Edited by
Ian Stirling
and
Holly Cleator

Polynyas in the Canadian Arctic

Occasional Paper
Number 45
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Service canadien de la faune

Recurring polynya in the area of Dundas Island and northern Queens Channel on 19 June 1973. The dark area is open water (photo: Can. Centre for Remote Sensing)

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Contents

Introduction

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Polynyas are areas of open water surrounded by ice. They vary in size and shape, and may be caused by a variety of factors, the most important of which are currents, tidal fluctuations, wind, upwellings, or a combination of these forces. In terms of their biological significance, recurring polynyas (those that occur at the same time and place each year) are the most important. Consequently, they will be dealt with most extensively in this volume. There are two categories of recurring polynyas: those that remain open throughout the winter, and those that may be ice-covered through the coldest months in some years. In the latter category, open water appears in the spring, usually by late March or early April, when the first migrating marine mammals and birds arrive.

In addition to the classical type of localized recurrent polynyas, there are extensive systems of shoreleads throughout the Arctic where variably sized areas of semi-permanent open water are maintained largely by offshore winds and, to a lesser degree, by local currents. These lead systems may be frozen during part of the winter, particularly during periods of calm or onshore winds. Nevertheless, they are among the first areas in which open water occurs in the spring. Because these leads parallel shorelines, they tend to be linear in shape and therefore differ slightly from the somewhat restrictive technical definition of a polynya. However, shoreleads are recurrent and predictable in their location, and are among the areas in which open water is found most consistently during winter and early spring. Because of these factors, shorelead systems are of enormous biological importance and are discussed in the papers that follow.

The association between marine mammals and birds and the occurrence of open water, including leads, has been reported upon consistently since the first explorers entered the Arctic and, later, the Antarctic. More specifically, concentrations of birds and mammals along the interface of the ice edge and the open water have also been noted often. Beyond these rather anecdotal comments, however, few quantitative data have been collected. Consequently, little progress has been made toward gaining an understanding of the ecological significance of polynyas to individual species.

In the Canadian Arctic, the distribution of recurring polynyas is quite localized (Fig. 1) and their combined areas account for a relatively small proportion of the total arctic marine habitat. Nonetheless, the influence of polynyas and shoreleads on the survival of viable populations of marine birds and mammals appears to be profound. Despite their obvious biological importance, most polynya areas are threatened with extensive disturbance and possible pollution as a result of proposed offshore petrochemical exploration and year-round shipping. In several areas, more than one type of project may be undertaken simultaneously. Unfortunately, at the present time, we cannot adequately evaluate the effects of such disruptions. We simply have not conducted enough baseline research to have a quantitative understanding of the ecological processes that may be unique to polynya areas. It is clear, however, that many important decisions will have to be made in the near future.

Fortunately, in some areas at least, we still have variable amounts of lead time in which to conduct baseline studies. In other areas large-scale activities are, or soon will be, underway. This will provide unique opportunities to quantitatively assess the effects of such activities upon the marine environment. Through maximizing these opportunities to monitor natural and man-made changes in the marine ecosystem, we may be able to develop some predictive capability to aid in future environmental assessments. However, it cannot be emphasized too strongly that the available time is running out.

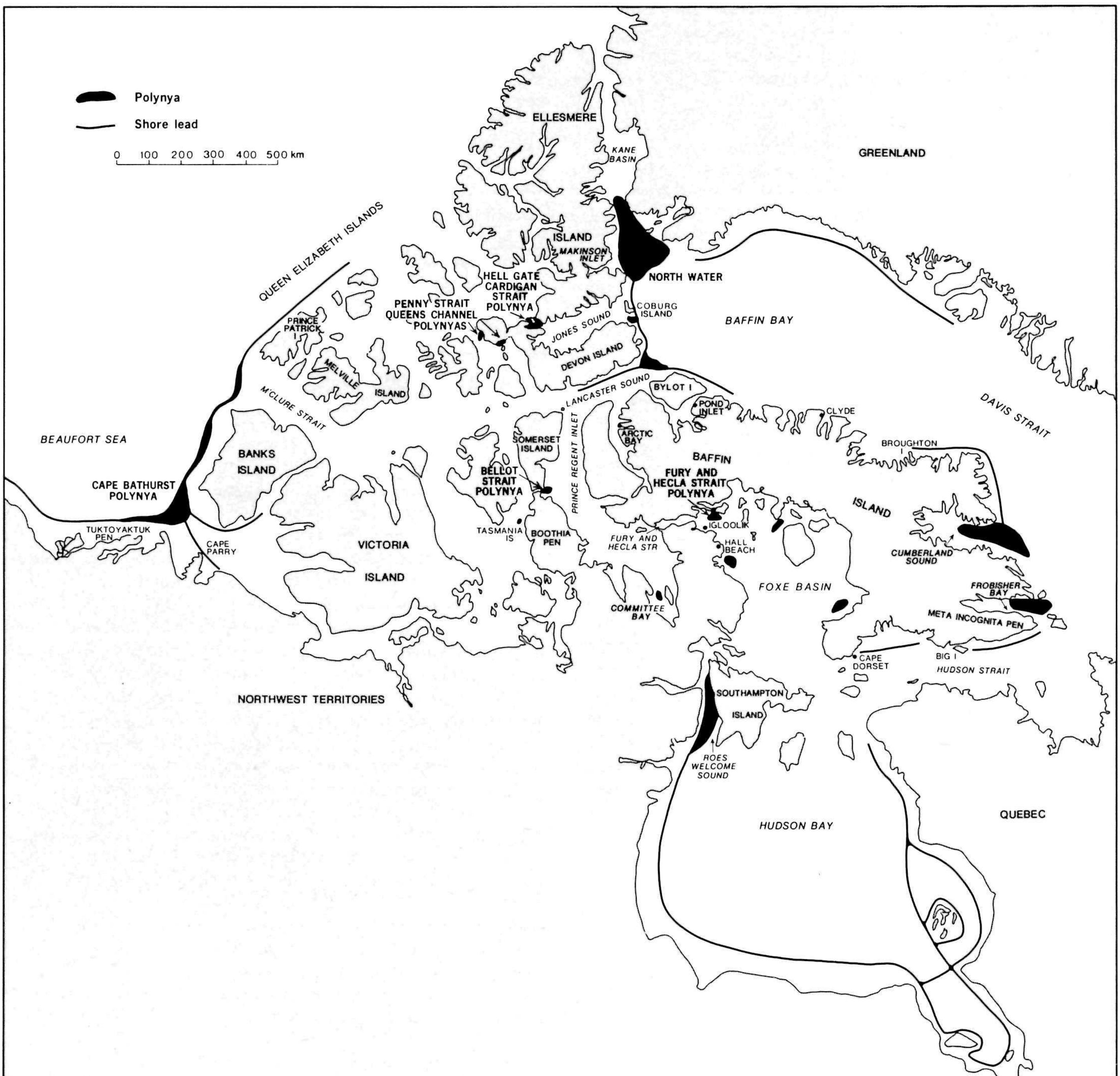
This volume contains five reviews of subjects vital to our understanding of the biological importance of polynyas in the Canadian Arctic. The first paper describes the distribution of polynyas and shoreleads and discusses variability in their size and locations. Although some of this information is available in various reports and ice maps, nowhere before has the distribution of polynyas been reviewed so thoroughly in one paper. The second paper discusses the physical causes and biological significance of polynyas and other open water areas in sea ice. The remaining three papers discuss the importance of polynyas to marine mammals (including polar bears), sea birds, and sea ducks, using the available literature and the baseline information provided in the first two papers.

The purpose of this review is to assemble the scattered body of information on polynyas in one place in order to help focus attention on specific areas where research is required. As such, it is not intended that this volume be the definitive work, but rather that it can serve as a useful starting point for more thorough, integrated, interdisciplinary research. Although the papers deal with fairly independent topics, several themes are recurrent. One, of course, is the limited nature of the available data base. More importantly, several areas in which information is required are identified by more than one writer. These include evaluating the significance of biological productivity at the edge of the ice, the basic biology of key invertebrates, site-specific data on biological oceanography on a year-round basis, the biology and distribution of the two cod species, and specific evaluation of how critical each polynya is to the survival of viable regional populations of different species. I hope that in summarizing some of the information available, this volume can serve as a stimulus for additional research on polynyas in the Canadian

Arctic, and that new information will make this publication seriously outdated in a few years.

The production of this volume was made possible by a special grant from the Baseline Studies Programme of the Department of Environment and the Scientific and Technical Publications Section of the Canadian Wildlife Service (CWS). A special acknowledgement should also go to the Polar Continental Shelf Project which has played a vital role for many years in helping to coordinate support for much of the research reported on and referred to in the following papers. We are grateful to the staff of the Drafting Division of the Environmental Conservation Service for their help in drafting the figures.

Figure 1
Map of the Canadian Arctic, showing distribution of recurring polynyas



Distribution of polynyas in the Canadian Arctic

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1. Abstract

A polynya is an area of open water surrounded by ice. In the Canadian Arctic, there are three types of recurring polynyas that appear in the same locations each year. These polynyas may vary considerably in size and shape between areas and between years in the same area. The ecological importance of these open water areas appears to depend upon the timing of freeze-up and the formation of the polynya, the size of the polynya at the time of maximum ice accumulation, and the pattern of break-up and disappearance of the polynya. This chapter discusses these aspects for all recurring polynyas in Canadian arctic waters; it is based on analysis of National Oceanic and Atmospheric Administration (NOAA) and Landsat satellite imagery, weekly ice composite maps, published literature, and personal communications.

