

Seasonal Variations of Sea Ice Extent in the Davis Strait-Labrador Sea Area and Relationships with Synoptic-Scale Atmospheric Circulation

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ABSTRACT. Using published data sources for south-eastern Baffin Island, Ungava Bay and the northern Labrador Sea area, a study of the general patterns of sea ice growth and decay has been made for the years 1964 to 1974. From a comparison of individual years an "early" and a "late" pattern of both ice advance and ice retreat are recognised. Mean daily sea-level pressure patterns for June-July and for October-mid-November are examined and a relationship is established between the type of ice advance or retreat pattern and the synoptic circulation over the area. In the years of early ice retreat there is an increased frequency of southerly airflow over the region. Strong winds and the advection of warm air leads to the more rapid removal of the ice compared to years of late ice retreat. Similarly for the years of early ice advance there is an increased frequency of northerly and westerly flow, bringing lower temperatures and an influx of second-year and multi-year ice into the area.

INTRODUCTION

Satellites and routine ice patrol flights of the Canadian Atmospheric Environment Service (A.E.S.) have made available large amounts of data for the Davis Strait-Labrador Sea area (Fig. 1). Little of the information however has appeared in a summarised form. Some dates on ice clearance are given for specific sites in the *Pilot of Arctic Canada* (Canadian Hydrographic Service, 1968) and the *Labrador and Hudson Bay Sailing Directions* (Dept. of Environment, 1974). Schematic representation of summer and winter ice conditions are given by Dunbar (1954, 1972) and a brief description of ice conditions further north in Jacobs *et al.* (1975). This area is now becoming increasingly important in view of active developments with respect to offshore resources. In this respect, reconnaissance studies of the coastal environments of south-east Baffin Island, Ungava Bay and northern Labrador have recently been undertaken to assess their susceptibility to possible contamination by marine oil slicks, Barry *et al.* (1977). On average, sea ice is present in this area for up to 40 weeks of the year in the Davis Strait and for 30 weeks off the northern Labrador coast. Patterns of sea ice melt and accumulation have been examined to determine how they may affect the dispersal of an oil spill throughout the study area. Results of this study pertaining to ice advance and retreat are presented here and then the relationship of the ice conditions to the synoptic pressure patterns are examined.

