditions at any given point in space or time.

The VHRR and ERTS-1, if used in combination, might provide the greater part of data necessary for weekly ice forecast maps, thus freeing ice reconnaissance aircraft for detailed mapping in critical locations and for general mapping when cloud conditions render satellite systems inoperable.

The SLAR imagery is quite promising because of its ability to penetrate the early season snowcover. The complex interrelationships between the microwave radar signals and the surface electrical and physical properties make "ground truth" data essential for correct interpretation of the imagery.

Further work should include more quantitative comparisons of relative information content of the VHRR and ERTS-1 systems using the surface oblique photography and solar radiation measurements collected in 1973 (and proposed for 1974). Manual and automatic contrast enhancement techniques leading to surface classification such as the method presented elsewhere in this volume must be tested against the field observations.

Reference

Dunbar, M. 1972. Increasing severity of ice conditions in Baffin Bay and Davis Strait and its effect on the extreme limits of ice. in Sea Ice: Proc. of an International Conference, Reykjavik, pp. 87-93.

Table 5.1

NOAA-2 and ERTS-1 Operational Characteristics [1]

NOAA-2 Operational Weather Satellite

Orbit:

Sun synchronous at 790 n. mi. (1464 km.)

Equator crossing time (northbound) 1500 and 2100 local solar time

Modal period 115.14 min.

Sensors:

2 scanning radiometers (SR) each with 2 channels

1) .5 to .7 μm; 4 km minimum resolution
2) 10.5 to 12.5 μm; 7.5 km minimum resolution, N.E.D.T. 8-10°C for 185°K target

2 vertical temperature profiling radiometers (VTPR)

2 very high resolution radiometers (VHRR) each with 2 channels

1) .6 to .7 μm; .9 km minimum resolution
2) 10.5 to 12.5 μm; .9 km minimum resolution N.E.D.T. 6-8°C for 185°K target

ERTS-1 Earth Resources Technology Satellite

Orbit:

Orbital path: approximately 100 n. mi. (185 km) wide traveling N to S

Orbit (nominal): 494 n. mi. (915 km)

Modal period: 103 minutes or 14 orbits per day

Satellite passes over same point (within 20 n. mi.) every 18 days

Sensors:

Multispectral Scanner System (MSS)

Instantaneous field of view: 79 meters by

MSS bands	Spectral wavelength (μm)	Detector type
4	.5 to .6	photomultiplier
5	.6 to .7	photomultiplier
6	.7 to .8	photomultiplier
7	.8 to 1.1	silicon photodiode

Image positional fidelity

Mean MSS positional mapping uncertainty on a Universal Transverse Mercator grid: 710 m rms

Positional mapping accuracy of paper products: 757 m rms

Registration accuracy: 159 m rms

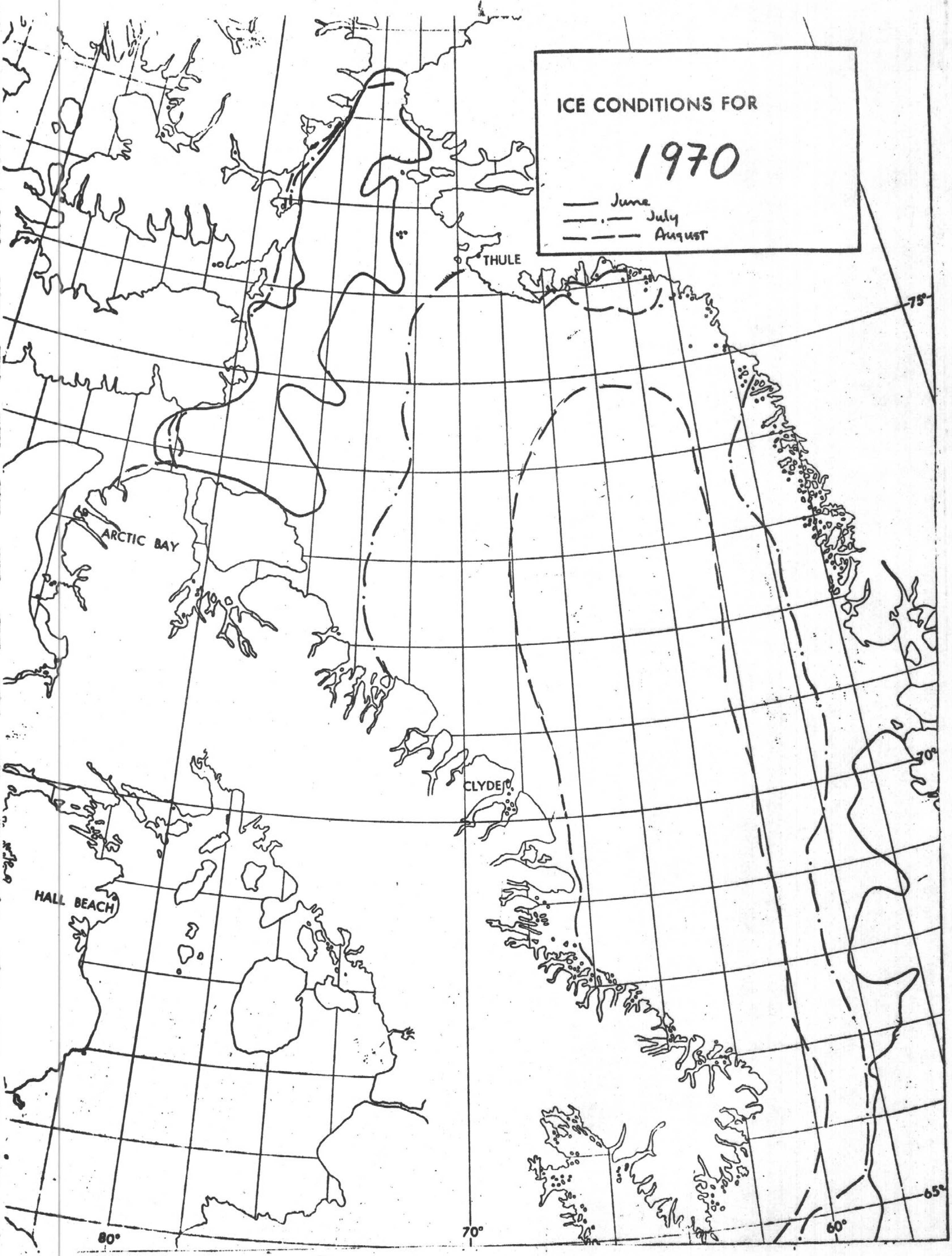
Image side lap

60°N 57%

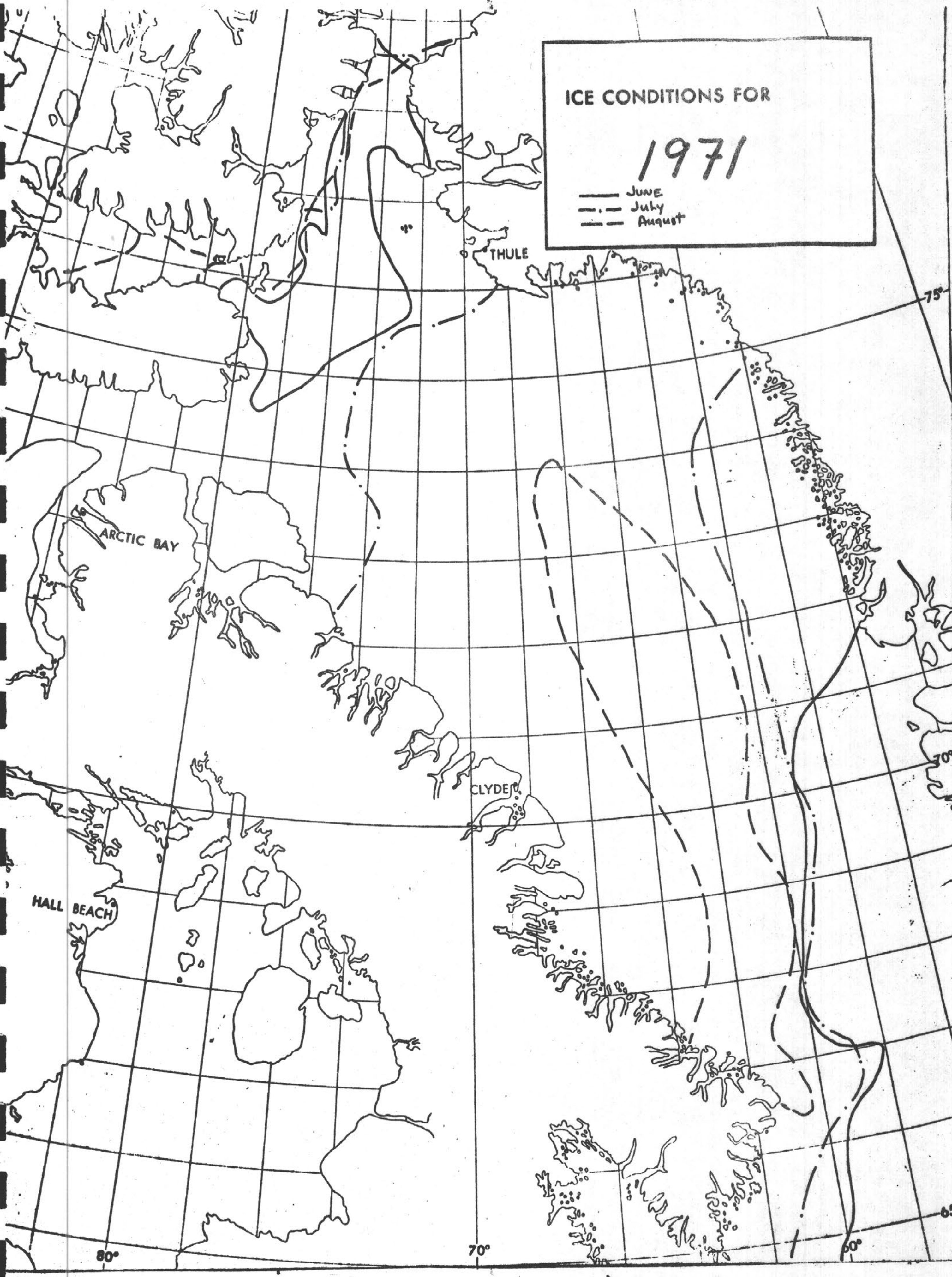
70°N 70.6 %

[1] after ERTS users handbook, 1972 and Schwalb, 1972

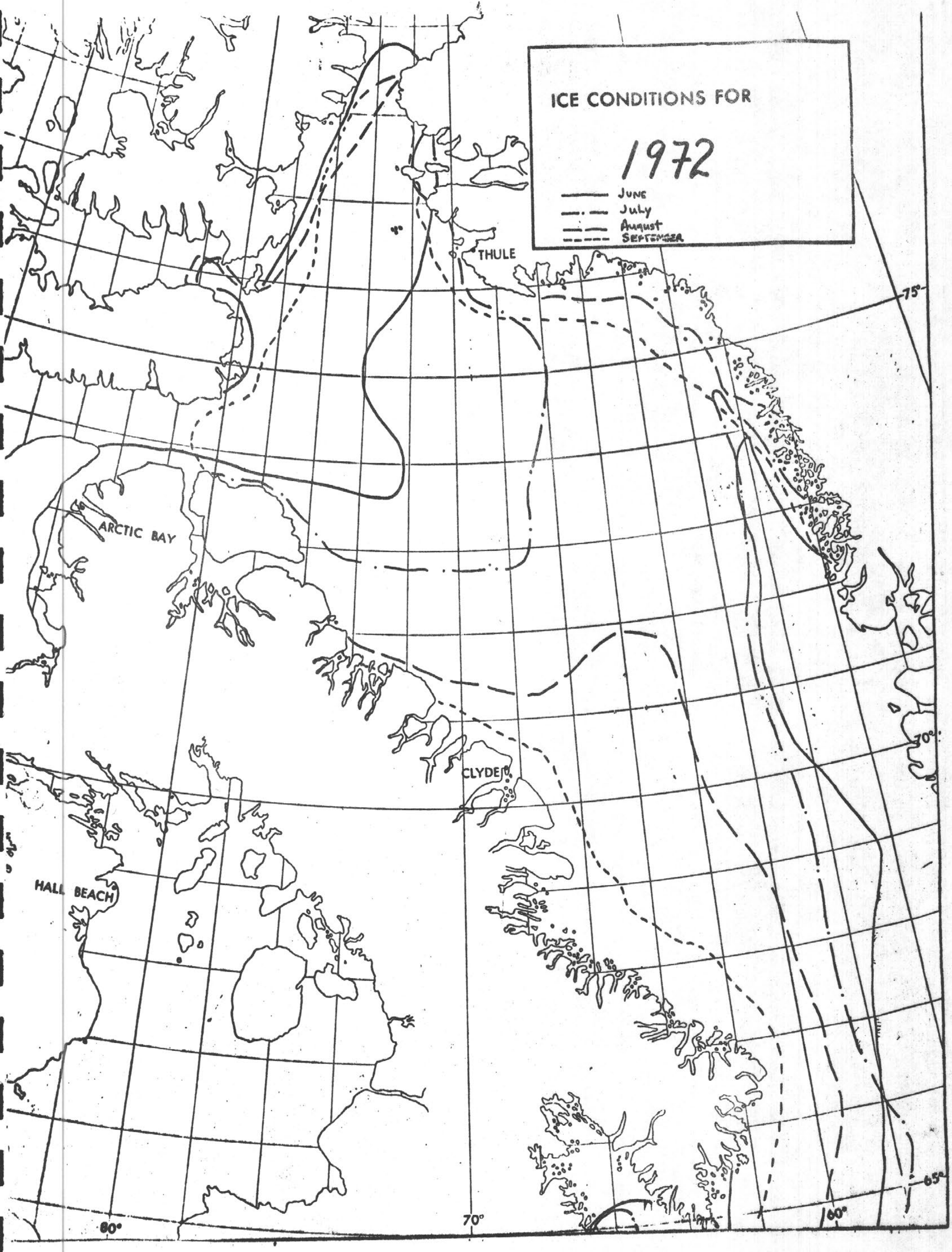
Figure 5.1 (a-d). Mean monthly maps of pack ice concentration, 1970-1973