2. Résumé

Une polynie est une étendue d'eau libre entourée de glace. Dans l'Arctique canadien on dénombre trois types de polynies récurrentes qui apparaissent aux mêmes endroits chaque année. La taille et la forme de ces polynies peuvent varier considérablement selon les régions et les années dans une même région. L'importance de ces étendues d'eau libre sur le plan écologique semble dépendre de la date de l'englacement et de la formation de la polynie, de la taille de la polynie au moment de l'accumulation maximale de glace et du processus de la débâcle et de la disparition de la polynie. Dans le présent chapitre, on examine ces aspects pour toutes les polynies récurrentes dans les eaux de l'Arctique canadien; il est basé sur une analyse de la *National Oceanic and Atmospheric Administration* et de l'imagerie satellite Landsat, de cartes composites hebdomadaires de l'état des glaces, de la documentation publiée et sur des communications personnelles.

3. Introduction

A polynya is an area of open water surrounded by ice. The *Pilot of Arctic Canada* specifies that polynyas must be non-linear in shape, and that "polynyas may contain *brash ice* and/or be covered with *new ice*...; submariners refer to these as skylights. At times the polynya is limited on one side by the coast, and is called a *shore polynya,* or by *fast ice* and is called a *flaw polynya.* If it recurs in the same position every year, it is called a *recurring polynya*" (Canadian Hydrographic Service 1970).

In the Canadian Arctic, there are three kinds of recurring polynyas: the large and unique North Water, smaller polynyas such as those in Hell Gate and Penny Strait, and extensive shorelead systems which contain variably sized areas of semi-permanent open water during the winter and are the first and most persistent areas of open water in the spring. Although in the technical sense shoreleads do not qualify as polynyas because they are linear, they are included in this review because of their biological significance.

Polynyas may be caused by various combinations of currents, tides, upwellings, and winds. They may vary considerably in size and shape between areas and between years in the same area. In terms of their ecological significance, it is the recurring polynyas that are most important; consequently we have restricted ourselves to these in this paper.

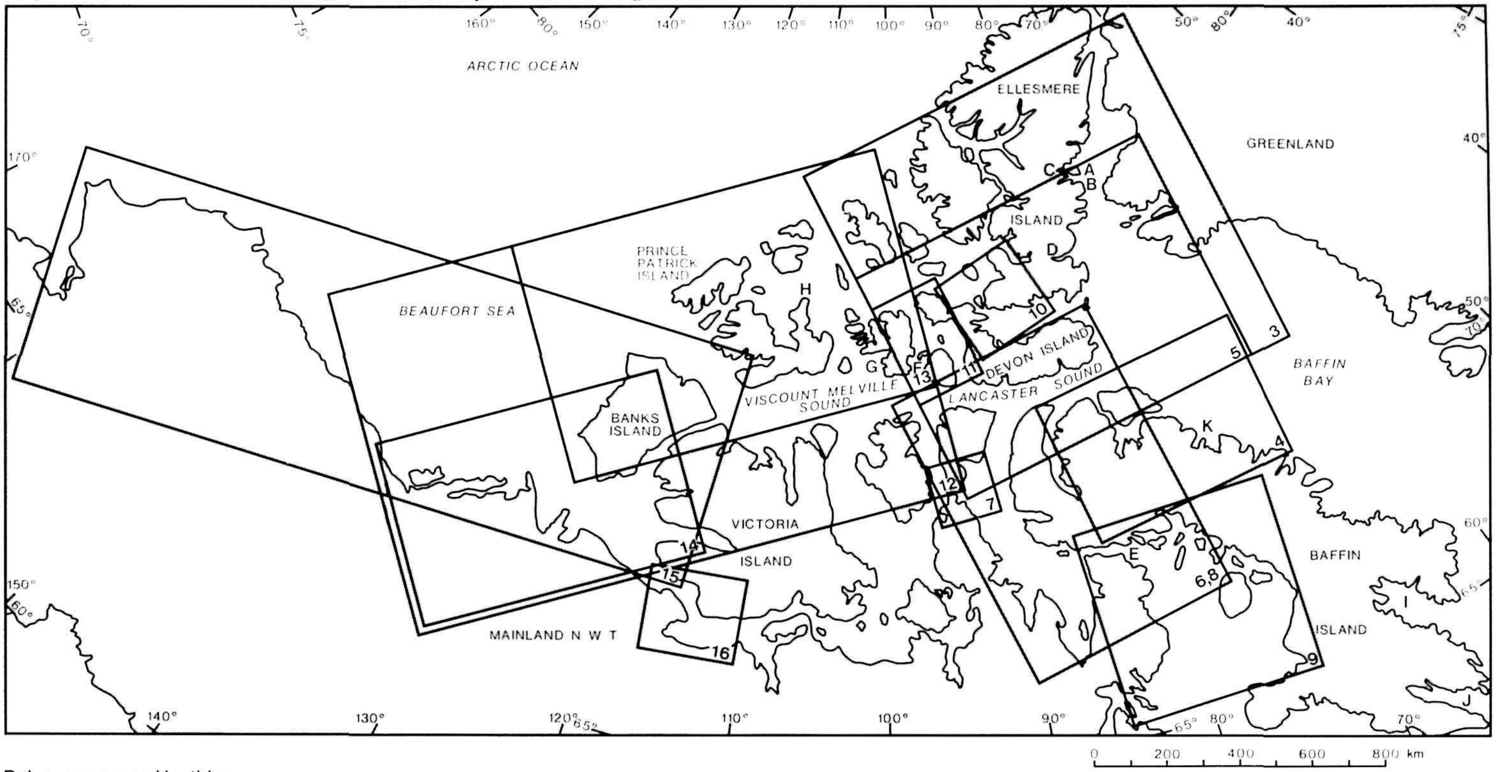
There has been no previous comprehensive study of polynyas in Canadian Arctic waters, although Stirling (1980) has recently drawn attention to their biological importance. Nevertheless, there have been a number of studies related to individual polynyas, for example Dunbar (1958, 1969), Aber and Vowinckel (1972), Sadler (1974), Muench (1975), Müller (unpub.), Tooma (1978), Carleton (1980), and Schledermann (1980).

Several terms are used in the text of this paper that may be unfamiliar to the reader. Definitions (taken from Canadian Hydrographic Service 1970) are given here. Grey ice refers to "*Young ice* 10 to 15 centimetres thick. Less elastic than *nilas* and breaks on swell. Usually rafts under pressure." Grey-white ice refers to "*Young ice* 15 to 30 centimetres thick. Under pressure more likely to ridge than raft." The rating system applied to ice cover (e.g. 8/10) refers to the "ratio of an area of ice of any *concentration* to the total area of sea surface..." An ice cover of 9+/10 indicates an unconsolidated ice surface of 100% coverage.

4. Materials and methods

The present study was carried out by mapping ice conditions bi-weekly, using NOAA-4 and NOAA-5 satellite imagery (both visual and infra-red) for the period January 1975 to December 1979. The resolution of the NOAA imagery is 1 km, and a single picture covers an area of about 2000 km × 2000 km. The frequency of images is twice daily: once daily in the visible band and twice in the thermal infra-red band. The infra-red imagery facilitates identification of open water and new ice during the winter dark period. Unfortunately, many photos are unusable because of poor weather conditions. Nevertheless, because we mapped approximately on a bi-weekly basis, the frequency of coverage in the intervening periods allowed considerable choice in selecting the best images.

Figure 1
Map of the Canadian Arctic, showing locations of maps contained in Figures 3–16



Polynyas covered by this paper
(numbers refer to figures in text)

3 North Water
3 Coburg Island
4 Bylot Island
5 Lancaster Sound
6 Prince Regent Inlet
7 Bellot Strait
8 Committee Bay
9 Foxe Basin
10 Hell Gate – Cardigan Strait
11 Queens Channel – Penny Strait
12 Arctic Ocean lead system
13 Prince Patrick Island
14 Cape Bathurst
15 West of Cape Bathurst
16 Lambert Channel Franklin Strait

Polynyas not covered by this paper

A Camperdown Polynya
B Rice Strait
C Hazler Bay
D Mackinson Inlet
E Fury and Hecla Strait
F Kailuk Brooman
G Alexander Polynya
H Melville Island
I Cumberland Sound
J Frobisher Bay
K Cambridge Fjord

Landsat imagery, which has been available since 1972, was also used, but only to a limited degree. Landsat has a higher resolution (80 m) than NOAA; however, each image covers an area of only 185 × 185 km with considerable overlap between images. For example, it can take up to nine separate photographs to cover the small polynya in Bellot Strait. The frequency of Landsat is only once every 18 days. Thus, both the smaller scale and more frequent coverage made the NOAA imagery more suitable for this survey study. Similarly, Dey *et al.* (1979) used the NOAA imagery for a study of freeze-up and break-up patterns in the Canadian Arctic for the period July to November, 1975–77. In contrast, Landsat would probably be better for detailed studies of individual polynyas.