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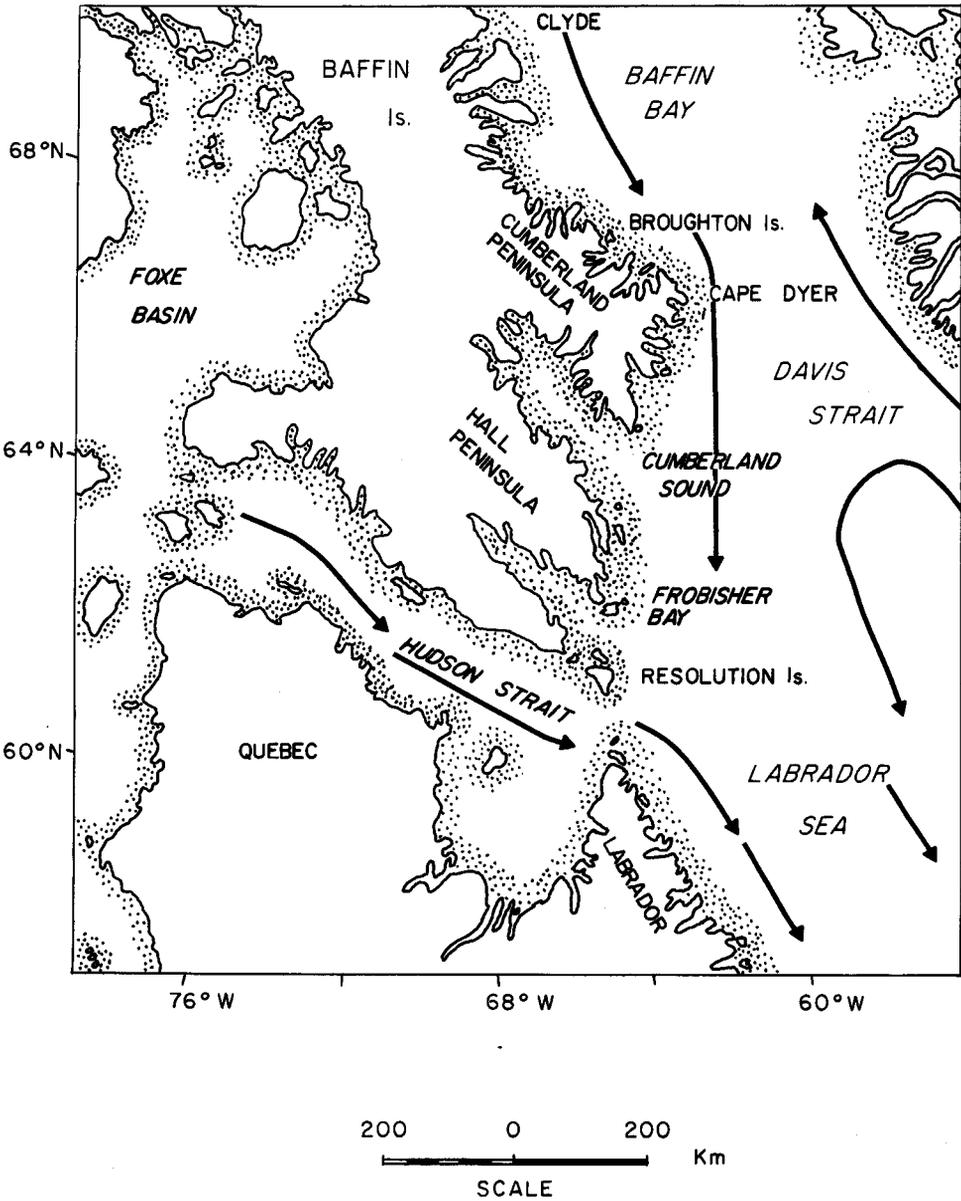


FIG. 1. Index to place names mentioned in the text. Arrows indicate the direction of ocean surface currents. (After Dunbar, 1951).

TABLE 1. Grouping of years according to ice conditions

ICE PATTERN	YEAR
Early ice advance	1964; 1965; 1969; 1970; 1972
Late ice advance	1966; 1967; 1968; 1971; 1973; 1974
Early ice retreat	1965; 1966; 1967; 1968; 1969; 1974
Late ice retreat	1964; 1970; 1971; 1972; 1973

DATA AND METHODS

Ice limits and concentrations for sequential dates have been compiled using the Canadian A.E.S. annual *Ice Summary and Analysis* for 1964-1971 and the A.E.S. *Southern Historical* charts for 1972-1974. For individual years, changes in the position of the open water boundary throughout the summer months have been mapped and used to depict the annual pattern of ice retreat. Ice advance patterns were similarly obtained by plotting the first appearance of ice and the increasing areal extent of ice with time. Using these data generalised patterns of ice melt and accumulation have been identified for each year and the individual patterns examined for similarities from year to year. On this basis an "early" and a "late" pattern of both ice advance and ice retreat can be recognised. The years are then grouped according to these patterns (see Table 1). This paper analyzes these patterns and examines their possible relationship to sea-level atmospheric circulation conditions over the area using an objective pressure pattern catalog (Barry and Keen, 1978).

ICE CONDITIONS

a) *Retreat*

Figs. 2 and 3 illustrate the two patterns of summer ice retreat as shown by the spread of open water throughout the area. In all years the Labrador coast is generally the first area to be clear of ice. In the south there is open water by 25 June but along the northern Labrador coast there can be a three week delay in clearance in late ice years (Fig. 2). Further north, off the Hall and Cumberland peninsulas this has extended to a delay of nine or ten weeks in late years. For years with the late pattern (Fig. 2), ice remains as far south as Hall Peninsula until late September. Final clearance does not occur until mid-October and in some years, such as 1973, residual ice remained off Cumberland Peninsula into the following winter. In contrast to this, Figure 3 shows the pattern of early ice retreat. In this type of season total clearance is achieved by mid-August.