ICE CONDITIONS FOR
1970
June
July
August
THULE
ARCTIC BAY
CLYDE
HALL BEACH
75°
70°
65°
80°
70°
60°



ICE CONDITIONS FOR
1971
June
July
August
THULE
ARCTIC BAY
CLYDE
HALL BEACH
75°
70°
65°
80°
70°
60°


ICE CONDITIONS FOR
1972
JUNE
JULY
August
SEPTEMBER
THULE
75°
ARCTIC BAY
CLYDE
70°
HALL BEACH
80°
70°
60°
65°

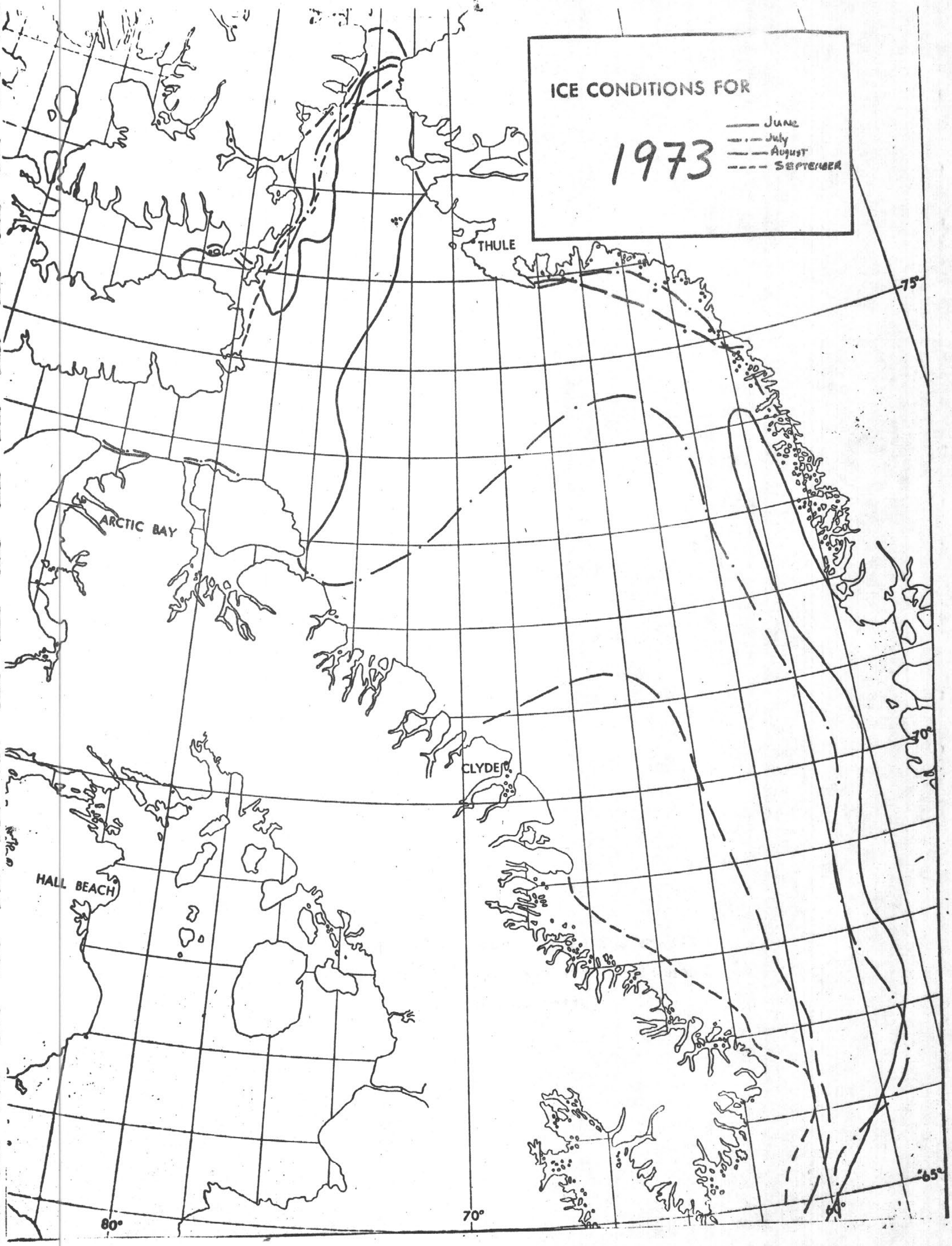
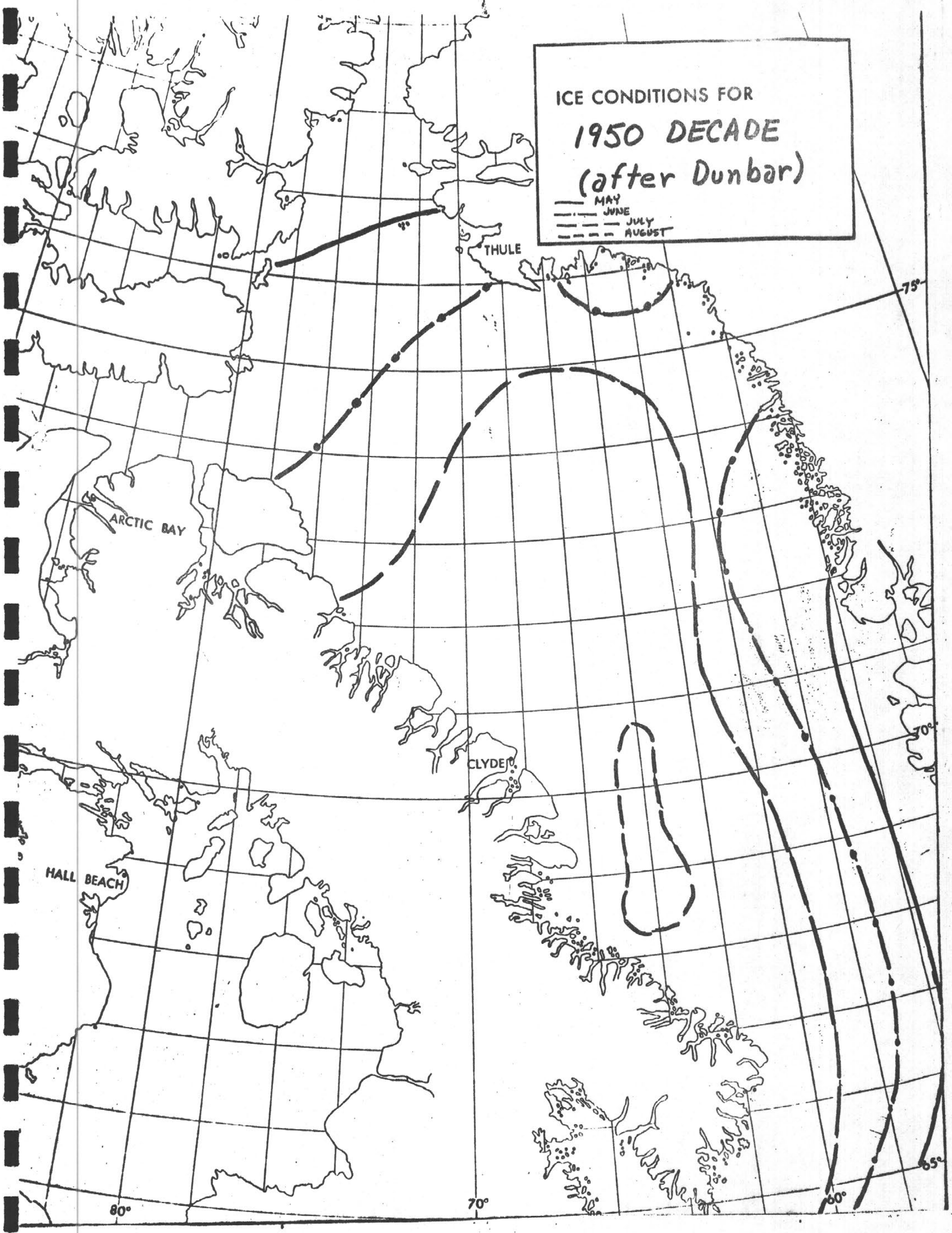

ICE CONDITIONS FOR
1973
JUNE
July
AUGUST
SEPTEMBER
THULE
ARCTIC BAY
CLYDE
HALL BEACH
75°
70°
65°
80°
70°
60°

Figure 5.2 (a-b). Mean monthly pack ice conditions for the 1950 and 1960 decades (after Dunbar, 1972).



ICE CONDITIONS FOR
1950 DECADE
(after Dunbar)
MAY
JUNE
JULY
AUGUST
THULE
ARCTIC BAY
CLYDE
HALL BEACH
75°
70°
65°
80°
70°
60°