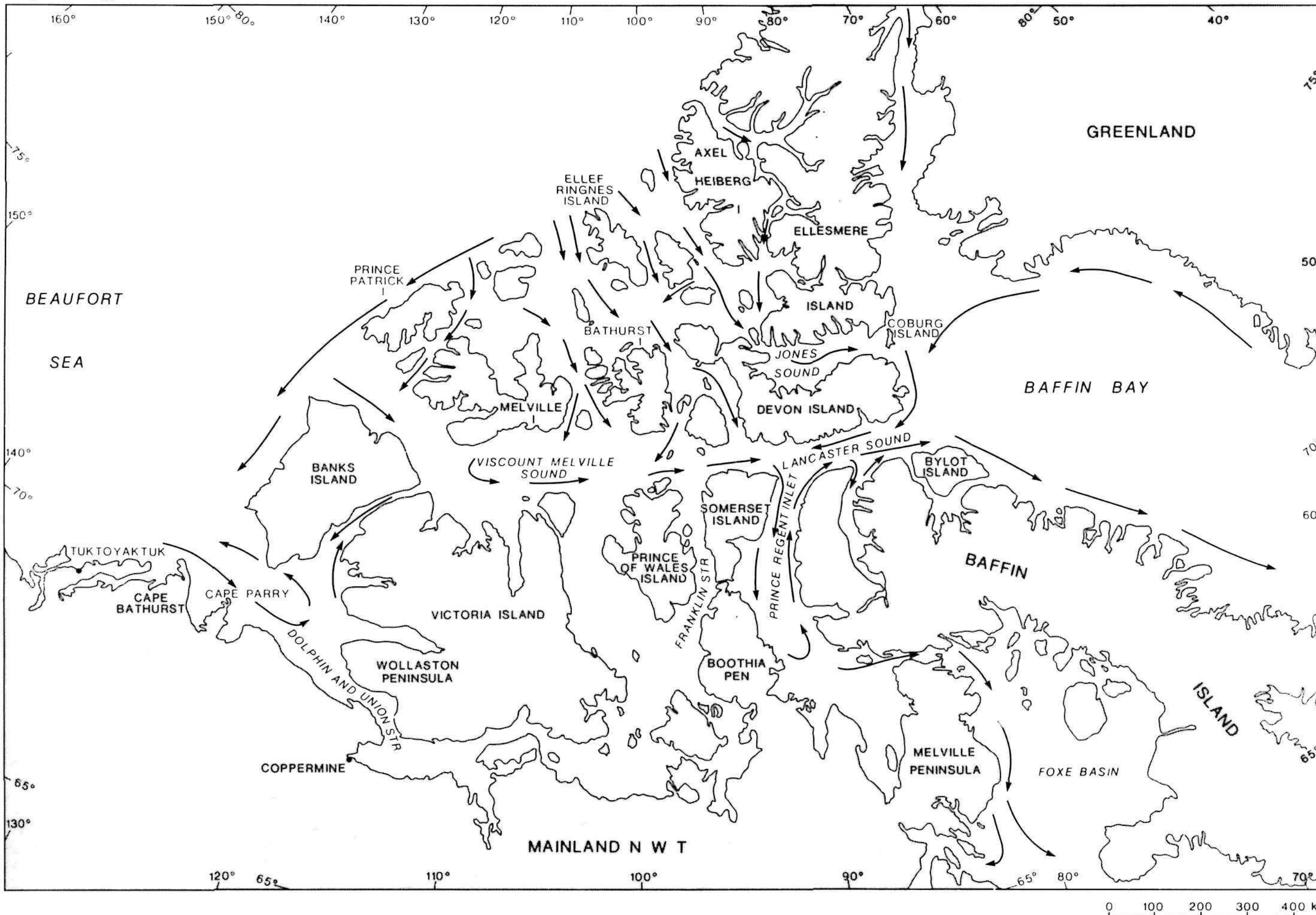
In addition to the NOAA imagery, weekly ice composite maps from the Ice Climatology and Applications Division (Atmospheric Environment Service) were also used. These composites were compiled from NOAA imagery, ice reconnaissance flights, laser profilometry, and various other ice observations, but cover only the duration of the northern shipping season (generally May to November). Finally, information was also obtained from published literature and personal communications.

The polynyas analysed in this study are illustrated collectively by Stirling (this publication, Fig. 1). For this paper, it was necessary to consider individual areas of the Arctic separately on a larger scale as shown in Figure 1. In addition, a number of smaller existing features are also indicated although they were not analysed here. Because of their importance to the location and recurrent nature of many polynyas, the major arctic marine current systems are shown in Figure 2.

The study period was limited to the last 5 years, primarily because, prior to 1975, the quality of the NOAA imagery was much poorer. This made interpretation more difficult and less reliable. The AES composite maps were also available from 1975 through 1979 so that we were able to verify our interpretations. Even so, some errors in the interpretations could have occurred due to the interpreter, or because of aberrations introduced by photo quality, cloud cover, and fog banks. In addition, because newly-formed thin ice is difficult to distinguish from open water in both the visual and infra-red bands, all dark areas were simply mapped as open water. Some small features, such as the polynya in Fury and Hecla Strait, were detectable on the photos but were very difficult to map accurately.

Because of the limitations of the imagery, and our conservative interpretation, only the main characteristics of the larger recurring polynyas were mapped in this study. In analysing the data, we concentrated on the aspects that seemed to be most important ecologically. These included
(1) the timing of freeze-up and the formation of the polynya,
(2) the size of the polynya at the time of maximum ice accumulation, and
(3) the pattern of break-up and disappearance of the polynya and its eventual connection to other water bodies.
In each instance we have tried to indicate what is "normal" as well as the range of variation over the 5-year period.

Figure 2
Map showing surface water currents in the Canadian Arctic



5. Locations and variability of polynyas

5.1. The North Water

The North Water, situated in northern Baffin Bay, is the largest and best known polynya in the Canadian Arctic. During the early winter, pack ice being carried south through Kane Basin becomes congested and forms an ice bridge across the narrow head of Smith Sound. New ice that is formed south of the bridge is apparently swept away by the current, aided by the prevailing northerly winds (Nutt 1969) although some have suggested that the upwelling of water is important. Because of the ice bridge, the northern limit of the North Water is fairly constant from year to year; however, the southern edge is more variable and depends on weather conditions and the time of year. A number of papers have been written on various aspects of the North Water (e.g. Dunbar 1969; Aber and Vowinckel 1972; Muench 1975; Tooma 1978; Müller, unpubl.).

Freeze-up in Smith Sound usually begins in mid September (except in 1979, when it occurred during mid to late August), commencing in the northwest and growing southwards. The eastern and western waters of Kane Basin freeze fast to the shore at this time, although a central "corridor" of mobile ice (some new, some 1-year-old, and some multiyear) persists until December or January when the ice bridge begins to form. The ice bridge and open water area at the head of Smith Sound formed in mid January in 1975, 1977, and 1979, in February in 1976, and in mid March in 1978.

By late October, northern Baffin Bay is covered with ice, most of which is less than 1 year old. An extremely constant fast-ice edge develops along the eastern coasts of Ellesmere and Devon islands to Lancaster Sound, and along the northwestern coast of Greenland to Northumberland Island (Fig. 3*a*). Some open water is always present along the Ellesmere and/or Greenland coasts, with an especially consistent patch just southwest of Coburg Island (see section 5.2). Very often there is also open water around Northumberland Island and in Melville Bay. In 2 of the past 5 years (1975, 1976) there has been open water in northernmost Nares Strait in January and February (Fig. 3*a*).

The northernmost area of Baffin Bay south of the ice bridge remains in a disturbed state throughout the winter. Currents, winds, and the counterclockwise gyre in the main part of Baffin Bay keep the ice in constant motion. During winter this area always shows as quite dark on the NOAA infra-red imagery (Fig. 3*b*–*d*), indicating thin ice that may contain partly or completely open areas.

Persistent open (or semi-open) water exists in confined areas at the northern end of Smith Sound, at the entrance to Jones Sound off Coburg Island, in Lancaster Sound off the southeastern coast of Devon Island, and around Northumberland Island (Fig. 3*e*). The main area of open water begins to expand southwards in northern Baffin Bay in the first half of May (Fig. 3*f*) (early to mid April in 1977, late April in 1979). The spread of the polynya southwards proceeds somewhat differently in detail from year to year, but typically by the end of May the southern edge is around 76°N± ½° (Fig. 3*g*, *h*). The southern extent of the open water is greater down the western side of Baffin Bay. Nevertheless, the North Water does not normally join Lan-