A second major difference between the early and late ice years is in the spatial pattern of retreat. Years with late ice retreat tend to have a south to north sequence of ice retreat. Conversely, years with early ice retreat tend to show a meridional pattern, clearing from east to west, in the Labrador Sea and Davis Strait.

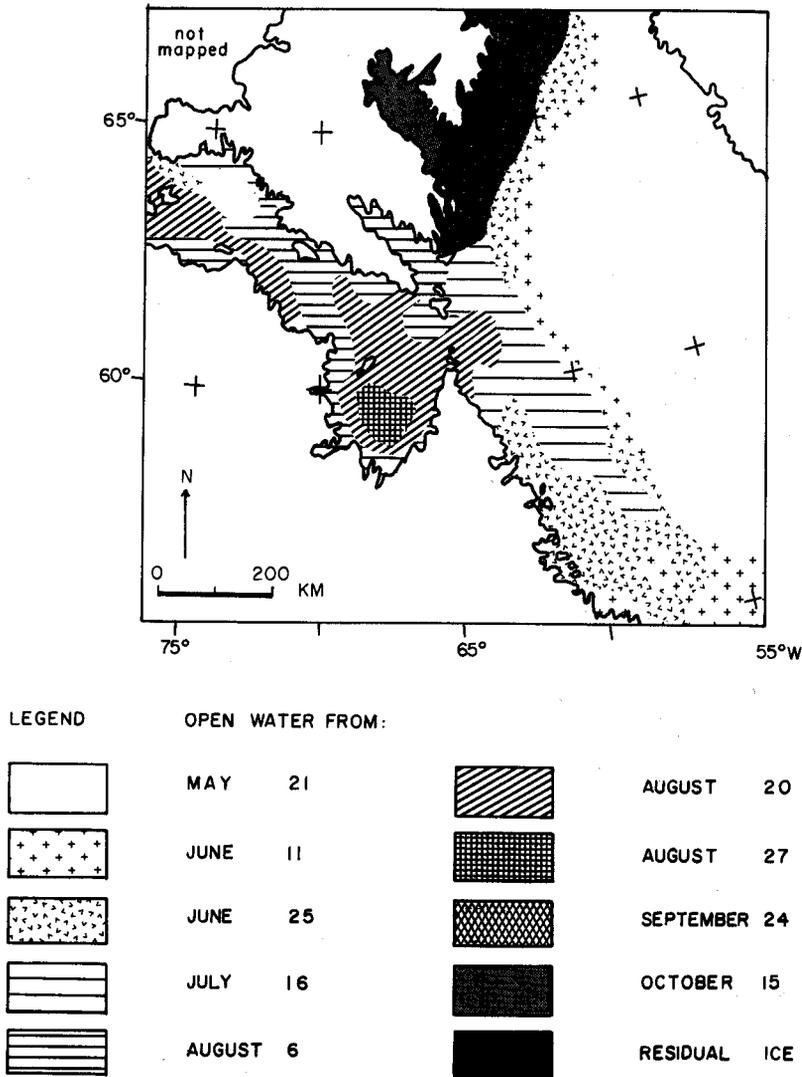


FIG. 2. "Late" pattern of ice retreat, illustrated by the 1973 ice season.

b) *Advance*

The pattern of early ice advance, Figure 4, shows ice developing off Cumberland Peninsula by 22 October. Ice then spreads southwards to Resolution Island occupying Cumberland Sound and Frobisher Bay by 19 November. By this date there are also large concentrations of ice in Hudson Strait and Ungava Bay. The pattern of late ice advance on the other hand, often shows ice only just beginning to form around Cumberland Peninsula by this date, although some years do have new ice forming down to Frobisher Bay at this time (Fig. 5).