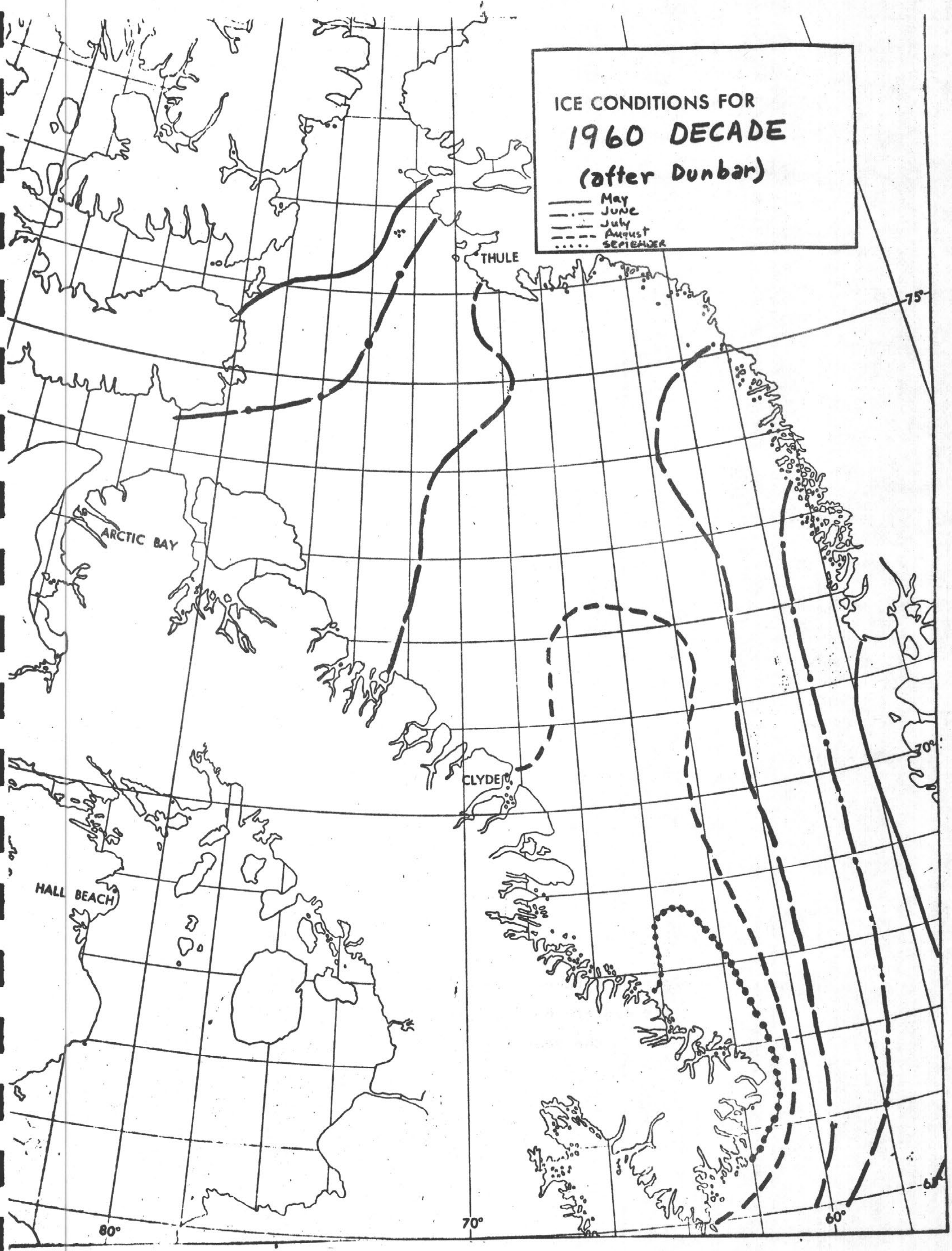
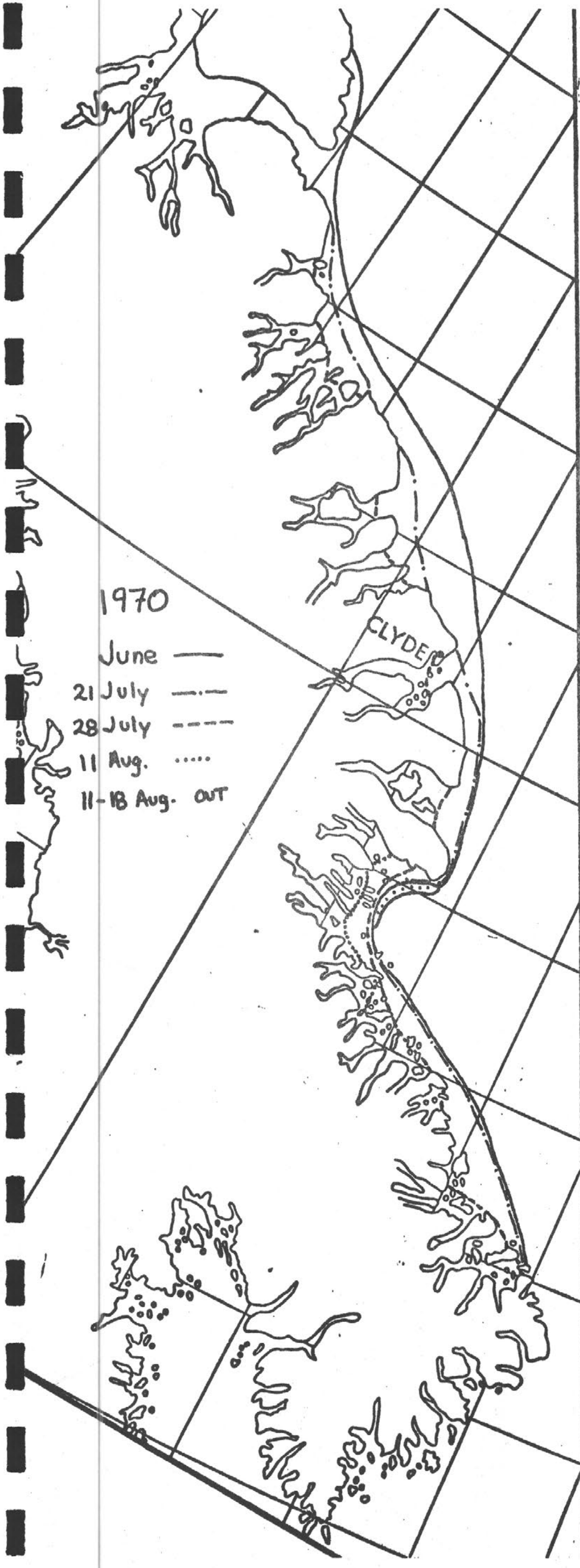
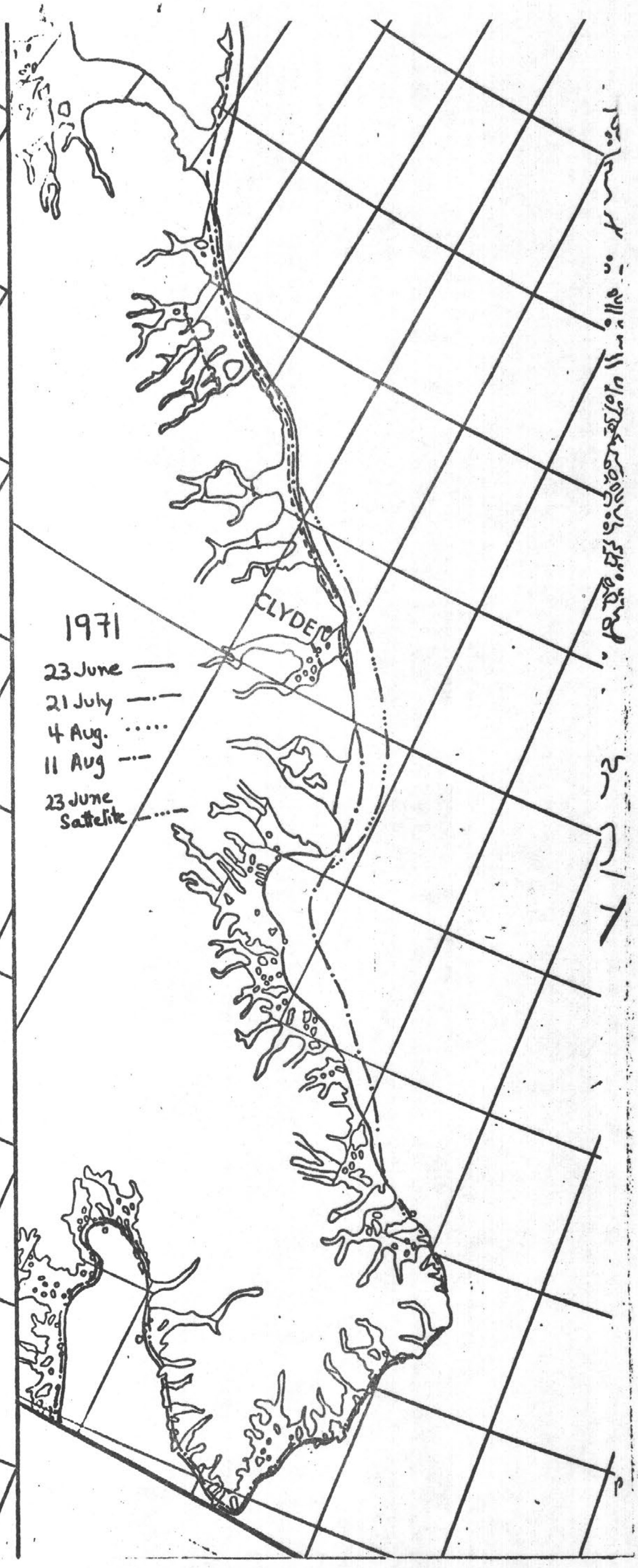
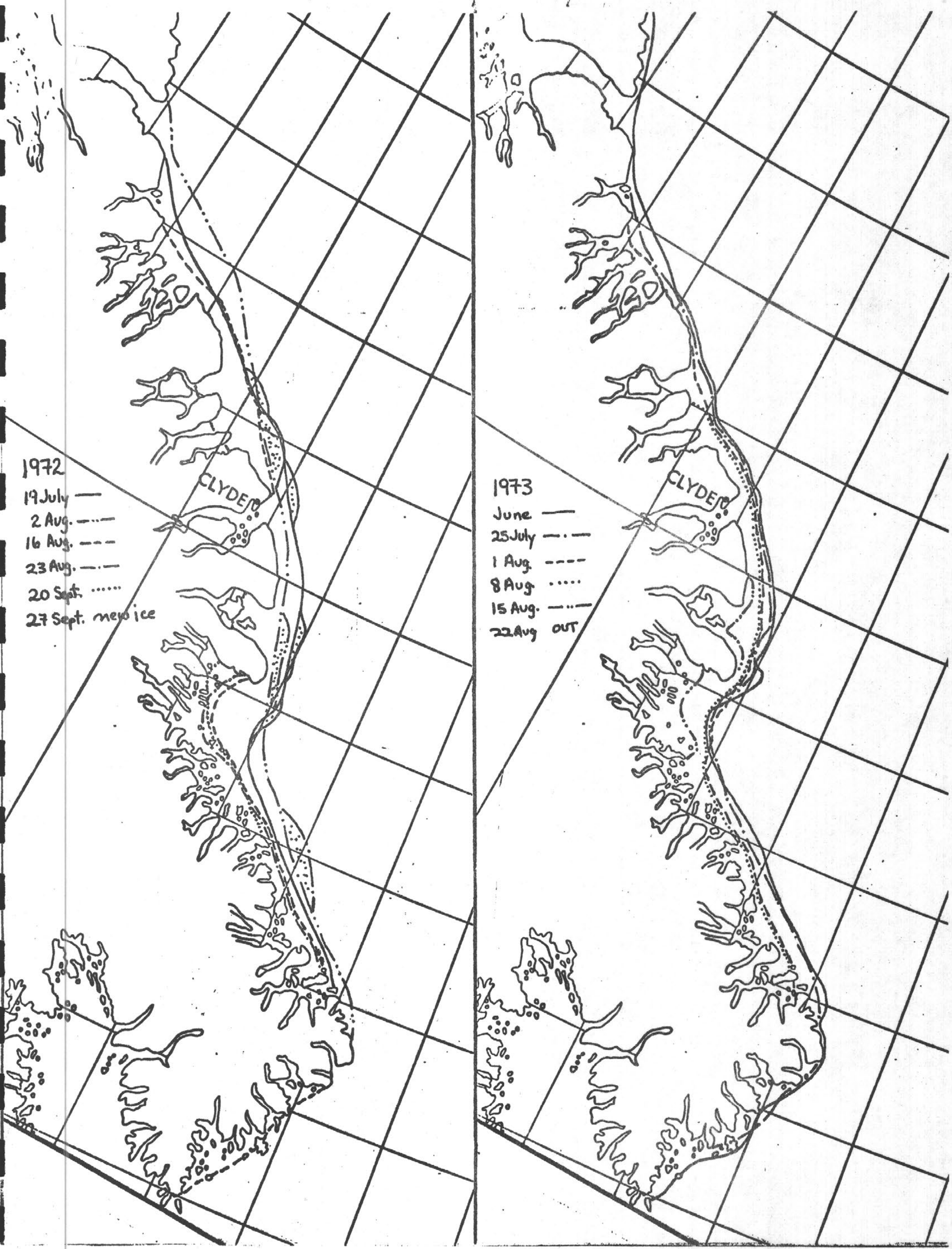

ICE CONDITIONS FOR
1960 DECADE
(after Dunbar)
May
JUNE
July
August
SEPTEMBER
THULE
ARCTIC BAY
CLYDE
HALL BEACH
75°
70°
80°
70°
60°

Figure 5.3 (a-d). Fast ice margin along the eastern Baffin Island coast for the years 1970-1973.


1970
June
21 July
28 July
11 Aug.
11-18 Aug. OUT
CLYDE


1971
23 June
21 July
4 Aug.
11 Aug
23 June Sattelite
CLYDE


1972
19 July
2 Aug.
16 Aug.
23 Aug.
20 Sept.
27 Sept. new ice
CLYDE
1973
June
25 July
1 Aug.
8 Aug.
15 Aug.
22 Aug OUT
CLYDE

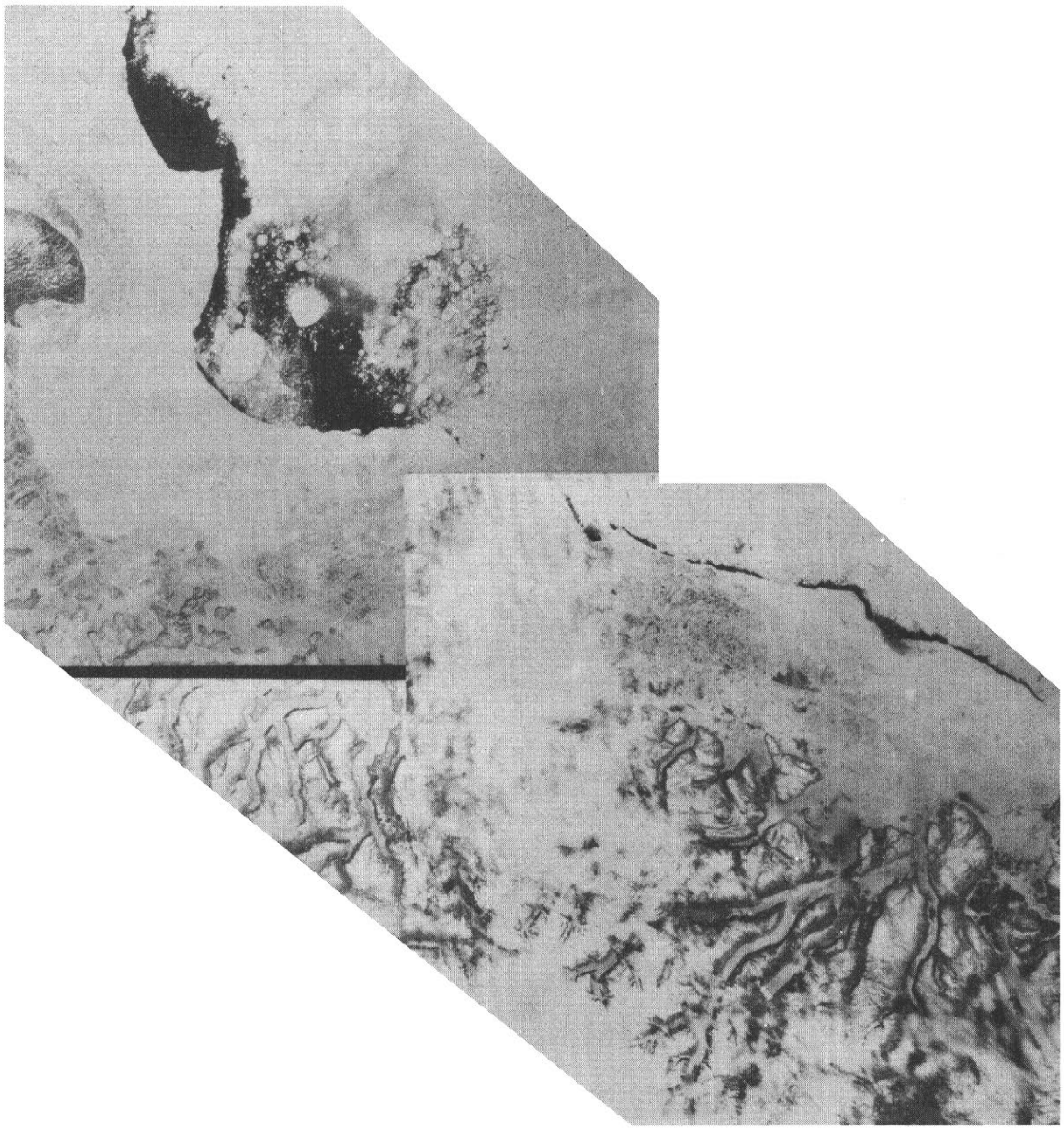


Figure 5.4. Mosaic of ERTS-1 imagery showing ice conditions in the eastern Battin Island region, early July, 1973.