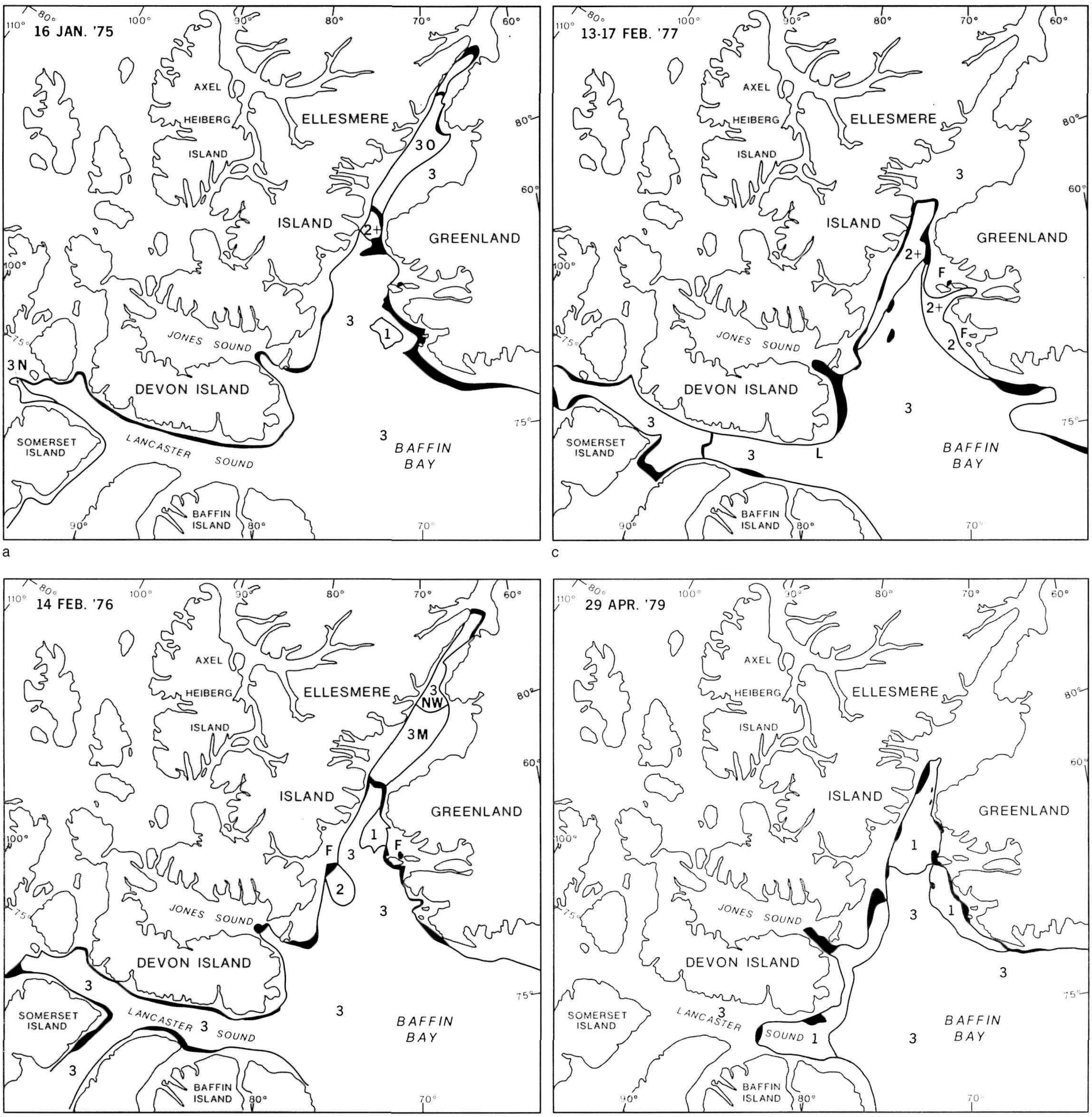
Figures 3a–h
Maps of the North Water polynya, showing ice conditions during particular months and years as indicated

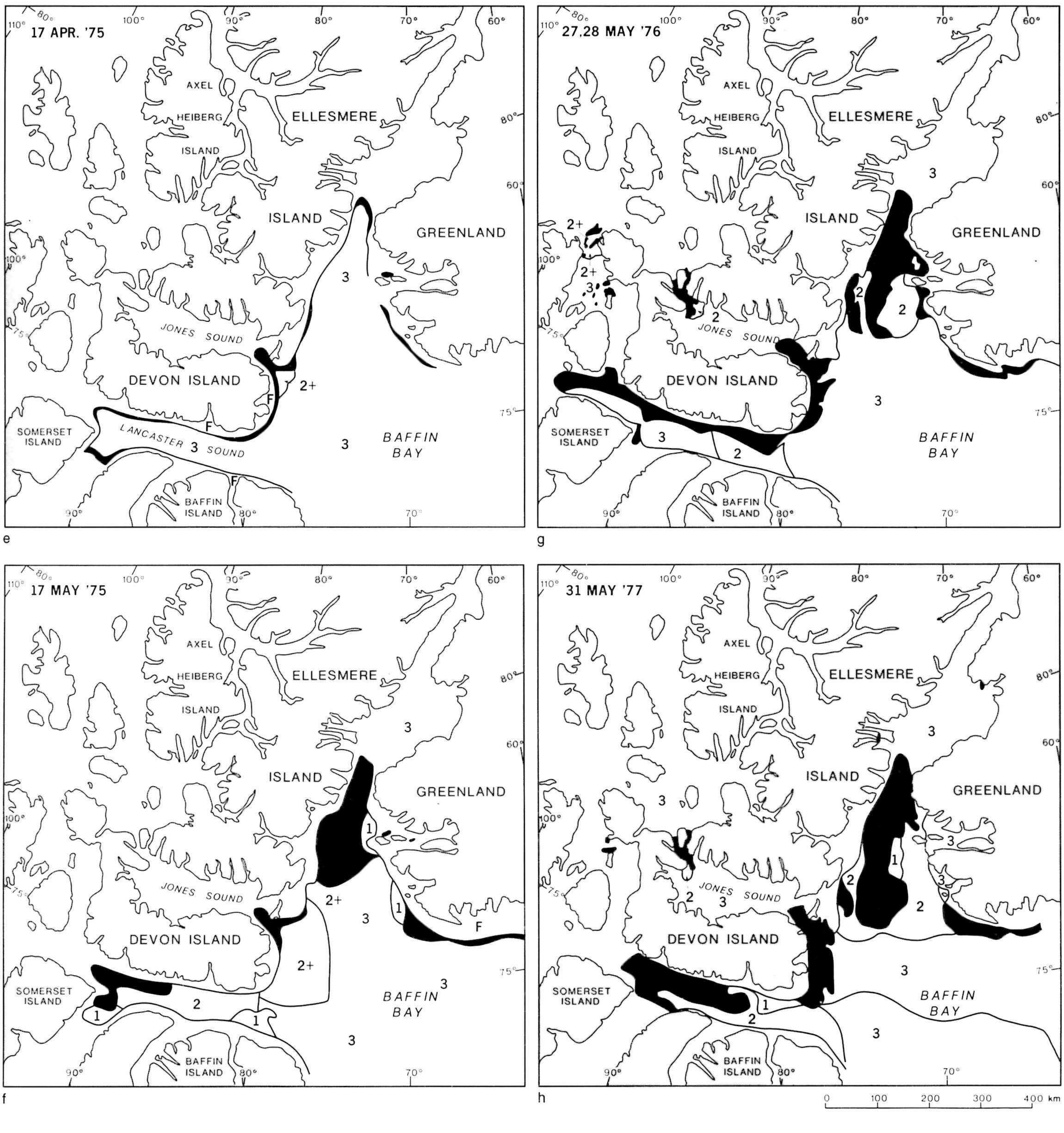
- large black areas indicate open water to 1/10 ice cover
- thin line leading into thicker line indicates a crack/lead
- single thin line indicates division between ice cover categories
- **L** indicates an open lead and is inserted in some cases where the lead is not obvious

1 2/10 – 5/10 ice cover
2 6/10 – 7/10 ice cover
2+ 8/10 ice cover
3 9/10 – 10/10 ice cover

F fast ice
N new ice
O old ice
M multiyear ice
A 1st-year ice
<A less than 1st-year ice

S 2nd-year ice
U unknown
G grey ice
W grey-white ice




17 APR. '75
AXEL
HEIBERG
ISLAND
ELLESMERE
ISLAND
GREENLAND
JONES SOUND
DEVON ISLAND
SOMERSET ISLAND
LANCASTER SOUND
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AXEL
HEIBERG
ISLAND
ELLESMERE
ISLAND
GREENLAND
JONES SOUND
DEVON ISLAND
SOMERSET ISLAND
BAFFIN BAY
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0 100 200 300 400 km
110° 100° 90° 80° 70° 60°
80° 75°

caster Sound until mid June (late May in 1979). Sometime in July the North Water merges with the open water spreading northwest from Davis Strait, although in 1978 this did not occur until September.

The ice bridge in Smith Sound breaks up in late July (1979) or early August (1975–78 inclusive), at which time open water can extend north into Nares Strait.

5.2. Coburg Island

An especially persistent area of open water occurs during the winter every year in the vicinity of Coburg Island. This polynya remains as a separate feature for some months before joining the main body of the North Water in May or June.

Freeze-up occurs in late September or early October, beginning in Jones Sound and encompassing Coburg Island by mid to late October. Annual ice prevails in this region. Open water first appears in January (except December 1978), typically in the form of a horseshoe-shaped lead in Lady Ann Strait, southwest of Coburg Island (Fig. 3*a*). The lead develops at the boundary between the fast ice in Jones Sound and the pack ice of Baffin Bay. However, the open water is so regular in form and location from year to year that it may be related to the southeastern current from Jones Sound, which is channelled through the strait (Fig. 2).

Open water remains here all winter and can become quite extensive (e.g. Fig. 3*c–f*). Leads may extend to the North Water or south towards Lancaster Sound, usually connecting to the latter by April. The North Water extends south past Coburg Island from mid May to early June (mid July in 1978), although prior to this period it may be connected intermittently via the shorelead along the Ellesmere coast.