The charts in the annual *Ice Summary and Analysis* (Environment Canada, 1964-1971) end on 19 November and the pattern of ice accumulation after this date cannot be determined from these data. An examination of NOAA VHRR satellite imagery for 1975-1977 and the *Historical Charts* (Environment Canada, 1971-1974, which continue later in the year, indicates some tendency for late ice years to have new ice growth in Frobisher Bay and Ungava Bay with ice spreading seaward. Early ice years, on the other hand, tend to be characterised by ice spreading south in Davis Strait and east along Hudson Strait from Foxe Basin. In both cases and Labrador coast is generally the last to freeze. Although the ice margins in Figures 4 and 5 indicate the pack ice limit, the limit of 7/10 ice also lies very close to these margins with only small areas of less ice concentration at the edges in most years. The early and late years do however show differences in the type of ice present. Late ice years tend to be characterised by the growth of new ice during this early part of the

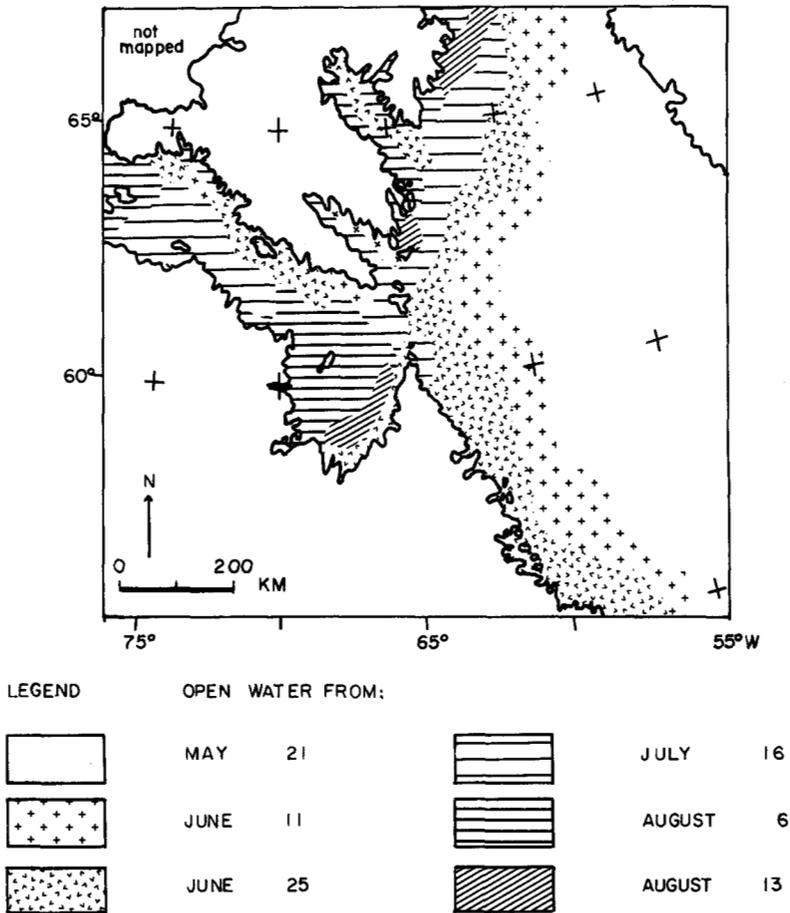


FIG. 3. "Early" pattern of ice retreat, illustrated by the 1965 ice season.