Figure 5.5. Fast ice in Home Bay mapped from ERTS-1 for 27 June and 13 July, 1973.

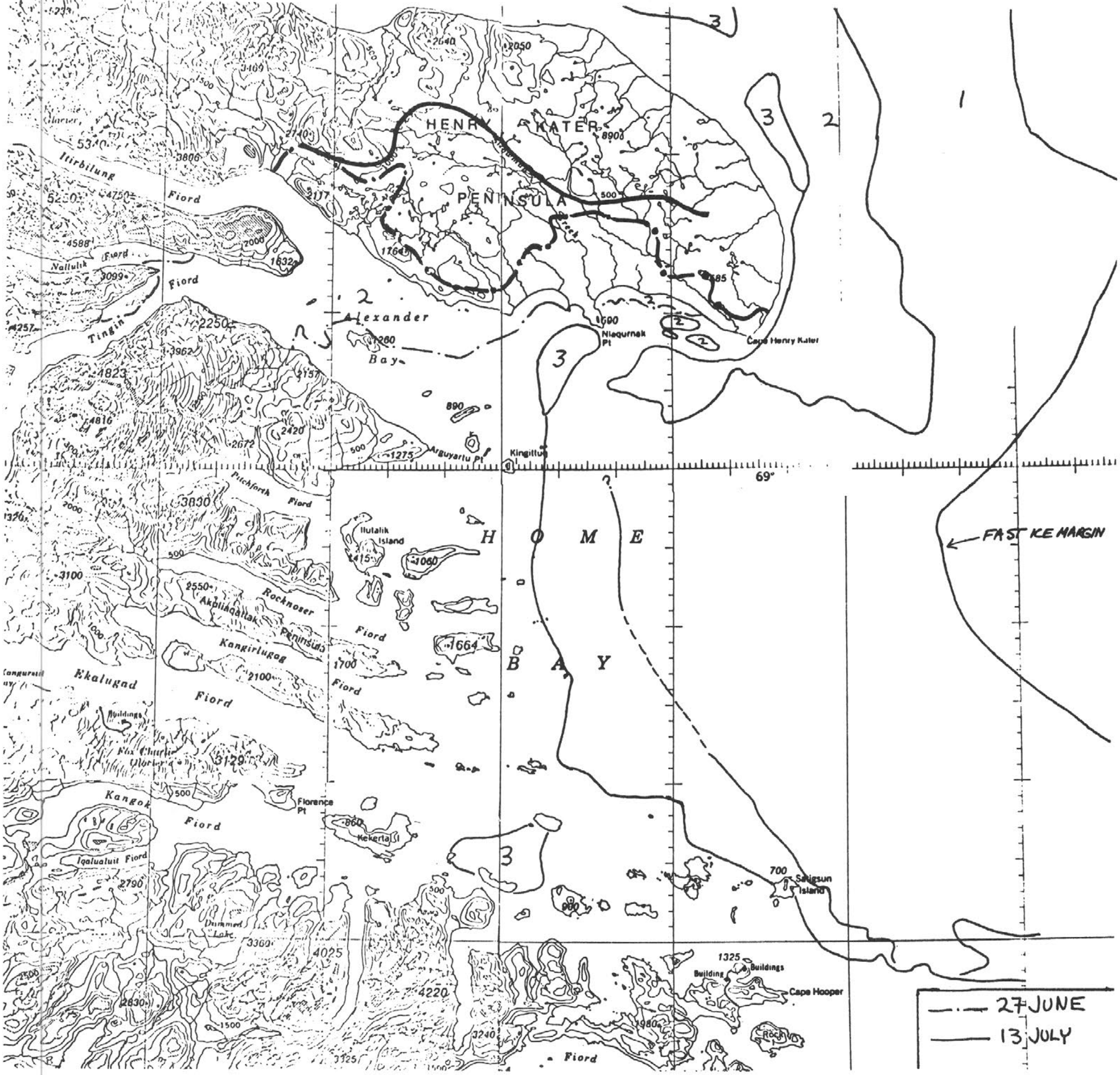
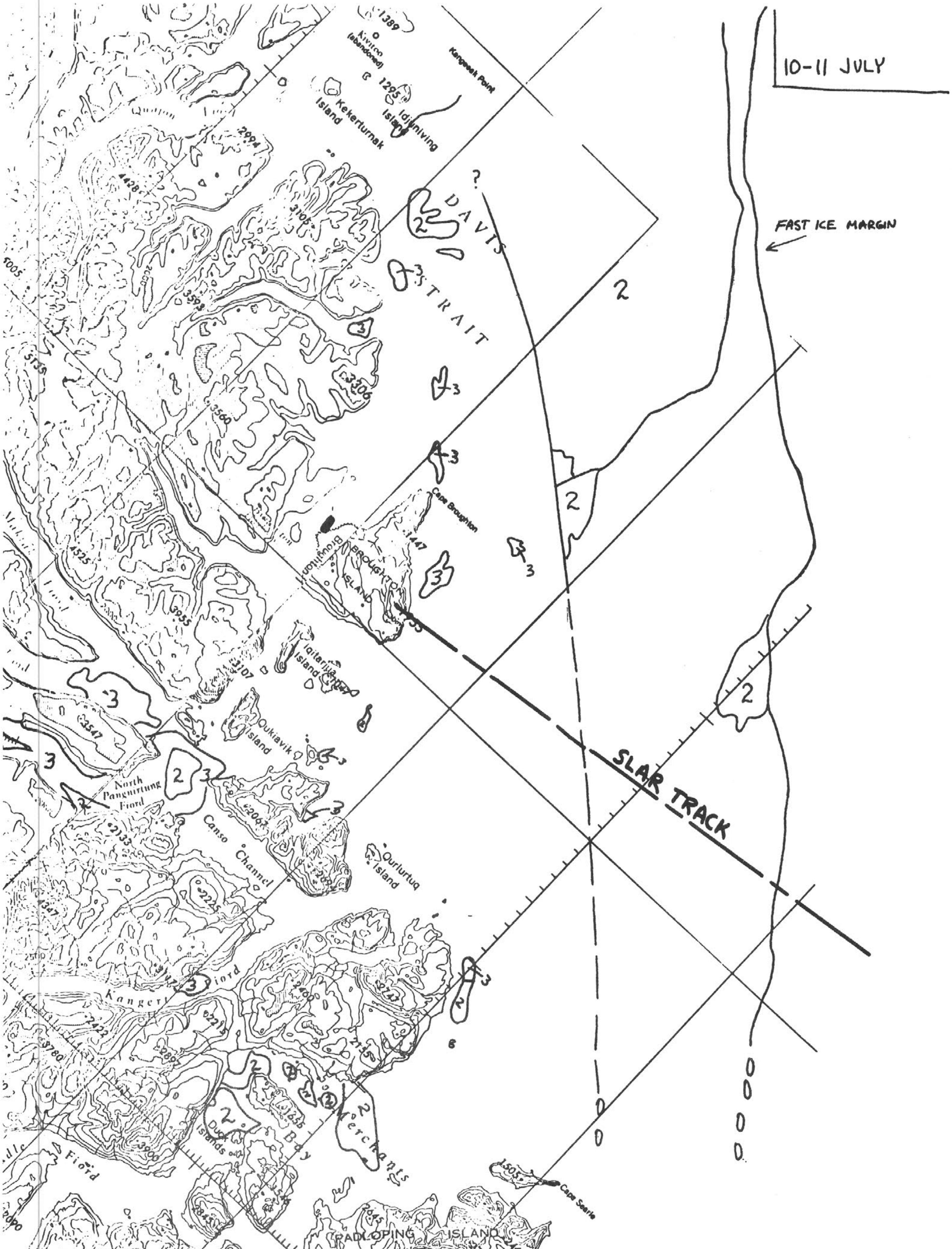

HENRY KATER
PENINSULA
Itirbilung Fiord
Nallulik Fiord
Tingin Fiord
Alexander Bay
Niaqurnak Pt
Cape Henry Kater
Arguyartu Pt
Kingittuq
69°
HOME BAY
FAST ICE MARGIN
Pitchforth Fiord
Ilutalik Island
Rocknoser Fiord
Akpiliaqattak Peninsula
Kangirlugag Fiord
Ekalugad Fiord
Buildings
Kangok Fiord
Iqalualuit Fiord
Florence Pt
Kekertal I
Dummer Lake
Satigsun Island
Building
Buildings
Cape Hooper
Rock
Fiord
27 JUNE
13 JULY

Figure 5.6. Details of fast ice composition from ERTS-1 and SLAR imagery, 10 and 11 July, 1973.



10-11 JULY
FAST ICE MARGIN
SLAR TRACK
DAVIS STRAIT
Kangeeak Point
Kivitoo (abandoned)
Idjuniving Island
Kekerturnak Island
Cape Broughton
Broughton Island
Igitarijuag Island
Oukiavik Island
North Pangnirtung Fiord
Canso Channel
Ourlurtuq Island
Kangert Fiord
Merchants Bay
Duck Islands
Padloping Island
Cape Searle

6. An Optical Contrast Enhancement Technique For Fast Ice - Pack and Ice - Cloud Boundary Using ERTS-1 MSS Imagery

R. L. Weaver

Introduction

A simple manual interpretive technique is presented here which enhances contrast between low cloud and sea ice and aids detection of individual large floes under close pack conditions in the Earth Resources Technology Satellite (ERTS-1) Multispectral Scanner (MSS)[1] imagery. This method also better defines pack or fast ice surface features over that attained from single MSS bands or simulated Color Infrared (CIR) composites; however, this may in part depend on the melt stage at the time of data collection.

The working hypothesis used in this analysis is twofold: 1) Surface features, for example, melt water puddles, pressure ridges, or ice-open water boundaries have unique spectral signatures which theoretically are differentiable in the grey scale changes of the multispectral imagery. 2) Contrast enhancement of the multispectral data keyed to a particular feature should therefore increase the detectability of that feature.

Past Work

Barnes and Bowley (1973) concluded in their initial survey of MSS data application to sea ice detection that the ice could be separated from cloud using several pattern recognition and reflectance interpretive keys. They suggested use of bands 4 (.5 - .6 um) and

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[1]For more information about the orbital and scanning system characteristics consult the ERTS-1 Data Users Handbook (1972).

7 (.8 - 1.1 μm) to differentiate between nilas (thin black to grey-white ice) and open water or to contrast thaw holes from deep surface melt puddles. In general, they found bands 4 and 5 best for determination of ice boundaries and band 7 best for ice feature interpretation.

Data and Methods

The 70 mm bulk processed MSS transparencies were combined by means of a color additive viewer[1] to make color multispectral composites. The MSS images were projected onto the ground glass screen of the color additive viewer and photographed with a 35 mm camera using Kodachrome II Professional Type A film to make the composite image. The 70 mm transparencies were produced from the original ERTS-1 data tapes by the Canadian Center for Remote Sensing (CCRS), Ottawa.

The frame used in this example (Figure 1) depicts sea ice southeast of Henry Kater Peninsula (69°, 19' N, 64°, 17' W) on the eastern Baffin Island Coast, N.W.T. Canada (ERTS-1 orbit 4949, 13 July 1973).[2] Henry Kater Peninsula is visible in the left hand center portion of the frame. Fast ice surrounds the peninsula and open water and pack ice of mixed concentration and floe size lie to the southeast.

Results

The fast ice margin and several giant floes are easily located in the band 4 (.5 - .6 μm) image. Low cloud is also visible above the pack ice in the center portion. Band 7 (.8 - 1.1 μm) provides more surface detail in the fast ice sheet. However, the separation of individual floes evident in band 4 are not present in band 7. The cloud-ice definition is also not as good.

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[1] Itek Corp., Lexington, Mass.

[2] Acquisition was from the Prince Albert Tracking Station (Saskatchewan) and the imagery reformated by CCRS.