5.3. Bylot Island

In all 5 years, an area of open water was observed parallel to the eastern or southeastern coast of Bylot Island (Fig. 4*a*). It is a rather difficult feature to map because of the frequent heavy cloud in this region. Although this open water area eventually joins up with the North Water, initially it develops as a separate feature.

The waters around Bylot Island are usually frozen by the end of October, accompanying the freeze-up of Baffin Bay. A lead develops between the shorefast ice around Bylot Island and the drift ice in Baffin Bay; the opening and closing of the lead is related to winds and the general motion of the pack ice in Baffin Bay. The feature varies somewhat in size and specific location from year to year, but is always located along the eastern coast of the island, extending south across the entrance to Pond Inlet and past Cape Macculloch on Baffin Island.

From 1976 to 1979, the Bylot Island lead first appeared in February, while in 1975 the opening was first noted in March. In 1977, 1978, and 1979, it consisted of an open lead off the southeastern coast of Bylot Island, extending southwards past Cape Jameson, Baffin Island (e.g. Fig. 4*a*). In 1976 it also extended around the northern coast of Bylot Island (Fig. 4*b*). In 1975 the lead was quite wide and closer inshore, and ran south along the east coast of Bylot Island to Cape Macculloch (Fig. 4*c*).

The opening usually disappears by April, as it did in 1976, 1977, and 1978. In 1975, it disappeared in early May. In 1979, the opening became confined to a small open water area off the southeastern corner of the island, and in 1976 this same small opening reappeared in May (Fig. 4*d*).

As previously stated, this polynya eventually merges with the North Water when break-up occurs in Baffin Bay.

This linkage can occur as early as June (as in 1975) or as late as August (as in 1977).

5.4. Lancaster Sound

Landfast ice forms by late September or early October in Lancaster Sound. By mid to late October the sound usually becomes completely ice-covered, although still unconsolidated (9+/10). A system of open shoreleads and cracks usually develops between mid November (1975, 1976) and mid December (1974, 1977), remaining in some form throughout the winter until break-up. It was absent in winter 1978–79, however, as ice in Lancaster Sound became consolidated. The lead system runs along the northern and southern sides of Lancaster Sound, extending south into Prince Regent Inlet where it may be open south of Creswell Bay on the western side (e.g. Fig. 5*a*). The pattern of leads changes periodically under the influence of currents and winds. Included in this system is a lead which begins near the western end of Lancaster Sound and may extend as far west as Griffith Island and Lowther Island, as it did in January and February of 1975, 1976, 1977, and 1978 (Fig. 5*a*). In 1976, the lead remained in this position throughout the winter (Fig. 5*b*) until break-up in late May. In 1975 and 1977, the lead around Lowther Island froze over in about early February and late March respectively. At about this time, another lead develops in the vicinity of Prince Leopold Island, and runs north toward Maxwell Bay and then east along the south coast of Devon Island (Fig. 5*c*, *d*). Historically, the location of this opening has been remarkably constant (Smiley and Milne 1979) and may be related to the submarine sill in Lancaster Sound at this point.

In 1978, the lead at Prince Leopold Island first appeared around March 11 but had refrozen by March 25. At this time, open water was restricted to a lead running between Cape Sherard (Devon Island) and Navy Board Inlet. In 1979, the only open water in Lancaster Sound was contained in a transverse lead running north–south near the entrance to the sound (Fig. 5*e*). The lead developed by early January and joined with the North Water in the second half of May.

During the winter, the lead along the northern side of Lancaster Sound may be continuous throughout its whole length and can link with the polynya near Coburg Island, depending on wind conditions and the movement of ice in Baffin Bay (Fig. 5*a*, *c*). At other times the lead is discontinuous (Fig. 5*b*). On the southern side of Lancaster Sound, the lead is not usually continuous as far east as the polynya off Bylot Island.

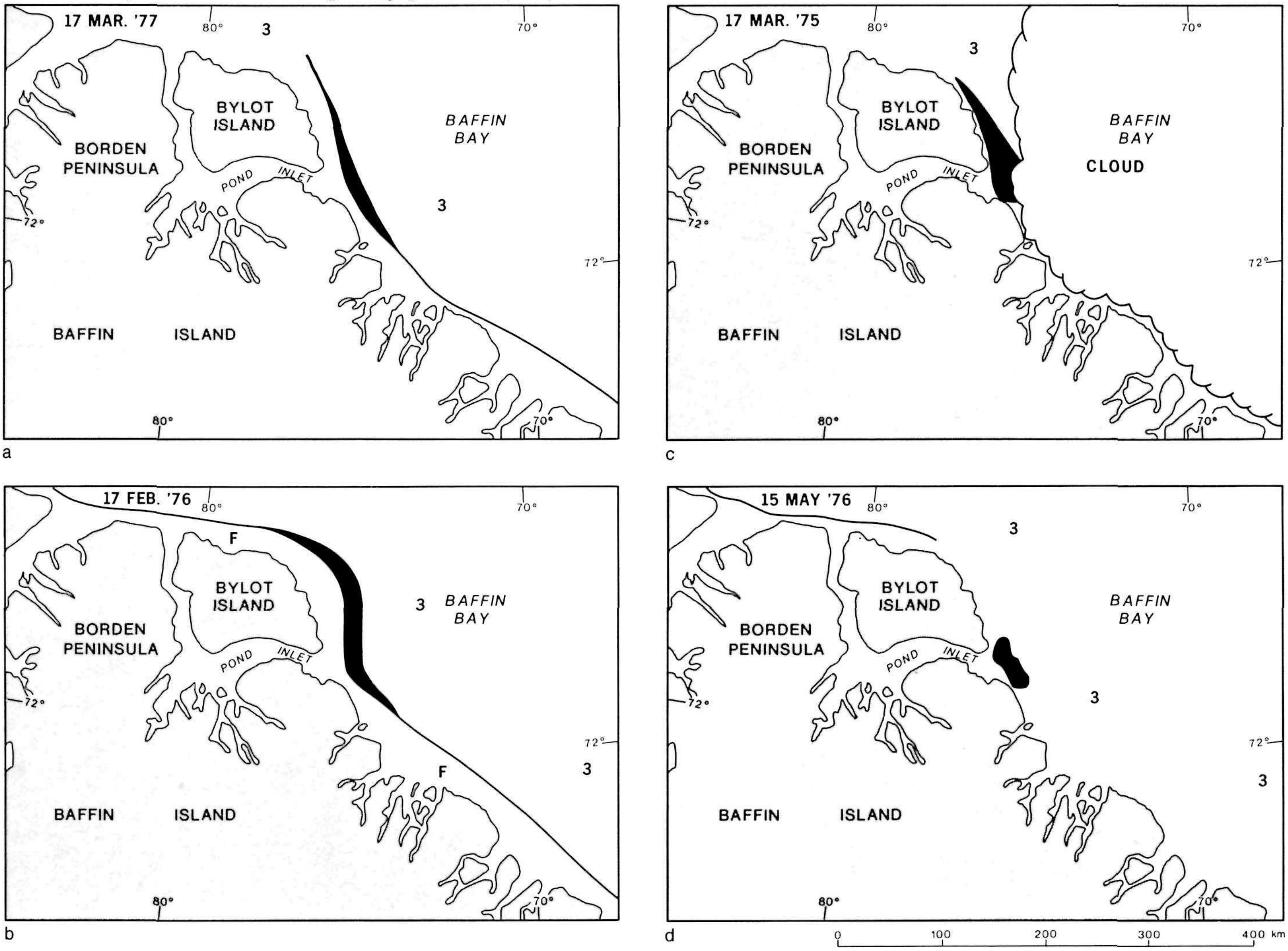
Break-up commenced in early to mid May in 1975 and 1977 and late May in 1976. In 1978 and 1979, break-up did not occur until sometime in August.

5.5. Prince Regent Inlet

Freeze-up usually occurs in Prince Regent Inlet and the Gulf of Boothia no later than mid October. Since Prince Regent Inlet only becomes ice free as far south as a line between Lord Mayor Bay, Boothia Peninsula, and Crown Prince Frederick Island, there is a division between the annual ice in Prince Regent Inlet and multiyear ice in the Gulf of Boothia.