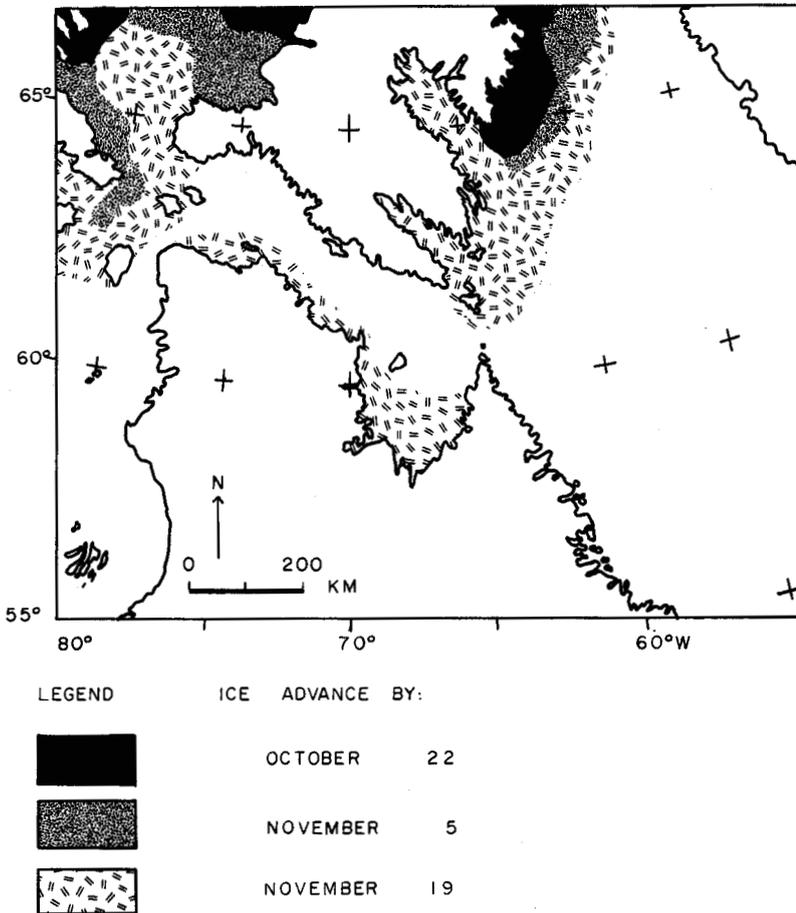


FIG. 4. "Early" pattern of ice advance, illustrated by the 1970 ice season.

accumulation season. In early ice years on the other hand, there is often a large influx of second-year or multi-year ice from Baffin Bay to the north and Foxe Basin to the west, in addition to the growth of new ice along the coast.

c) Comparison

Table 1 shows the number of years in each of the groups. For both the ice advance and the ice retreat periods, the division between late or early patterns is roughly equal. From the table it would appear that ice conditions in the advance and retreat periods are independent of each other. That is, late ice retreat in the summer is not necessarily followed by early ice advance in the following winter, similarly early ice advance is not necessarily followed by late ice retreat in the following summer.

There is a clear differentiation between both sets of early and late patterns, particularly for the ice retreat period. All years of early ice removal are totally clear by early-to-mid August. Conversely, late ice years always show delayed

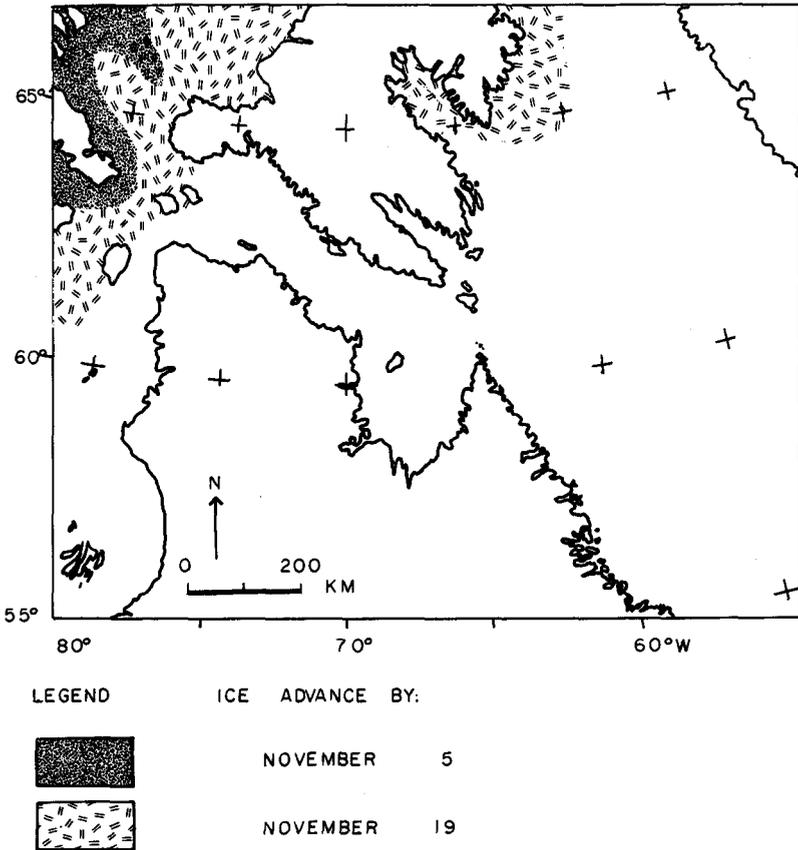


FIG. 5. "Late" pattern of ice advance, illustrated by the 1966 ice season.