By combining bands 4, 5, and 6 on the color additive viewer, a simulated color infrared image (CIR) is created. The imagery in this format does show increased contrast between the flooded and unsaturated areas of the fast ice sheet. The giant floe in the lower center portion is differentiated from the surrounding brash and smaller diameter floes. Little improvement in the ice-cloud contrast is noted.

Following the results of Barnes and Bowley (1973a and 1973b) a multispectral composite of bands 4 and 7 was made which accomplished a slight improvement in the cloud definition. In general, the information content was not greatly increased over that found in the CIR composite.

The best results were attained by combining a positive band 4 and a negative band 7 image (Figure 2). Contrasts between saturated and unsaturated surfaces and associated structural details of the fast ice were improved. Several lower reflectance areas to the south of Henry Kater Peninsula are more evident in the positive-negative composite.

The giant floes and many of the large floes embedded in brash or small floes are easily singled out. The cloud-ice separation is improved mainly due to increased contrast of the cloud shadow area on the pack ice surface.

Summary

Of the five single-band and composite image formats studied, it is concluded that the most information about ice-water contacts and surface features is found in the band 4 positive-band 7 negative composite. This technique also improves contrast between low cloud and pack ice by enhancing the cloud shadow.

More quantitative interpretation techniques such as point by point ratioing of the digital MSS data and optical density slicing of the 70 mm transparencies are being evaluated. The technique is also being applied to other stages of the fast ice melt sequence to estimate surface information content under less saturated surface conditions.

Acknowledgments

The author thanks the Colorado School of Mines Department of Geology, Golden for use of their color additive viewer. This research was supported by the Office of Polar Programs, National Science Foundation under grant number GV28218.

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1973a: Mapping Sea Ice from the Earth Resources Technology Satellite. Arctic Bulletin, National Science Foundation, Summer, 1973.

__________. 1973b: Monitoring Arctic Sea Ice Using ERTS Imagery, Proceedings Third ERTS Symposium. NASA/Goddard Space Flight Center, Greenbelt, Md.

Data Users Handbook.

1972: NASA-Goddard Space Flight Center, GE Document 71SD4249.

Figure 1. ERTS-1 MSS (Band 6) Frame showing
Home Bay, eastern Baffin Island, 13 July 1973

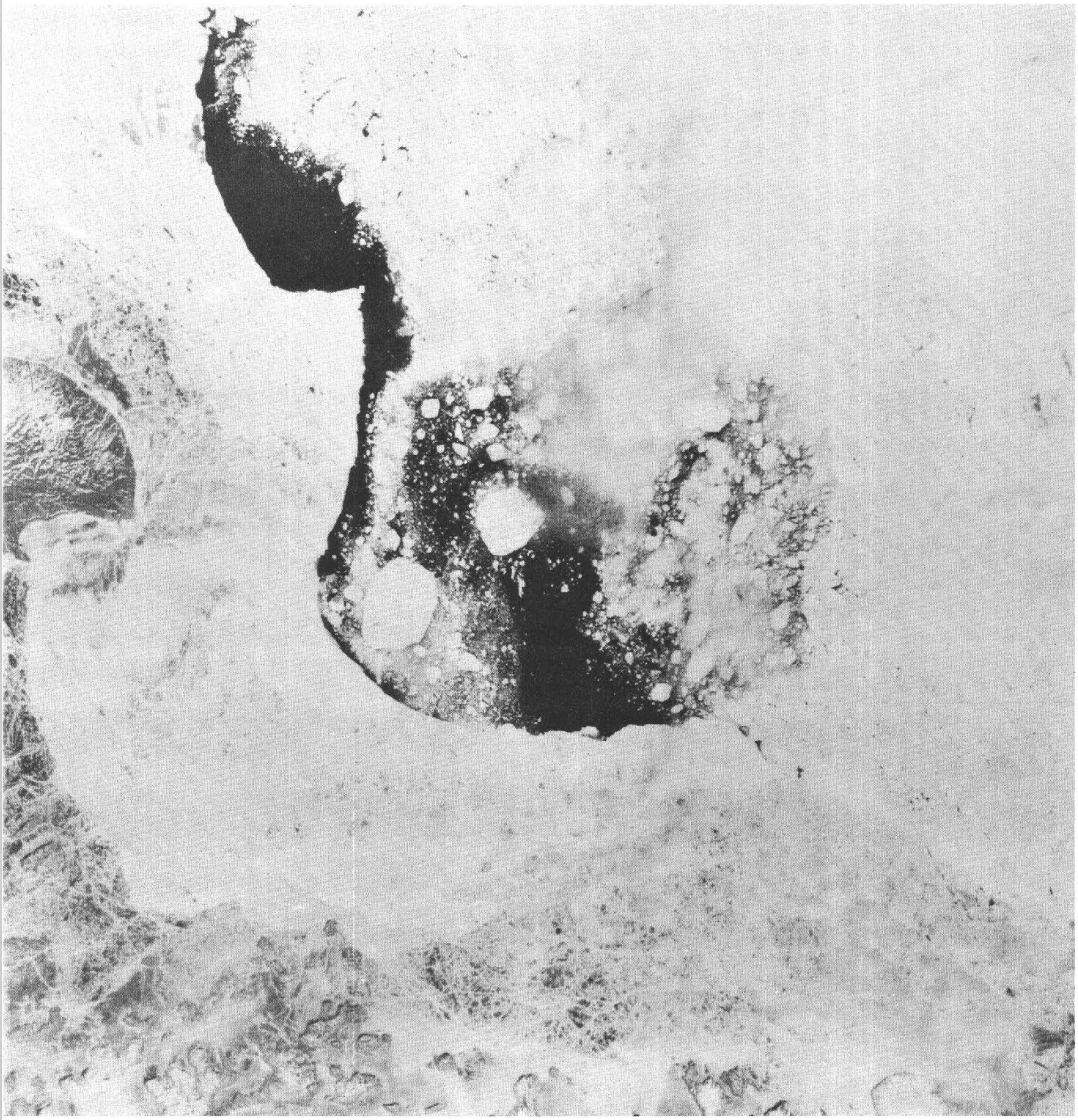

Figure 2. Black and White Print of Color Composite Derived from Positive Band 4 and Negative Band 7 Images for ERTS-1 MSS Frame Shown in Fig. 1.

7. Seasonal Variations in Temperatures and Salinities of Near-Surface Waters around Broughton Island, Eastern Baffin Island

J. D. Jacobs

Introduction

Seasonal changes in temperatures and salinities in the upper 100 m or so in Arctic waters occur in direct response to climatic conditions. Furthermore, the absolute salinity and stability of the water column affects the formation and growth of sea ice. In order to obtain basic information on the relationship of sea ice to climate, a program of oceanographic measurements was carried out in the vicinity of Broughton Island (67° 34' N, 64° 03'W), off the east coast of Baffin Island, during the period May through December, 1973, i.e. through breakup and subsequent freezeup of the annual ice cover.

Background

The coastal topography and submarine geomorphology of this part of the Baffin Island coast have been described by Løken and Hodgson (1971) and the oceanography of the region by Collin and Dunbar (1964). Detailed information on this coastal area is contained in the Pilot of Arctic Canada (Canadian Hydrographic Service, 1968) and associated hydrographic charts numbers 7053 and 7184.

The coastal zone is characterized by high relief and deep fiords, with numerous islands lying immediately offshore. The continental shelf is some 50 km wide in this area. The coastal highlands contain many ice caps and glaciers, 6000 km^2 Penny Ice Cap being the dominant feature. The surface waters along the western side of Davis Strait are Arctic waters with the possibility of some contribution from a westward setting branch of the West Greenland Current (Collin and Dunbar, 1964).

Broughton Island (Figure 7.1) is separated from the Baffin Island mainland by a 2 km wide strait of some 20 m minimum depth, referred to as "Broughton Harbor". The island lies 30-40 km north of a major fiord complex, and immediately south of the island a 400-500 m deep trough cuts the continental shelf. Waters to the north are considerably shallower. Tides are small at Broughton Harbor, the mean amplitude being 0.95 m, and of a "mixed" semidiurnal nature, i.e. two complete oscillations daily, of differing amplitudes (Canadian Hydrographic Service, 1973). The tide is observed to set northward through the strait at flood, consistent with the bottom topography. While the normal tidal range is small, during autumn storm periods, ledges in the vicinity of Cape Broughton which stand some 4 to 5 m above normal high water may be swept by waves.

The distribution of annual ice in the region is discussed by Weaver in this report and by Jacobs, et al (submitted). The fast ice area includes all of the fiords and inter-island areas and extends seaward beyond the 100 fathom (183 m) isobath. Freezeup occurs initially in sheltered waters around the first week of November and a sheet of some 1 m thickness and 10 km or more in extent is usually established by the end of December. By late May, the fast ice -- pack ice boundary may lie 20 km east of Broughton Island, with ice thicknesses of up to 2 m in the outer portions and from 1 to 1.5 m in the fiords (Figure 7.2). Breakup begins progressively from the fiord heads and from polynyas over shoals in mid-June, with the fast ice sheet becoming broken and mobile by mid-August in most years. Drift ice may persist in the area until freezeup in the subsequent winter.

Method

The program was basically one of measuring salinities and temperatures at selected locations throughout the period. Earlier attempts to measure salinities in the area using an inexpensive conductivity meter were unsuccessful due to the unreliability of the instrument. More acceptable instrumentation proved to be too expensive for the project budget and it was decided to rely on the reliable and inexpensive, but more tedious silver nitrate titration method (Strickland and Parsons, 1972). A Lamotte field kit[1] was used in the analysis, the samples being taken with a simple, but effective, sampling bottle (Figure 7.3). Temperatures were measured with a thermistor bridge[2] by immersing the thermistor in the water sample immediately upon retreival.

The accuracy of salinities determined by the titration method was estimated by analyzing 7 aliquots of a single sample, resulting in a standard deviation of 0.6 o/oo. As no comparison was made with standard sea water, the absolute accuracy is not known. Frequent calibration showed that temperatures were within $\pm$ 0.1 °C. Such accuracies in temperature and salinity measurement do not approach those of general oceanographic practice; however, for the purposes of showing relative differences in space and time, the methods used were considered acceptable.

A station was established over 200 m deep water off the southwest corner of Broughton Island (Figure 7.2), and regular sampling made to a depth of 100 m from May through November, 1973. In addition, repeated traverses were made to the head of Kingnelling Fiord both before and after breakup. Sampling was also done in North Pangnirtung Fiord to the south, in Broughton Harbor, and in the vicinity of Cape Broughton. About 300 samples were taken and analyzed during the period.[3]

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[1]Lamotte Chemical Co., Chestertown, Md.

[2]Atkins Technical, Inc., Gainesville, Fla.

[3]The author gratefully acknowledges the assistance of Yvonne Jacobs, who carried out the analysis.

Note: Reference to manufacturers' products does not imply institutional endorsement.

Results

Examination of temperature and salinty profiles for the station south of Broughton Island (Figures 7.4 and 7.5) reveals the magnitude of the seasonal variation and shows that the thermocline extends to below 50 m. Most samples were taken above 50 m. However, a total of 7 taken at 50-100 m at various times during the period had an average salinity of 32.1 o/oo (σ=0.5 o/oo), indicating that these are indeed Arctic waters.

Referring to conditions between the surface and 50 m, the seasonal pregression is as follows. At the end of the ice formation period, in mid to late May, the water column is nearly isothermal at - 1.5 to -1.7°C with a salinity of 32 to 33 o/oo, and is overlain by 1 to 2 m of ice (of salinity 5 to 7 o/oo) and possibly as much as 0.5 m of snow on the ice.

With the onset and advance of ablation, fresh water moves from the ice surface to form a thin layer just beneath the ice. In the fiords and coastal areas, runoff of meltwater is occuring and this water also moves beneath the ice. Because of its low salinity (hence, low density) the fresh water layer enhances the stability of the water column, inhibiting mixing. Even after breakup, so long as the drift ice remains compact enough to suppress wave action, this stratification persists. Figure 7.6 shows the progress of such mixing clearly, the upper 5 m remaining reasonably fresh well after breakup.

Stratification may persist in the fiords even when no ice remains and some wave action is present. Samples were taken in North Pangnirtung Fiord, which is some 50 km long and 4 to 5 km wide, and is fed by a system of rivers which drain part of the Penny Ice Cap and other ice bodies. Table 7.1 gives temperatures and salinities in the top 10 m for August 31, 1973, when no ice was present but runoff from the rivers was continuing. The entry of the Owl River at the fiord head was marked by a zone of high turbidity for a distance of some 5 km downfiord. Temperatures at the surface near the fiord head were some 3 to 4 °C higher than any midsummer diurnal maximum surface temperature observed on the outer coast suggesting that considerable heat is contributed to the coastal water by runoff from the land.

The maximum in mixing of the surface layer occurs in the autumn, the period of greatest storm activity. If the station south of Broughton Island is typical, it is evident that the dilution of the upper 50 m amounts to about 3 o/oo, i.e. the difference between a salinity of 32 o/oo in June and about 29 o/oo by autumn. An estimate of the relative importance of the contributions from melting sea ice and runoff from the land can be made by viewing the former feature as a 1.5 m fresh water stratum that becomes completely mixed throughout the 50 m layer. It is clear that this will not account for even half of the observed decrease in salinity, pointing to the importance of runoff.