In January, a characteristic pattern of cracks and shoreleads develops along both the east and west sides of Prince Regent Inlet, south into the Gulf of Boothia and Committee Bay (Fig. 6*a*). This lead system also joins with leads along the southern side of Lancaster Sound. The pattern is very similar to the pattern of currents in this region (Fig. 2). An open lead commonly occurs along the eastern and north-

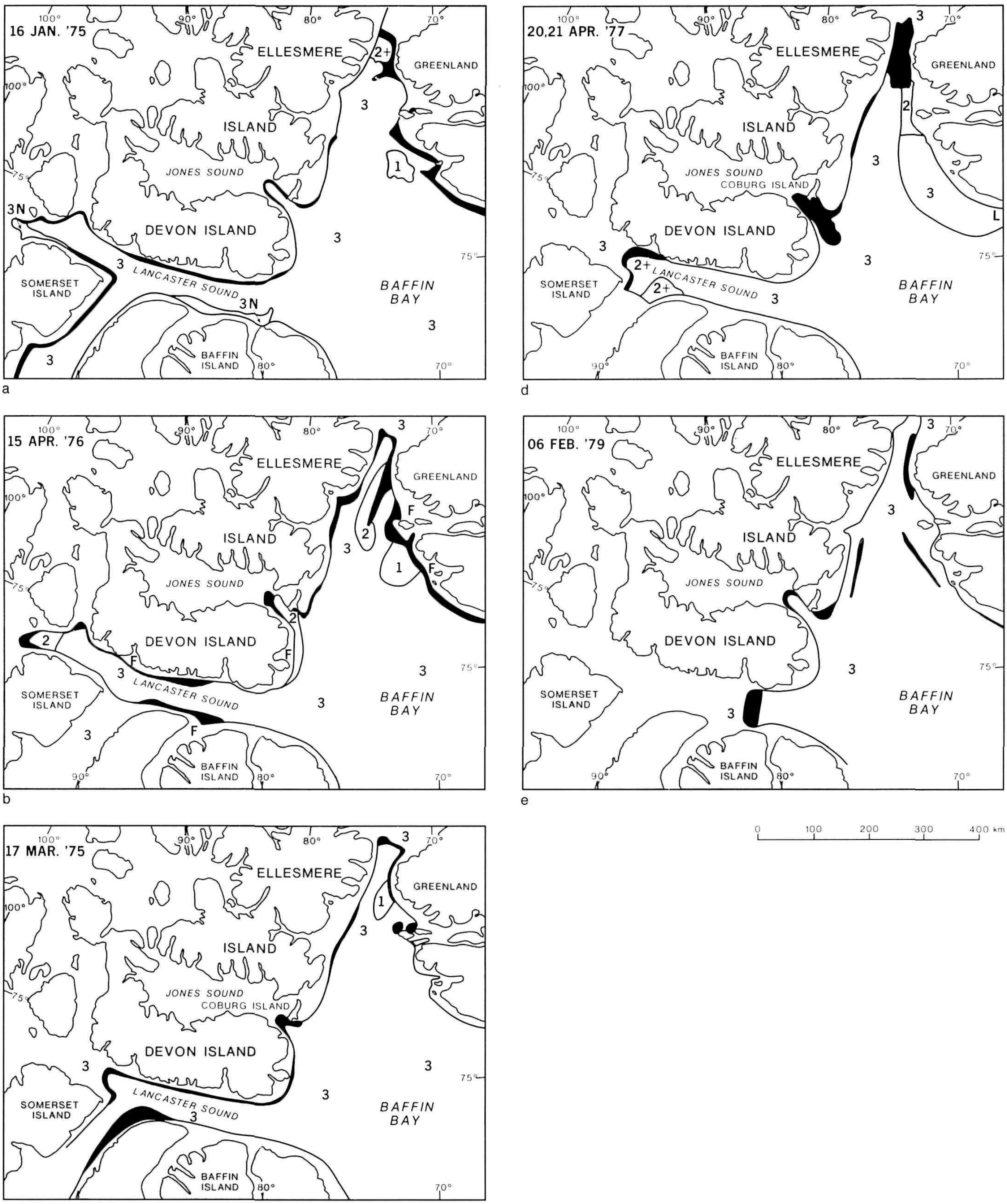
Figures 4a–d
Maps of the Bylot Island lead system, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



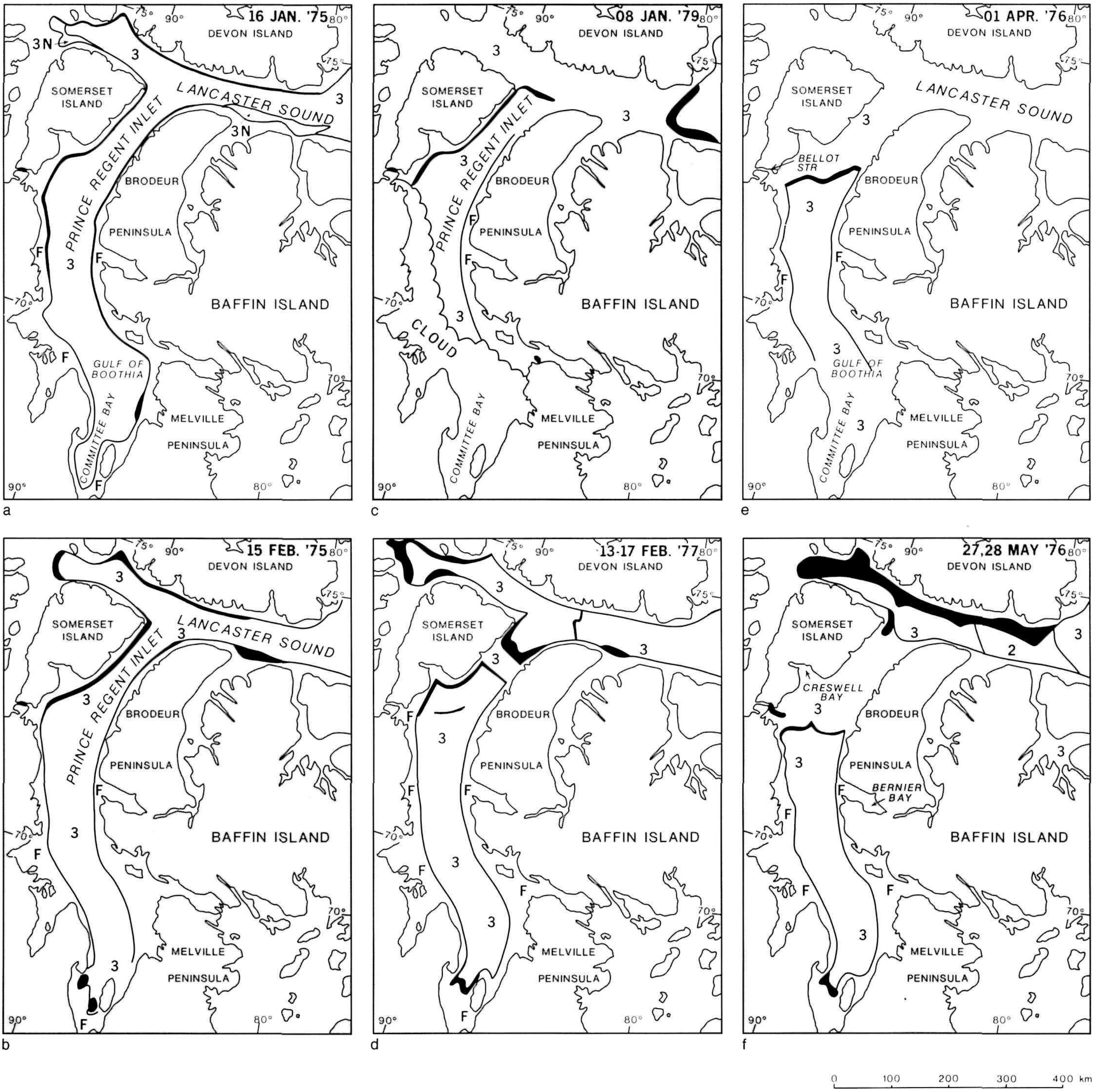
eastern coasts of Somerset Island in January and February (e.g. Fig. 6*a*, *b*), and there is sometimes open water along the Brodeur Peninsula at this time of year. A patch of open water may also occur at the entrance to Prince Regent Inlet (e.g. Fig. 6*c*), or an open lead across the inlet south of Lancaster Sound (Fig. 6*d*). In most years, there is a transverse lead that runs somewhere between Bellot Strait and Bernier Bay, Brodeur Peninsula, from March until mid to late June (Fig. 6*e*, *f*). This is a very constant feature from year to year, and only disappears with the progression of break-up. (The only exception to this pattern during the study period was in 1979, when the lead did not appear until mid June.) The location of this transverse lead may be related to the submarine topography of Prince Regent Inlet, since there is a sill across the sound in this vicinity. This sill may also influence the development of counter-clockwise currents in Prince Regent Inlet (Fig. 2). Finally, the large open lead that occurred in Creswell Bay in January and/or February in 4 of the past 5 years (Fig. 6*d*) should be noted. This lead tends to disappear with the development of the transverse lead in March.

Prince Regent Inlet was open from Lancaster Sound as far south as Bernier Bay before the end of August in 1975, 1976, and 1977. In 1979, it opened only as far south as Creswell Bay, and in 1978 only the bays and a passage along the eastern side of the inlet were open. Elsewhere, there was 8/10 to 10/10 ice cover.

Figures 5a–e
Maps of the Lancaster Sound lead system, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



Figures 6a–f
Maps of the Prince Regent Inlet lead system, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



5.6. Bellot Strait

The polynya in Bellot Strait can probably be attributed to the effect of currents passing through the narrow channel between Somerset Island and Boothia Peninsula (see Fig. 2). The Canadian Hydrographic Service (1970) mentions the existence of strong currents on the eastern side of the strait, which may explain the regular extension of the polynyas into that area.

Between the end of September and December, Bellot Strait and the areas off each end of the strait, in Prince Regent Inlet and Franklin Strait, become ice-covered (Fig. 7*a, b*). Open water occurred in the middle of Bellot Strait between late December and March in all 5 years (e.g. Fig. 7*c*). It first appeared in December in 1975 and 1978, and in January in 1976, 1977, and 1979. In April and May the polynya moves to the eastern end of the strait and enlarges, extending into Brentford Bay (Fig. 7*d*). Break-up usually occurs in June, but conditions are highly variable from year to year, depending on break-up patterns in Prince Regent Inlet and Franklin Strait. During this period Bellot Strait can be completely frozen over (1976), open in the middle with ice at either end (1977, 1978, 1979), or totally open into Brentford Bay (1975).