clearance of Ungava Bay, with large concentrations of ice remaining well into September between Frobisher Bay and Cumberland Peninsula.

For the ice advance period there is more variability within the two groups. Some years have ice accumulation around Hall Peninsula by 19 November and, therefore, fall somewhere between the early and late ice advance positions. In these cases ice occurrence is generally due to new ice growth. There is little transport of second or multi-year ice from the north and the years are assigned to the late ice advance category. It should be noted however, that irrespective of the general pattern of ice accumulation, it is likely that shore-fast ice will form earlier along much of the coast, although there are few data to test this.

SYNOPTIC CONDITIONS

An objective classification of synoptic sea-level pressure patterns for the region has been developed on a daily basis for the years 1946-1974, (Barry and Keen, 1978). This catalog has been used to determine the frequency of each

synoptic type for June-August, corresponding to the ice retreat period, and for mid-October-November, for the ice advance period. The types have been grouped according to their direction of airflow over the Labrador Sea, in the case of the ice retreat season, and over northern Davis Strait for the ice advance season. On this basis the types are grouped into eight classes corresponding to flow from the eight cardinal points of the compass. The percentage occurrence of each class has been calculated for each year and the years grouped according to the type of ice pattern identified in Table 1.

The similarity of the synoptic conditions for the years in each group, and the differences between the groups, has been tested using discriminant analysis. The test show that the two pairs of groupings are significantly different at the 5 per cent level (using an F test) for the ice advance period and at the 1.5 per cent level for the ice retreat period. A stepwise discriminant analysis of the wind classes shows that easterly and north or westerly airflow contributed most to the groupings in the ice advance season. The years of late ice advance have more flow from the east and less from the north or west, relative to the years of early ice advance. The most frequent synoptic type occurring with easterly flow has a low over northern Quebec and high pressure north of Baffin Island (type 2 in the synoptic typing scheme). The most frequent type with northerly flow is type 1, with a low over Davis Strait, and with westerly flow, type 15, with a low centered over northern Cumberland Peninsula. (See Fig. 6). The number of days with easterly flow during October-mid-November increases, on average, from 14 to 42 from early to late ice years. Similarly the number of days with northerly or westerly flow increases, on average, from 30 to 44 between late and early ice years, for the same period.

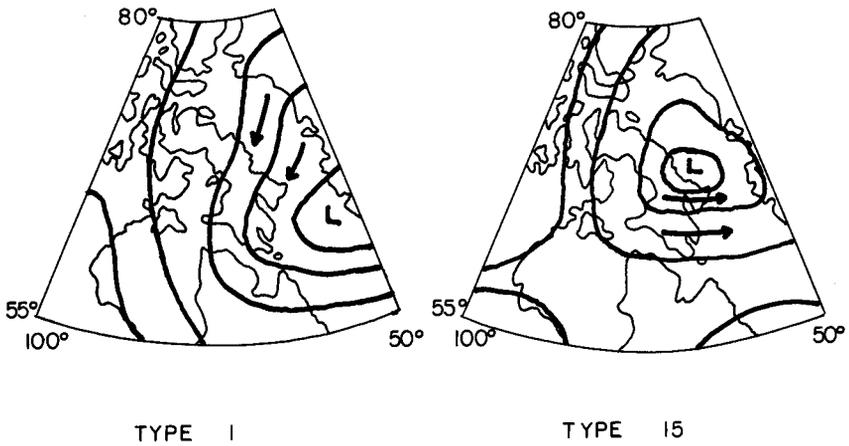
For the ice retreat period, the years of early ice retreat have more southerly airflow. The types with southerly airflow that have the greatest difference in their frequency of occurrence between early and late ice years are type 11, with a low over Foxe Basin and type 20, with lows over northern Quebec and northern Baffin Bay and a ridge over Davis Strait (Fig. 7). During June-August the number of days with southerly flow decreases, on average, from 27 to 19 between early and late ice years.