Although frazil and thin nilas were observed to form on several occasions in late September and early October, this ice did not survive storm periods, and only in mid-November did general freezeup begin. Significantly, as Figure 7.4 shows, at the time of freezeup the entire water column to at least 50 m was isothermal at -1.5°C, the freezing point for seawater at the observed salinity,[1] suggesting that this is a necessary condition for freezeup to occur.

After freezeup the salinity of the column increases due to the precipitation of brine from the growing ice sheet and advection of salt water beneath the ice, the fresh water input from the land having ceased. As the salinity increases, the freezing temperature drops. Since convection is taking place due to the salinity and density inversion, the freezing temperature becomes the equilibrium temperature for the column, i.e. -1.7 to -1.8°C for the maximum salinities observed here.

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[1]An approximation to freezing temperature as a function of salinity that is accurate to within .02°C of published experimental values (Riley and Chester, 1965) is given by T_f(°C) = -0.0544 S(o/oo).

Conclusion

The results presented here, although approximate, nonetheless provide useful information on seasonal variations in seawater characteristics in the Broughton Island region. It remains to consider how representative a single year's measurements are or, in other words, how do these seasonal patterns vary from year to year?

In Section 5 of this report, it was shown that large interannual differences occur in the extent of the fast ice and in the amount of late-summer drift ice in the coastal area. The persistence of such ice through subsequent freezeup, as occurred in 1972, must certainly have some effect on mixing and, hence, the freezing temperature. Also, although no estimate has been made of actual runoff volumes from the land in the Broughton Island region, such information exists for Ekalugad Fiord, some 250 km to the north, where runoff differed by a factor of about 3 between a warm ablation season (1963) and the succeeding cold one (Church, 1970). Clearly, such large interannual variations will be reflected in coastal water salinities.

Thus, a warm summer will see a large relative contribution from runoff to dilution of the surface layers, while a cold ablation season will have less runoff but also less mixing due to the presence of drift ice throughout the autumn season. That the two effects are opposite should tend to smooth the differences in surface water stratification between warm and cold years.

Additional investigations of the coastal waters seem justified, preferably in conjunction with runoff studies. Such work would greatly enhance our understanding of the complex system of land, sea, ice, and atmosphere which the eastern Baffin Island coast represents.

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Jacobs, J. D., R. G. Barry, and R. L. Weaver, 1974. Fast ice in the Canadian Arctic, submitted to Weather.

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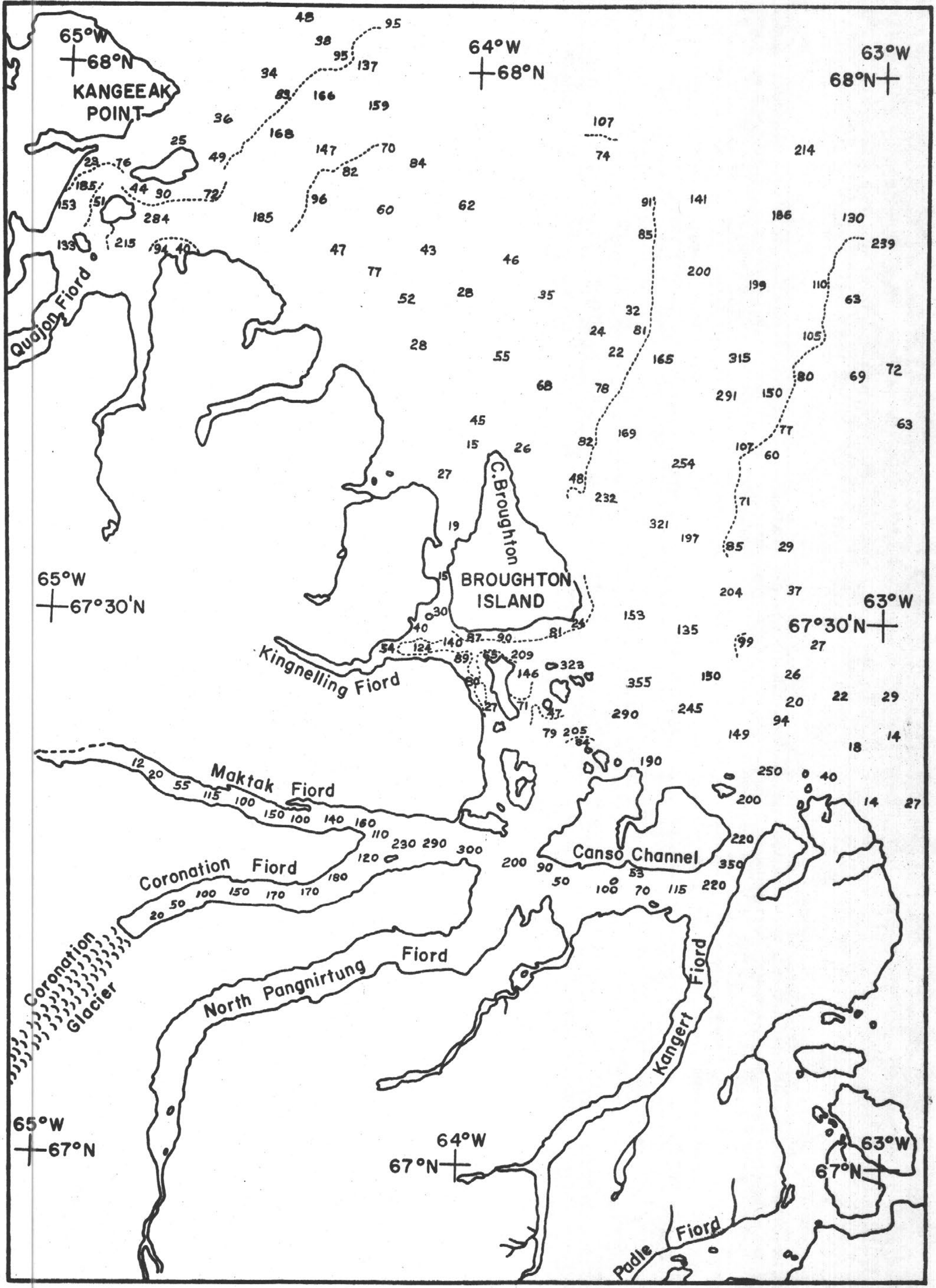
Riley, J. P. and R. Chester, 1965. Introduction to Marine Chemistry, London. Academic Press, 465 pp

Strickland, J. D. H. and T. R. Parsons, 1972. A Practical Handbook of Seawater Analysis, Bull. 167., Fisheries Research Board of Canada, Ottawa, 310 pp

Table 7.1 Salinities and temperatures measured in North Pangnirtung Fiord (67.0°N 64.5°W), August 31, 1973

	Fiord Head		5 km		mid-Fiord (20 km)		Mouth (50 km)	
	S(‰)	T(°C)	S(‰)	T(°C)	S(‰)	T(°C)	S(‰)	T(°C)
Depth (m)								
sfc	2.2	6.0	18.3	6.0	20.4	ND	23.0	3.7
1	20.0	4.7	20.9	4.5	21.0	ND	23.5	3.6
2	21.0	4.6	21.5	4.4	21.7	ND	22.9	3.6
5	21.1	4.5	22.3	4.2	24.1	ND	23.8	3.2
10	32.1	0.3	32.6	0.3	32.6	ND	33.4	1.8

Figure 7.1. Bathymetry of the Broughton Island Region Depths are in fathoms. The scale is approximately 1:500,000. (After Nautical Chart No. 7053, Canadian Hydrograpic Service).


65°W
68°N
KANGEEAK
POINT
64°W
68°N
63°W
68°N
Quajon Fiord
C. Broughton
BROUGHTON
ISLAND
65°W
67°30'N
63°W
67°30'N
Kingnelling Fiord
Maktak Fiord
Coronation Fiord
Canso Channel
Coronation
Glacier
North Pangnirtung
Fiord
Kangert
Fiord
65°W
67°N
64°W
67°N
63°W
67°N
Padle Fiord

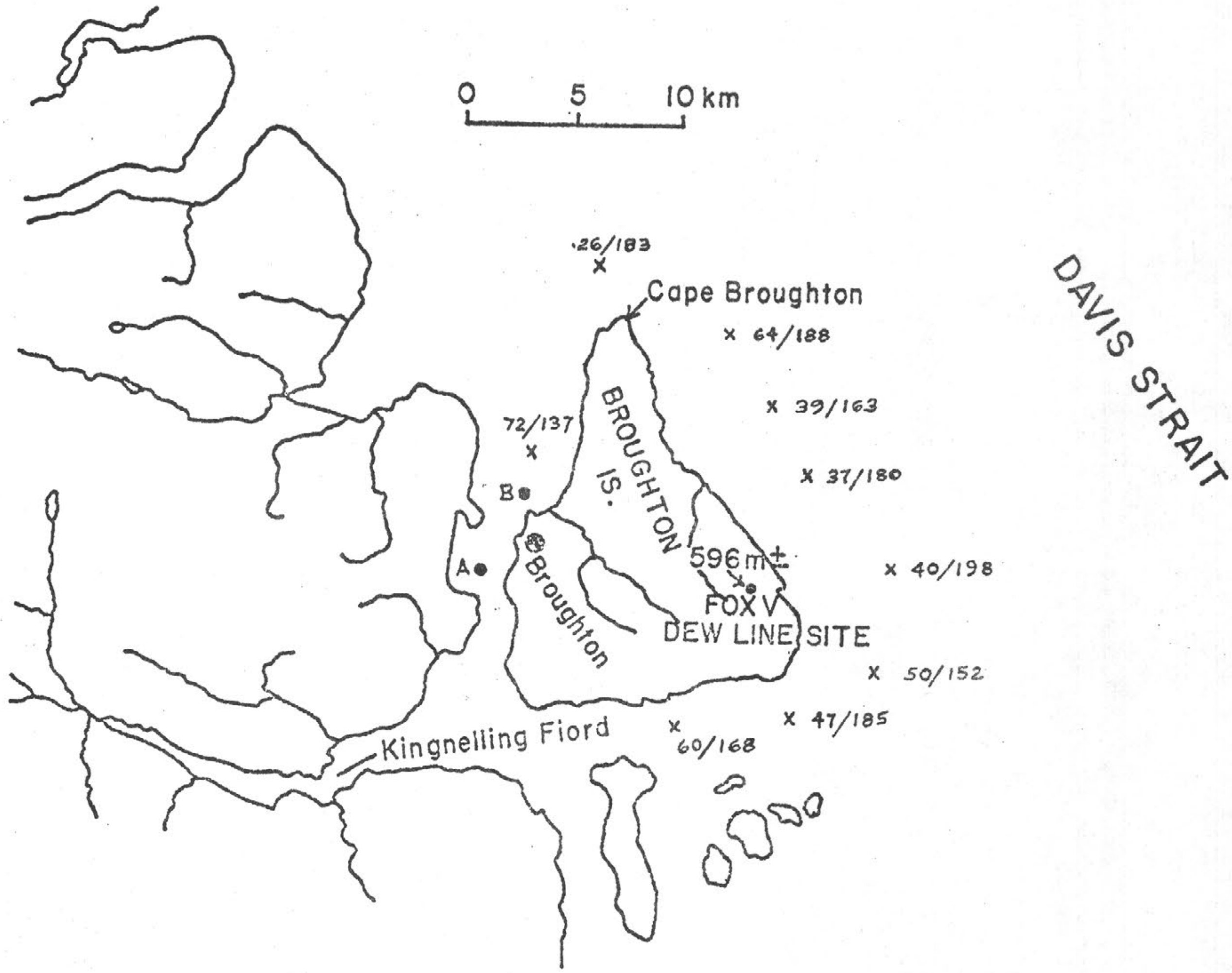


Figure 7.2. Snow depths and ice thicknesses (cm) measured on the fast ice in the vicinity of Broughton Island, early June, 1973.

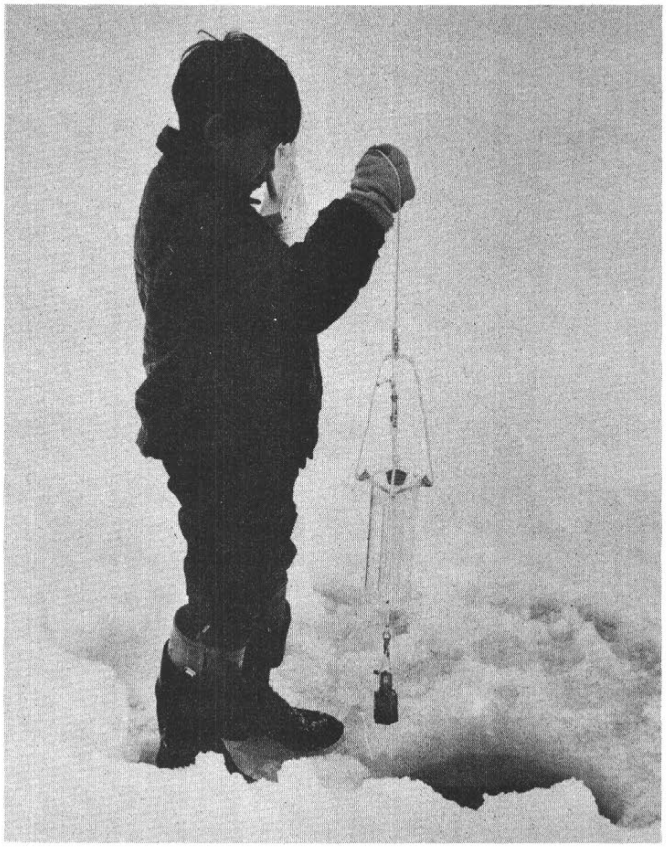


Figure 7.3. Lamotte sampling bottle being lowered through hole in fast ice, June, 1973.