From late June until the end of September, Bellot Strait remains open and connects to open water in Prince Regent Inlet (Fig. 7*e*). In 3 years (1975, 1976, 1977), there was open water off both ends of the strait by late August/early September (Fig. 7*f*). In 1978 and 1979, open water was present only at the eastern end of the strait.

5.7. Committee Bay

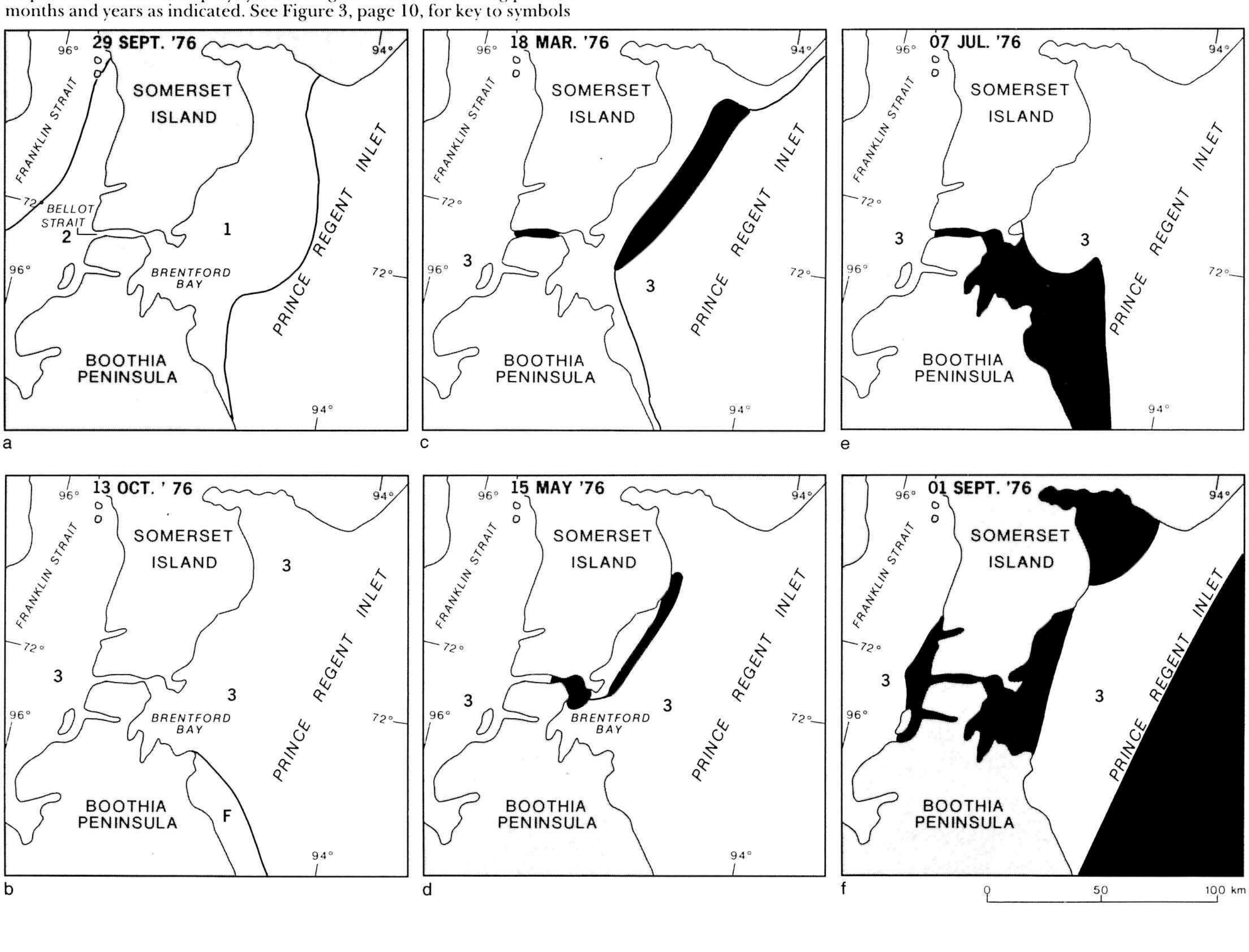
A polynya was present in Committee Bay, between Wales Island and Simpson Peninsula, in all 5 years, first appearing in either January (1977), February (1975, 1976, 1979), or April (1978). Although it initially varied in size, shape, and specific location between years, it usually adopted a fairly characteristic form by April (Figs. 6*a–f* and 8*a*).

Freeze-up in this area begins either in early September (1976, 1977, 1979), mid September (1977), or early October (1975). Landfast ice forms along the shore while the middle of the bay is filled with predominantly second and multiyear ice, which drifts in from the Gulf of Boothia.

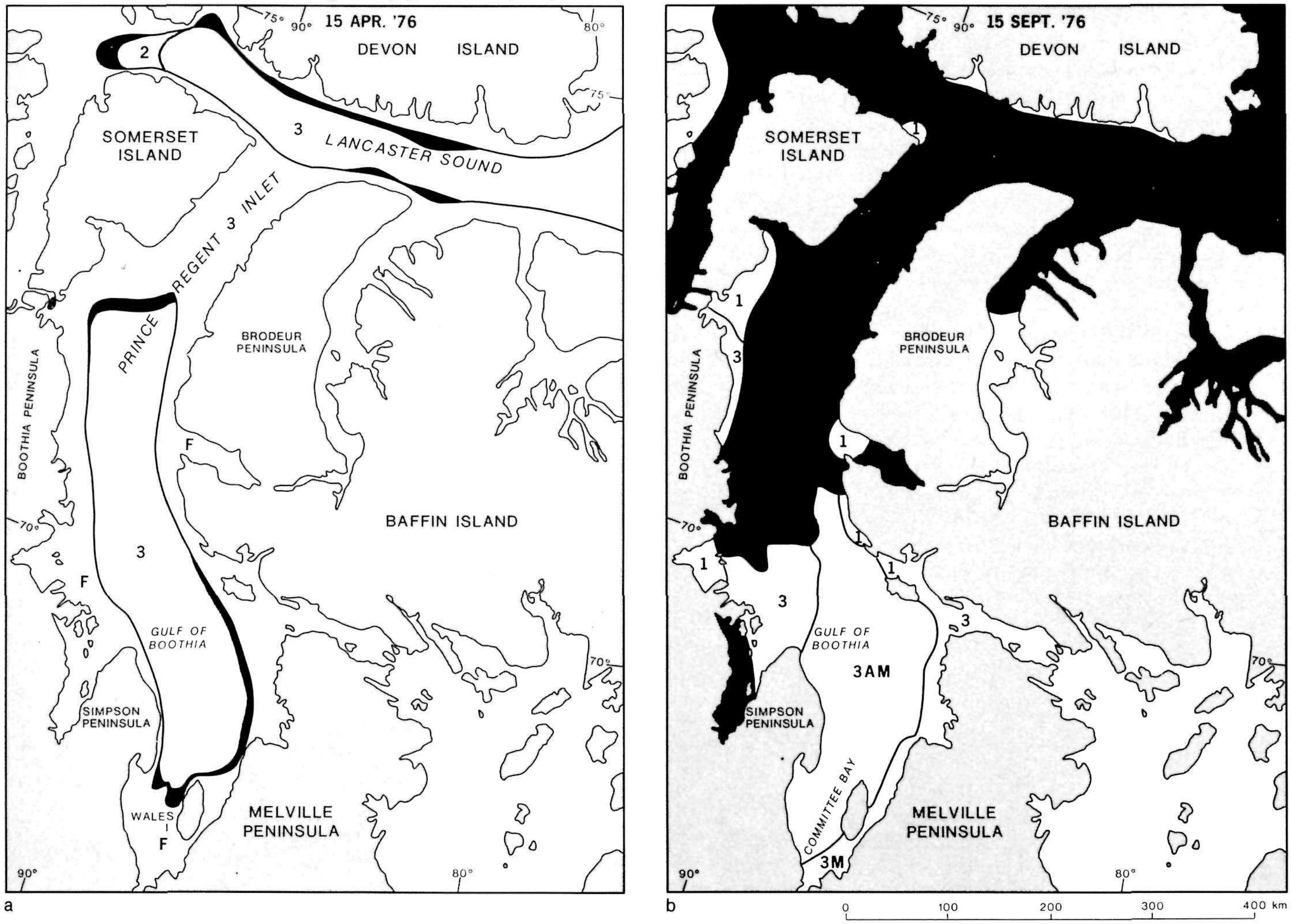
The polynya seems to be part of a shorelead system that develops between the shorefast and pack ice in Prince Regent Inlet, the Gulf of Boothia, and Committee Bay (Fig. 6*a*). It is difficult to explain why this polynya occurs since bathymetric and current information are lacking. Nevertheless, we think that wind and tidal action may be important. The maximum tidal range at Fort Ross, Bellot Strait, is 2.5–3 m, and it is likely to be greater to the south in Committee Bay.