DISCUSSION

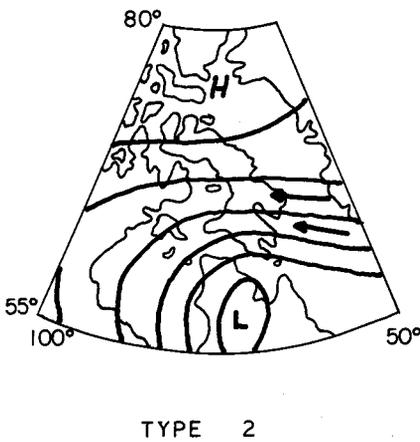
The analysis has shown that years with similar ice conditions have particular synoptic characteristics, indicating that there may be some relationship between atmospheric circulation and the type of ice advance or retreat pattern. The causal links between the meteorological conditions associated with a particular synoptic type and their effect on ice conditions, in terms of energy budgets, ice drift, etc., have not been examined in this study, although synoptic relationships relating to ice motion are routinely employed in the analyses of the Canadian Ice Central. Other work, for the Beaufort Sea (Rogers, 1978) and for Baffin Bay (Barry and Jacobs *et al.*, 1978; Keen, 1977) indicates that summer temperature has the greatest influence on the ice

ablation. If this type of relationship also applies to ice conditions in this area, the implication is that, in early summer, the advection of air from the south results in higher temperatures, leading to more rapid ice ablation. Thus an increased frequency of southerly flow causes earlier ice retreat.

The data, however, do not indicate the origin of the air affecting the region. It may be that in early summer water surfaces to the south are warmer than the land surfaces to the north and west, or more probably, that cyclones resulting in a southerly flow over the region have an origin over southern



MOST FREQUENT IN YEARS OF EARLY ICE ADVANCE



MOST FREQUENT IN YEARS OF
LATE ICE ADVANCE

FIG. 6. Most frequent synoptic types with northerly and westerly airflow, (1 and 15) and easterly airflow (2), for October-mid-November. (After Barry and Keen, 1978).

TABLE 2. Displacement of the summer 700 mb. trough for June, July and August (1964-1974)

EARLY ICE RETREAT 700 mb. TROUGH		LATE ICE RETREAT 700 mb. TROUGH	
YEARS	DISPLACEMENT	YEARS	DISPLACEMENT
1965	3.5° East	1964	5.5° East
1966	2.5° East	1970	9.0° East
1967	1.5° East	1971	8.0° East
1968	4.0° East	1972	10.0° East
1969	8.0° East	1973	11.5° East
1974	5.0° East		
MEAN	4.1° East	MEAN	8.8° East

south-east Baffin Island area are often associated with the passage of a low pressure system across central or southern Baffin Island. He illustrates this with examples from 1973 where, over a three day period near the end of June, cyclonic conditions caused a general warming of 10° to 16°C along the coast from Cape Dyer to Clyde. The progression of the system through the area caused a decrease in solar and net radiation, but rapid ablation occurred due to the increased advection of sensible heat from the south. This was repeated in mid July and again in early August. The July case has been examined in greater detail by LeDrew (1976) using a numerical model based on the steady state omega equation.

During the summer, pressure gradients in this region are generally weak. The steeper gradients however, are found with the low pressure systems, such as types 11 and 20 in Figure 7. Thus not only do these patterns cause increased ablation by the advection of warmer air, but the higher wind speeds may also assist in the more rapid removal of ice following the breakup of the pack.

In years of late ice retreat the pressure gradients tend to be fairly weak, the possible contribution of the wind in the removal of the ice is therefore much reduced. More important however is the reduced frequency of the low pressure systems referred to above. There are fewer days with warm southerly airflow, resulting in a slower rate of ablation. With weaker pressure gradients and a slower rate of ablation, the rapid removal of the ice does not occur and the ice tends to remain for longer periods over much of the area, particularly in Ungava Bay and in the vicinity of Cumberland Peninsula.