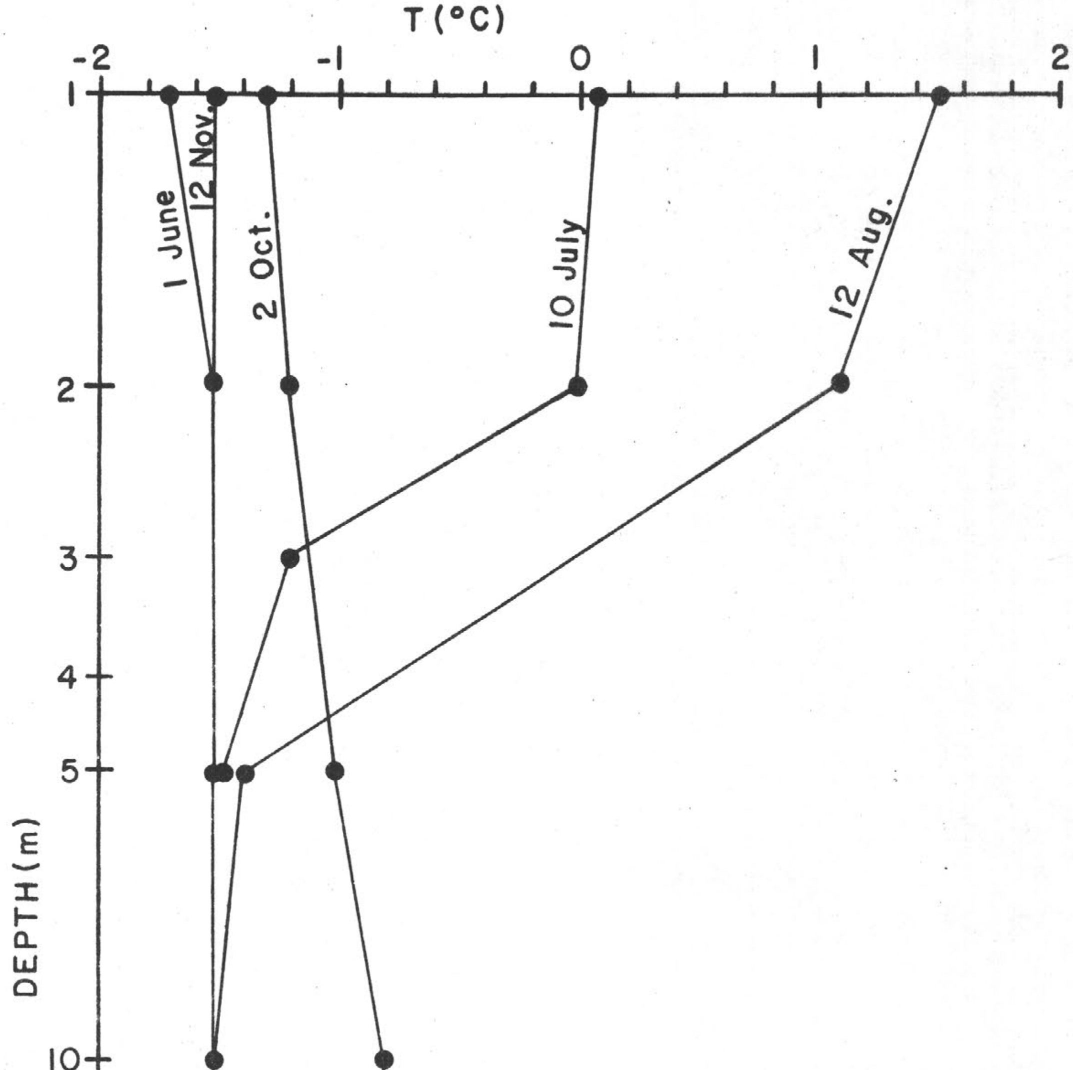


Figure 7.4. Temperature profiles for the oceanographic station south of Broughton Island.

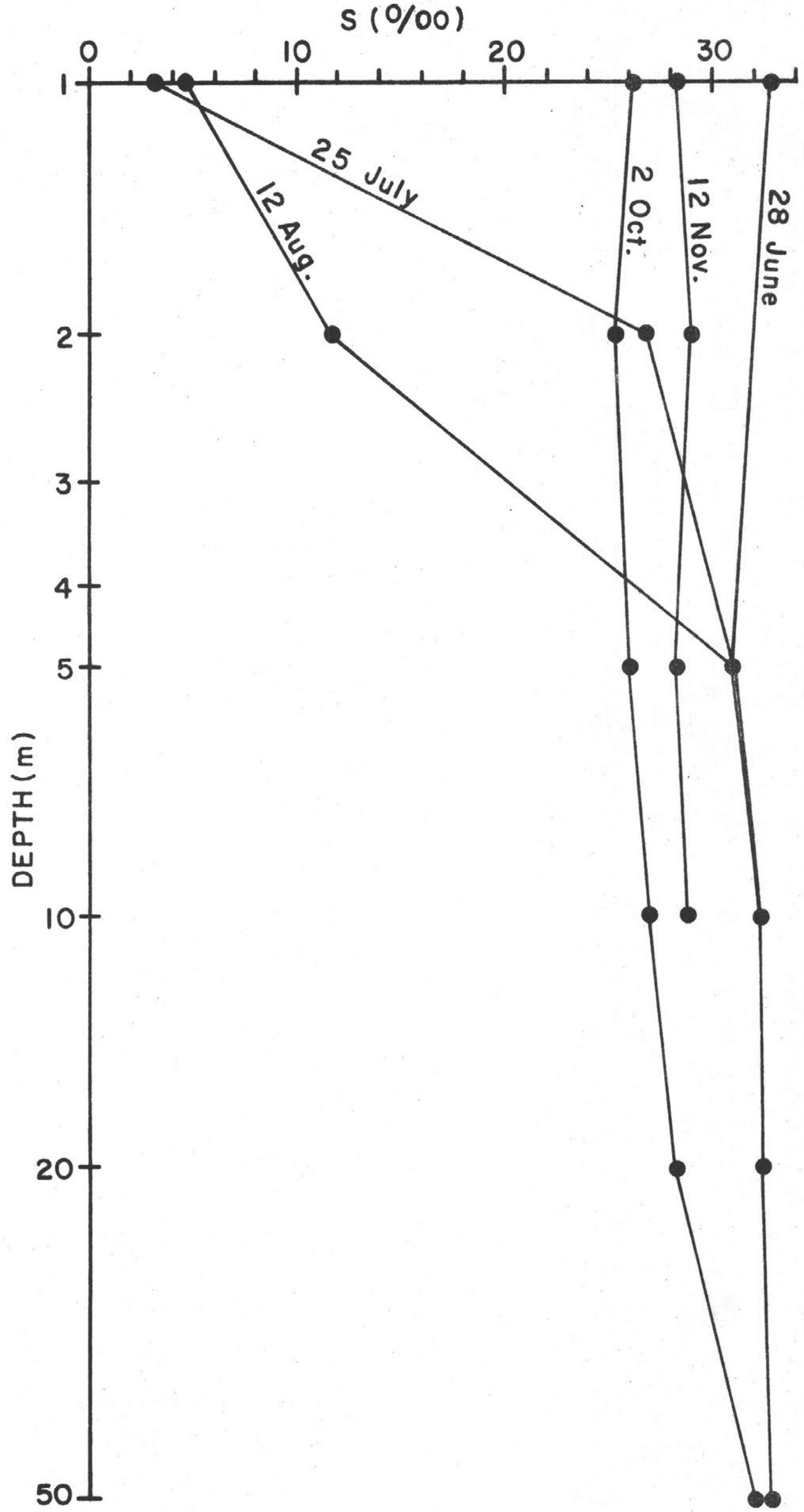


Figure 7.5. Salinity profiles for the oceanographic station south of Broughton Island.

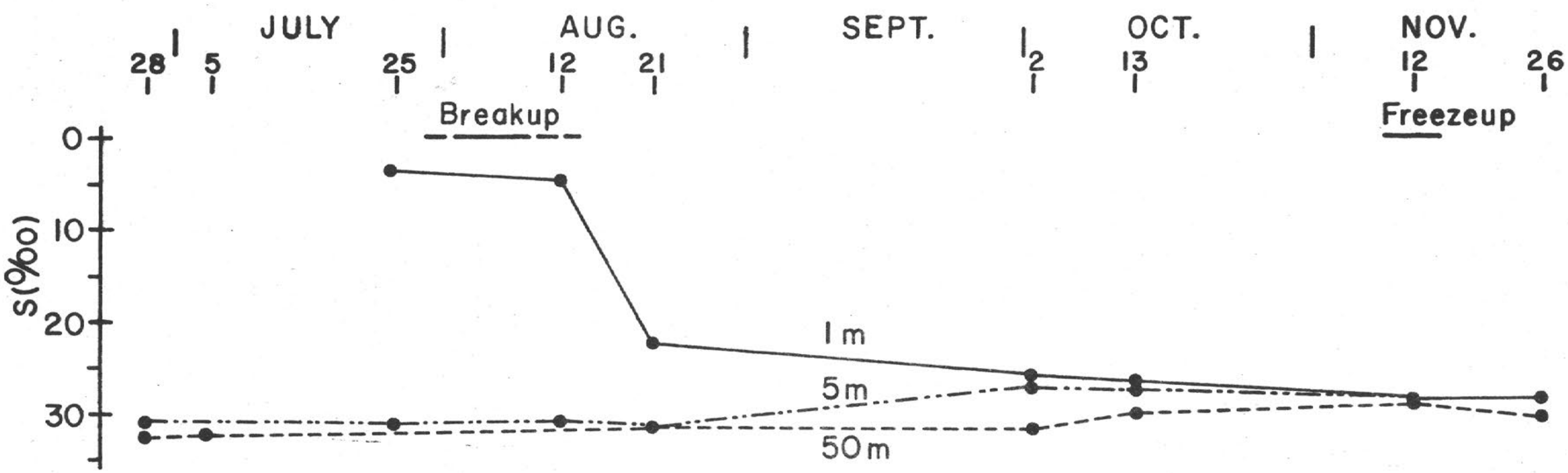


Figure 7.6. Time series of salinity measurements at 1, 5, and 50 m for the station south of Broughton Island.

8. Synoptic Activity, Climate and Ice Conditions for Summers 1971-73

R. G. Barry and J. D. Jacobs

The circulation conditions over the Baffin Island area during the three summers of 1971-73 are characterized descriptively in Table 8.1, based on the monthly analyses in Monthly Weather Review. The summers were quite different in general character with blocking (at 700 mb) in the first part of 1971 and in August 1973, compared with a deeper-than-normal 700 mb low and trough over Baffin Island - eastern Canada in 1972. In terms of the MSL circulation using the pressure pattern classification of Barry (1974) discussed in Section 3, Table 8.2 indicates that July - August 1971 and 1972 were not in fact substantially different from the 1961-70 mean conditions. In July-August 1973, however, there were fewer central and SW lows and more anticyclonic situations than for the decadal average. The variations in June are not very pronounced since they represent only ± 3 days, but at least June 1972 is shown to have been more cyclonic in character than 1971. June 1973 has a higher percentage of days with a central low (C1) and with anticyclonic easterly flow situations (A3).

The abnormally cool summer of 1972 is clearly demonstrated by the data in Table 8.3. Melting degree-days in 1972 totalled about half of those in 1971 and 1973 and the mean June-August temperature at Broughton Island was -1.2°C in 1972 compared with 2.6°C in 1971 and 1.7°C in 1973. This event was not related in amy simple manner to airflow patterns (Table 8.2). The warmer conditions in August 1973 can be related to the more frequent anticyclonic situations (cf. Table 3.7) but differences in type frequencies between 1971 and 1972 were small apart from June. The main difference between June 1971 and 1972 is probably attributable to additional days with A6 ridge pattern giving northerly airflow in June 1972. There is also no evidence of substantial differences in solar radiation (Table 8.4). Indeed, there was more global solar radiation in July 1972 than July 1971 if the whole month is considered. The net radiation data, which refer to a tundra surface, also show little or no difference between July 1971 and 1972.

Precipitation amounts (Table 8.5) show considerable variation among the three years but no trend is evident with respect to the normal. Both total amounts and relative proportions of rain and snow are generally consistent with temperatures and airflow patterns. Thus, June 1972, with cold northwesterly flow, had below normal snowfall and no rainfall. May and June 1973, on the other hand, saw well above normal snowfall and (for May) rainfall reflecting the enhanced vigor of the circulation during those months. One obvious effect of such abnormal spring snowfall is to retard ablation on both land and sea, as was observed to be the case in 1973.

It should be emphasized that the cool conditions in 1972 were also experienced in Keewatin and the Queen Elizabeth Island, so that it was not simply a local phenomenon. Undoubtedly, the broad 700 mb pattern of a persistent low and a southward trough with northerly flow components over the eastern Canadian Arctic provides the general setting, but the conditions also reflect a continuation of a cooling trend in summer temperatures in Baffin Island and the Canadian Arctic Archipelago noted by Bradley (1973 a, b) and the parallel increased persistence of pack-ice in Baffin Bay during late summer in the 1960's (Dunbar, 1972).

The severity of ice conditions in the Home Bay area in summer 1972 (the worst in living memory of the Eskimo population of Broughton Island), and to a lesser extent in 1973, is evident from the maps presented in Section 5. Summaries in the Marine Observer, vols. 42-44 (R.M.S. 1972, 1973; K.J. 1974) emphasize the residual effects of the cold 1971-72 and 1972-73 winters on pack ice conditions in this sector in the subsequent summers, coupled with anomalous northerly wind components over Baffin Bay during summer.

The temperature records for Broughton Island show that the period January-March 1972 was 4°C below normal whereas during the same period in 1973 it was only below normal in February and in 1971 temperatures overall were above normal.

A colder than normal winter in Baffin Bay means that more ice is produced to drift southward, resulting in a more extensive pack. Year-to-year differences in fast ice thickness are not particularly great due to the asymptotic nature of the growth rate curve with increasing thickness (cf. Section 4). Moreover, the effect of lower winter temperatures upon the "cold content" of the fast ice and, hence, the amount of additional heat needed to melt it is small. As with the pack ice, the extent of the fast ice sheet may be greater in a cold winter, both by reason of the lower air temperatures and consequent rapid formation of new ice, and the lower frequency of disturbances in such a winter leading to less disruption of the floe edge. In general, however, for the fast ice, summer weather conditions appear to be the main determinant of ice severity in a particular year.

Wind direction will affect the extent to which the pack and fast ice are held along the coast. A detailed study for the immediate Home Bay area shows that the estimated daily geostrophic wind at 68°N, 65°W, in terms of onshore/offshore components[1] was as follows:

	June	July	August
1971	Neutral	3:1 offshore	Neutral
1972	No data	Neutral	2:1 onshore
1973	Neutral	Neutral	2:1 onshore

These data are less definitive than might have been expected but they are broadly supportive of the inferences from the large-scale regional.

[1]The drift velocity of ice is 0.01-0.03 Vs (the surface wind speed) and 30° to the right of the surface wind direction. This is approximately parallel to the geostrophic direction. For this section of coast, 320°-090° is onshore, 140°-270° is offshore and the other directions are indeterminate.

The discussion illustrates the complexity of interaction between regional climatic and ice conditions and the larger scale circulation controls and air - sea interaction. It is very difficult to assign orders of importance to the processes considered, since there are too few years of observations as yet to formulate a model linking the seasonal trends of the different phenomena. Kellogg (1974) has illustrated the uncertainties involved even in putting correct signs on some of the air - sea - ice feedback processes. However, on the basis of our research over the past four years, we can summarize qualitatively the relative contributions of the various climatological parameters to summer sea ice conditions along the eastern Baffin Island coast. Clearly air temperature coupled with windspeed (and direction) are the dominant factors in the early part of the season. The radiative term becomes important only after the snow surface has "ripened" and its albedo decreased. Once puddling begins, the amount of incoming solar radiation that is absorbed increases greatly and radiation (and cloudiness) becomes important. The comparison between the summer of 1972 and 1973 illustrates this well: in 1972, strong northerly winds and low temperatures in June and early July retarded ablation in spite of a high proportion of clear days in the latter part of that period. In 1973, by contrast, frequent periods of strong warm-air advection caused rapid ablation of an unusually heavy snowpack. Although there was frequent cloudiness, breakup was achieved. Clearly, global scale processes are ultimately responsible for the major year-to-year differences in regional conditions, described here. There is therefore a clear need to examine the nature of the regional/global interactions.

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TABLE 8.1.

700MB Circulation Over the Eastern Canadian Arctic

	1971	1972	1973
June	Blocking ridge over Greenland. Low over northern Labrador - Ungava.	Deeper than normal low near Baffin Island.	Trough to SW from Davis Strait. Spells of ridging 12-16, 26-30 June.
July	Reduction in blocking. Nearly stationary low northern Ungava.	Normal low nearly stationary over Baffin Bay with trough towards Great Lakes.	Polar low; trough to S from Davis Strait and ridge over Keewatin.
August	Deep polar low NW of Axel Heiberg Island. Weak trough in Davis Strait.	Low over northern Baffin Bay with near normal trough southward.	Ridge over Baffin Island except 21-25 August.

TABLE 8.2.

Frequency of MSL Pressure Patterns Using

Type Groups of Barry (1974) Classification (Percent)

Type Group	June			July-August			
Cyclonic	1971	1972	1973	1971	1972	1973	1961-70
C1 Central Low	3.3	23.3	30.0	19.4	16.1	9.7	15.6
C2 Davis Strait Low	10.0	10.0	0	9.7	8.1	6.4	9.4
C3 Baffin Bay Low	0	13.3	13.4	8.1	8.1	11.3	4.7
C4 SW Low	6.7	0	3.3	4.8	6.4	1.6	10.2
C5 SW Low and Others	20.0	13.4	3.3	4.8	12.9	11.3	9.2
	40.0	60.0	50.0	46.8	51.6	40.3	49.1
Anticyclonic							
A1 Anticyclone	26.7	10.0	10.0	6.4	4.8	14.5	10.0
A2 Ridge	3.3	10.0	13.3	9.7	9.7	17.8	8.4
A3 Ridge, Low to S.	20.0	0	26.7	16.1	16.1	6.4	10.3
A4 High in E., Low to W.	0	3.3	0	9.7	8.1	11.3	9.8
A5 Ridge, Baffin Bay Low (NE flow)	3.3	3.3	0	0	1.6	6.4	3.7
A6 Ridge, Baffin Bay Low (N-NW flow)	6.7	13.4	0	11.3	8.1	3.2	8.7
	60.0	40.0	50.0	53.2	48.4	59.6	50.9

TABLE 8.3.

Summary of Summer Temperature Conditions, Broughton Island

A. Mean temperature (T) and departure from normal (ΔT) (°C)

	1971			1972			1973		
	(a) T	(a) (ΔT)	(b) T	(a) T	(a) (ΔT)	(b) T	(a) T	(a) (ΔT)	(b) T
June	-0.3	+0.5	1.1	-5.4	-4.6	-0.5	-1.7	-0.9	1.3
July	5.6	+0.4	3.2	1.1	-4.1	2.4	2.0	-2.6	3.1
August	2.4	-1.2	4.1	0.6	-3.1	1.7	4.8	+1.1	4.8
Sept.	-0.2	+1.6	1.0	-3.4	-1.7	-0.8	-1.7	+0.1	0.2

B. Melting degree days (°C) with respect to daily mean temperatures > 0°C

	1971		1972		1973	
	(a)	(b)	(a)	(b)	(a)	(b)
June	36	39	0	15	33	45
July	177	100	63	75	79	96
August	92	126	59	62	154	148
Sept.	13	40	14	27	22	22
	318	305	136	179	288	311

(a) = DEW line (581m)

(b) = Broughton Village (10 m)

TABLE 8.4.

Summer Radiation Conditions, Broughton Village[1]

Solar Radiation

	1971 Total $(cal\ cm^{-2})$	1971 Mean $(cal\ cm^{-2} day^{-1})$	1972 Total	1972 Mean	1973 Total	1973 Mean	Clear sky Theoretical Total	Clear sky Theoretical Mean
June 16-30	8369	558	7689	513	8311	554	11741	783
July 1-15	9052	603	7137	476	7360	490	11327	755
16-31	4648	290	7975	498	4938	308	10975	686
Aug. 1-15	----	---	5892	393	5584	372	8818	588
16-31	----	---	(2863)	(260)[2]	3674	230	7578	474

Net radiation (Tundra surface)

	1971 Total	1971 Mean	1972 Total	1972 Mean	1973 Total	1973 Mean	Clear sky Theoretical Total	Clear sky Theoretical Mean
June 16-30	4638	309	4103	274	3737	249	----	---
July 1-15	4030	267	3617	241	3912	261	----	---
16-31	2742	171	4003	250	2316	145	----	---
Aug. 1-15	----	---	2527	168	2519	168	----	---
16-31	----	---	(910)	(66)[2]	1525	95	----	---

[1]Radiation measurements are from the Broughton Village site; net radiation is measured over a representative dry tundra surface. (The radiation measurements will be discussed in a later report.)

[2]16-26 August only.

TABLE 8.5.

Ablation Season Precipitation (cm. w. e.)
for Broughton Island (elev. 581 m), 1971-1973

	1971 r	1971 s	1972 r	1972 s	1973 r	1973 s	Normal r	Normal s
May	0	1.07	0	1.47	.86	11.91	T	3.05
June	0	1.19	0	1.57	0	6.22	.48	2.56
July	1.87	.68	1.60	.94	1.98	2.18	.94	.22
August	4.34	.15	.61	3.05	1.45	T	1.45	.79
September	2.26	4.93	0	2.97	0	1.55	.51	3.86
Totals	8.47	8.02	2.21	10.00	4.29	21.86	3.38	10.48

Appendix

INSTAAR's Facility at Broughton Island

Since this Institute began activities in eastern Baffin in 1969, equipment and instrumentation have continued to accumulate at Broughton Island. Therefore, in 1972 a small building was purchased (with funds from NSF GV-28218) to provide accommodations and storage space, as well as a base for meteorological observations.

The building is a prefabricated wood and metal structure, 16 by 30 feet, containing one large common room and a small bedroom and storage area (Figure A.1). Additional storage space is in sheds at either end of the building. Water and fuel oil are provided to the house by the municipal service; cooking, bathing, and toilet facilities are minimal. The house can accommodate 3 - 4 people on a continuous basis and plans are being made for an addition to the building to provide more sleeping and work space.

The house is located some 100 feet back from a low bluff overlooking Broughton Harbor on the west side of the village. Although originally a good site for meteorological purposes--and still otherwise convenient--houses have begun intruding to the north and south, and relocation of the observing site may eventually be called for.

Apart from the intensive measurements described elsewhere in this report, the University's basic meteorological program at Broughton Island consists of the cooperative climatological station located east of the Hudson's Bay Company store and the instrumentation at the INSTAAR house, which includes a continuously recording anemometer (10 meters), a microbarograph, and a hygrothermograph in a shelter at the base of the mast. In the absence of a regular observer, occupants of the house (currently a couple who teach at the village school) maintain the instruments and provide brief daily comments on weather and ice conditions.

Field equipment at Broughton includes tents and camping equipment, radios, snowmobiles, boats and motors, as well as surveying instruments and other special equipment for various measurements programs. Repair and maintenance of this equipment is done by members of the summer field parties.

Travel to and from Broughton Island is provided by Nordair via Frobisher Bay, with flights usually twice-weekly. Heavy materials, supplies in quantity, etc., can be delivered by arrangement with Hudson's Bay Company or other suppliers on the annual sealift (September-October).

Under present costs, operating expenses relating to the house alone are about $100 per month. Food and basic supplies are obtainable from the Hudson's Bay Company store and, with reasonable care, subsistence can be provided for about $3.00 per man-day.

Research groups from other universities can be accommodated at cost provided space is available. Inquiries in this regard should be directed to Dr. J. T. Andrews, Associate Director of the Institute.

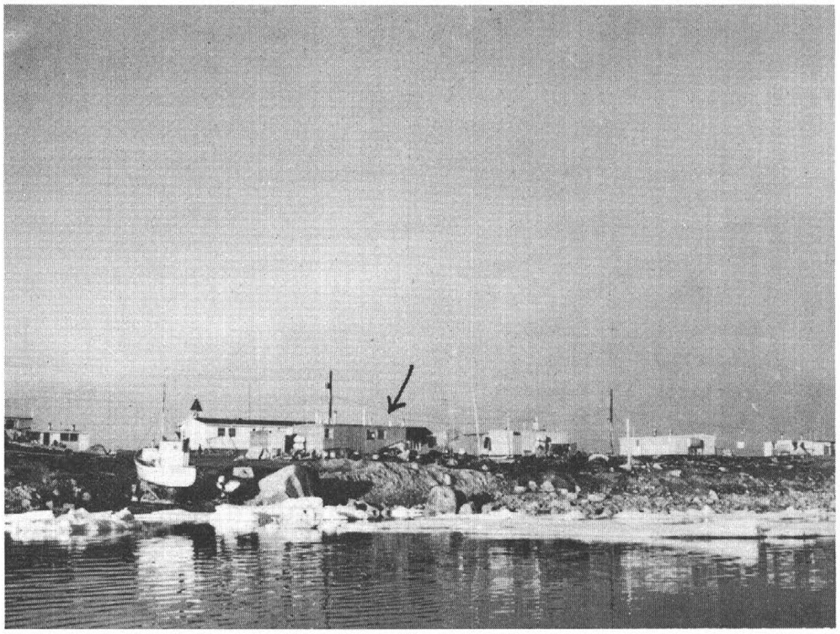

Figure A.1. INSTAAR's facility at Broughton Island viewed from the Harbor.

Errata: Figure 3.2. Figure labeled C4 should be relabeled C6, C5 relabeled C4 and C6 relabeled C5.

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