Analysis of the synoptic patterns for the ice advance period suggests that, assuming temperature to be an important controlling factor, then air crossing the water surfaces to the east should be warmer than that arriving from the land surfaces to the west, which are usually snow covered by this date. For

example, Barry and Keen (1978) show that with type 2, (figure 6), which is most frequent in late ice advance years, there is a $+1.7^{\circ}\text{C}$ temperature departure from the mean at Broughton Island (64°W , $67^{\circ}30'\text{N}$), for October-November. By comparison, types 1 and 15 (Fig. 6), which are most frequent in years of early ice advance, have temperature departures of -1.0°C and -1.6°C , respectively.

Type 2 shows that, as well as being warmer, airflow from the south to south-east will also tend to act in opposition to the southward flowing current in the Davis Strait (see Fig. 1). This may help to delay the southward spread of the pack and thus most of the early ice accumulation is by new ice growth in the more sheltered bays and inlets.

Conversely, with types 1 and 15, wind flow is from the north or west. This brings lower temperatures and also helps to bring pack ice down into Davis Strait from Baffin Bay and into Hudson Strait from Foxe Basin. This helps to explain the more rapid spread of ice and the tendency for more second-year and multi-year ice to be present in the years of early ice advance, compared to the years of late ice advance.

SUMMARY

Published data sources of ice conditions for the years 1964-1974 are used to determine the general patterns of ice advance and retreat in the Davis Strait and the northern Labrador Sea area. From this an "early" and a "late" pattern of both ice advance and ice retreat have been identified. The occurrence of the different patterns is associated with changes in the type of synoptic circulation over the area. (See table 3).

Years with early ice advance have more northerly and westerly airflow and less flow from the east, relative to years of late ice advance. The increased northerly and westerly airflow in the early ice advance years results in lower temperatures and an increased influx of second and multi-year ice into the region from Baffin Bay and Foxe Basin. In years of late ice advance the influx of second-year and multi-year ice is reduced and most of the early ice accumulation is by new ice growth in the more sheltered bays and inlets.

Similarly years of early ice retreat are characterised by synoptic conditions giving rise to increased southerly airflow in the summer. This results in the advection of warm air from the south and this, along with relatively strong pressure gradients and stronger winds, causes the rapid removal of the ice from the region. Conversely, years with late ice retreat have fewer days with southerly winds. The rate of ablation is reduced and ice remains for longer periods, particularly in Ungava Bay, Cumberland Sound and off the coast of Cumberland Peninsula.

The difference for the summer season of ice retreat can also be related to the relative displacement of the 700 millibar trough over the eastern Canadian Arctic. Years with early ice retreat have less easterly displacement of the trough than years of late ice retreat.

TABLE 3. Summary table showing relationship of the ice advance or retreat patterns to the synoptic conditions

ICE PATTERN	POSITION OF THE 700 mb TROUGH	SYNOPTIC CONDITIONS	EFFECT ON THE ABLATION ACCUMULATION OF THE ICE
Early ice retreat	Over Baffin Island	Pressure patterns have relatively strong west-east gradients resulting in strong winds and the advection of warm southerly air	Rapid ablation by the advection of warm air. Rapid removal of ice by strong southerly winds
Late ice retreat	Over Baffin Bay	Weaker pressure gradients with a reduced frequency of southerly winds.	Lower rate of ablation. Ice remains for a longer period, particularly in Ungava Bay and around Cumberland Peninsula.
Early ice advance		High frequency of patterns resulting in cold northerly and westerly flow.	Low temperatures cause rapid ice accumulation. Northerly and westerly winds bring second-year and multi-year ice into the area from Baffin Bay and Foxe Basin.
Late ice advance		Increased frequency of airflow from the east bringing above average temperatures	High temperatures delay the formation of ice. There is little influx of second-year or multi-year ice. Most early ice formation is by the growth of new ice in sheltered locations.

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