After formation, this polynya persists until early June, at which time the ice in the Gulf of Boothia and Committee Bay becomes more mobile and the landfast ice starts to break up. At maximum break-up there is open water along the coast but Committee Bay itself is never ice free (Fig. 8*b*). In September 1975 however, an exceptionally large portion of the bay was open to Prince Regent Inlet.

Figures 7a–f
Maps of the Bellot Strait polynya, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



Figures 8a and b
Maps of the Committee Bay polynya, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



5.8. Foxe Basin

Freeze-up usually begins in the northwestern corner of Foxe Basin in mid October and extends south to Southampton Island by early to mid November. In 1978, freeze-up occurred a few weeks earlier. The ice cover in Foxe Basin is characterized by annual ice, with fast-ice zones around the islands and along the shoreline. As a result of winds, tides, and currents, the main pack remains continually in motion. A large proportion of Foxe Basin almost always shows up as quite dark on the NOAA imagery, perhaps because the constant movement keeps it from getting too thick.

Normally, by the beginning of January a characteristic pattern of cracks, leads, and patches of open water develops in northern Foxe Basin, varying little from year to year (e.g. Fig. 9*a*). Open water appeared as soon as early December in 1975 and 1978, north and northeast of Prince Charles Island and from the southern end of Fury and Hecla Strait south past Igloolik Island in 1975, and between Igloolik Island and Jens Munk Island and north of Rowley Island in 1978.

By mid February or, more often, early March, one typically finds open shoreleads around Koch Island, Rowley Island, Baird Peninsula, Foley Island, and the Spicer Islands. An open lead also develops between the fast ice and the pack ice on the southeast side of Prince Charles Island and on the southern side of Air Force Island. In some years, the open water extends south along Taverner Bay, Baffin Island (Fig. 9*b*). The polynya off Rowley Island linked up with the Spicer Islands polynya in mid April 1978 (e.g. Fig. 9*c*), and in mid to late May in 1976, 1977, and 1979.

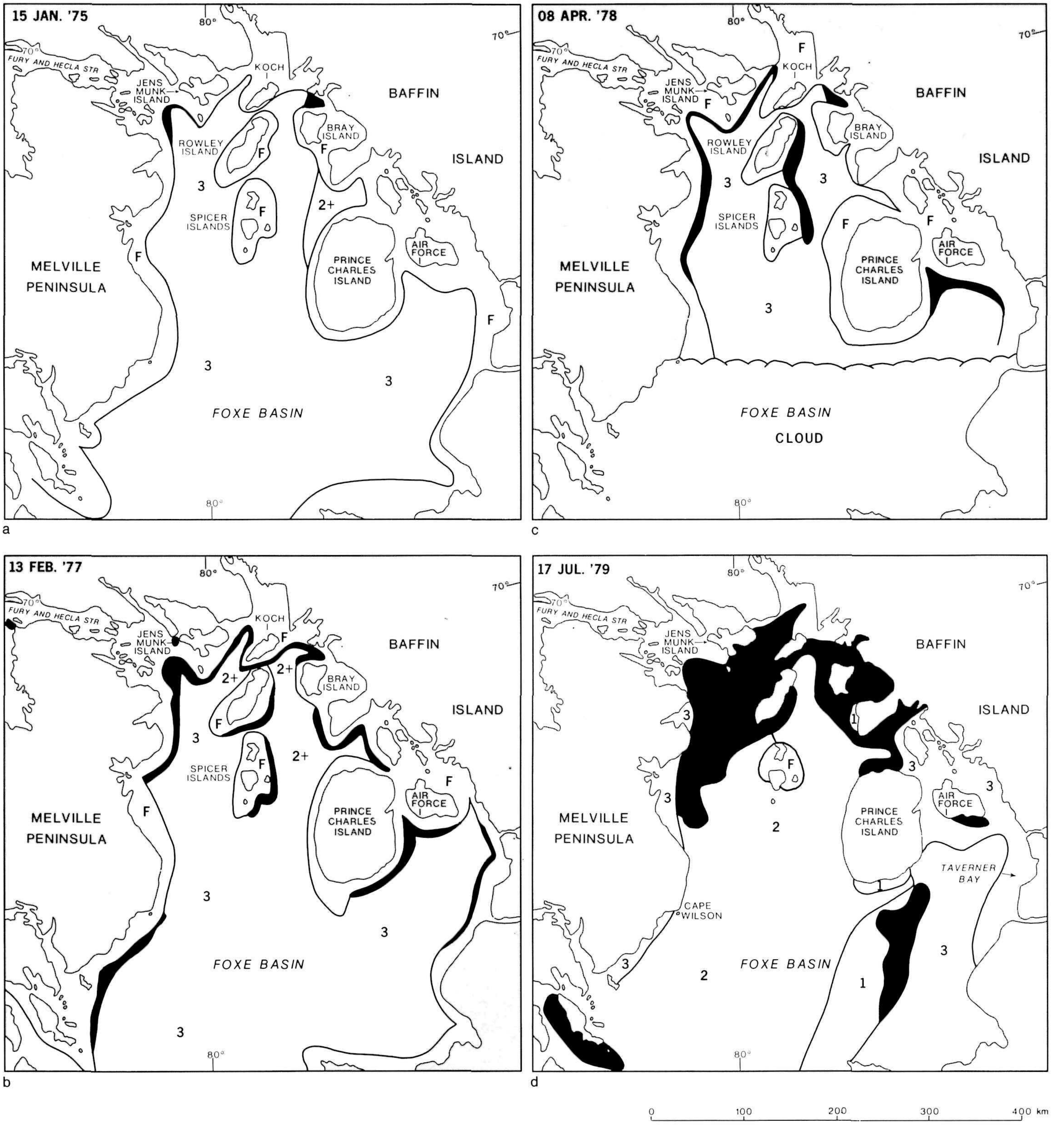
Usually by the beginning of January there is an open lead between Jens Munk Island and Igloolik Island (Fig. 9*a*). This polynya, which has a characteristic horseshoe shape, remains throughout the winter. There is also another open lead which develops sometime in February (1977, 1979) or March (1975, 1978) from Cape Wilson south past Winter Island (Fig. 9*b*). This lead also persists until break-up. In 1976, there was only a small patch of open water, which appeared off Cape Wilson in May.[1]

The polynyas off Rowley Island, Spicer Islands, Prince Charles Island, Air Force Island, and Cape Wilson are all to the south or southeast. Presumably, this is largely a result of winds predominantly from the northwest (Markham 1962); a similar effect has been noted previously in Ungava Bay and Hudson Bay (Stirling *et al.* 1977).

By mid May in all years, a large area of open water develops in northwestern Foxe Basin, between Hall Point, Jens Munk Island, and Rowley Island. This open water grad-

[1] The lead system off northern Southampton Island was not mapped consistently because it was peripheral to the main study area.

Figures 9a–d
Maps of the Foxe Basin polynyas, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



ually enlarges towards the southeast, and the other areas of open water described above gradually begin to coalesce (Fig. 9*d*). Open water frequently extends along the lead off Cape Wilson. The early opening of northwestern Foxe Basin has been related to prevailing northwesterly winds and southward-flowing currents (Markham 1962).

As break-up progresses, a complex and variable pattern of open water and loose ice develops, depending on wind conditions and the pattern of break-up itself. A general clearing of ice in Foxe Basin, through Hudson Strait, usually occurs by late August to late September, although it did not clear in 1978. Fury and Hecla Strait does not often clear in the summer, because it tends to be blocked with ice flowing out of the Gulf of Boothia.

5.9. Hell Gate – Cardigan Strait

Hell Gate and Cardigan Strait are narrow passages between North Kent, Devon, and Ellesmere islands, through which strong currents flow from Norwegian Bay to Jones Sound (Fig. 2). A well-known recurring polynya occurs there because of these currents. From the past 5 years of data it is possible to delimit a core area to the polynya which appears in a fairly constant pattern from year to year.

Freeze-up normally occurs in this area sometime in September; the bays and fjords freeze first with new ice. Elsewhere the ice is usually a mixture of grey, grey-white, and new; in some years there is 1st-year ice also, and occasionally some multiyear ice. The older ice comes from Norwegian Bay and gets clogged in the strait. Throughout October and November, Hell Gate and Cardigan Strait are covered with 9+/10 ice, although the ice appears to remain mobile within the area. In November 1978, there was only 6/10 to 8/10 ice cover, since Norwegian Bay did not break up that year and there was less clogging of the strait.

Open water usually reappears in early December, on either side of North Kent Island, frequently occurring first on the eastern side of the island. From December until July, open water remains, with the maximum extent occurring in May, June, and July. Conditions and concentrations of ice may be quite variable throughout the winter and between years (Fig. 10*a–f*). Nevertheless, the polynya often remains ice-free along the southeastern edge, possibly because of the submarine shelf that runs across Jones Sound between Cape Storm on Ellesmere Island and Cape Svarten on Devon Island. During the period of maximum extent (May–July) the core area is ice-free and isolated from Jones Sound.

In July, break-up normally occurs in Norwegian Bay, and ice flowing south from here tends to block Hell Gate and Cardigan Strait. Because of this, the area does not usually become completely ice-free in summer. In most years, Jones Sound is open during August, while there may still be 6/10–8/10 ice cover in Hell Gate and Cardigan Strait. When freeze-up occurs in September, the ice cover consists of a mixture of new ice, 1-year-old ice, and multiyear ice.

5.10. Queens Channel and Penny Strait

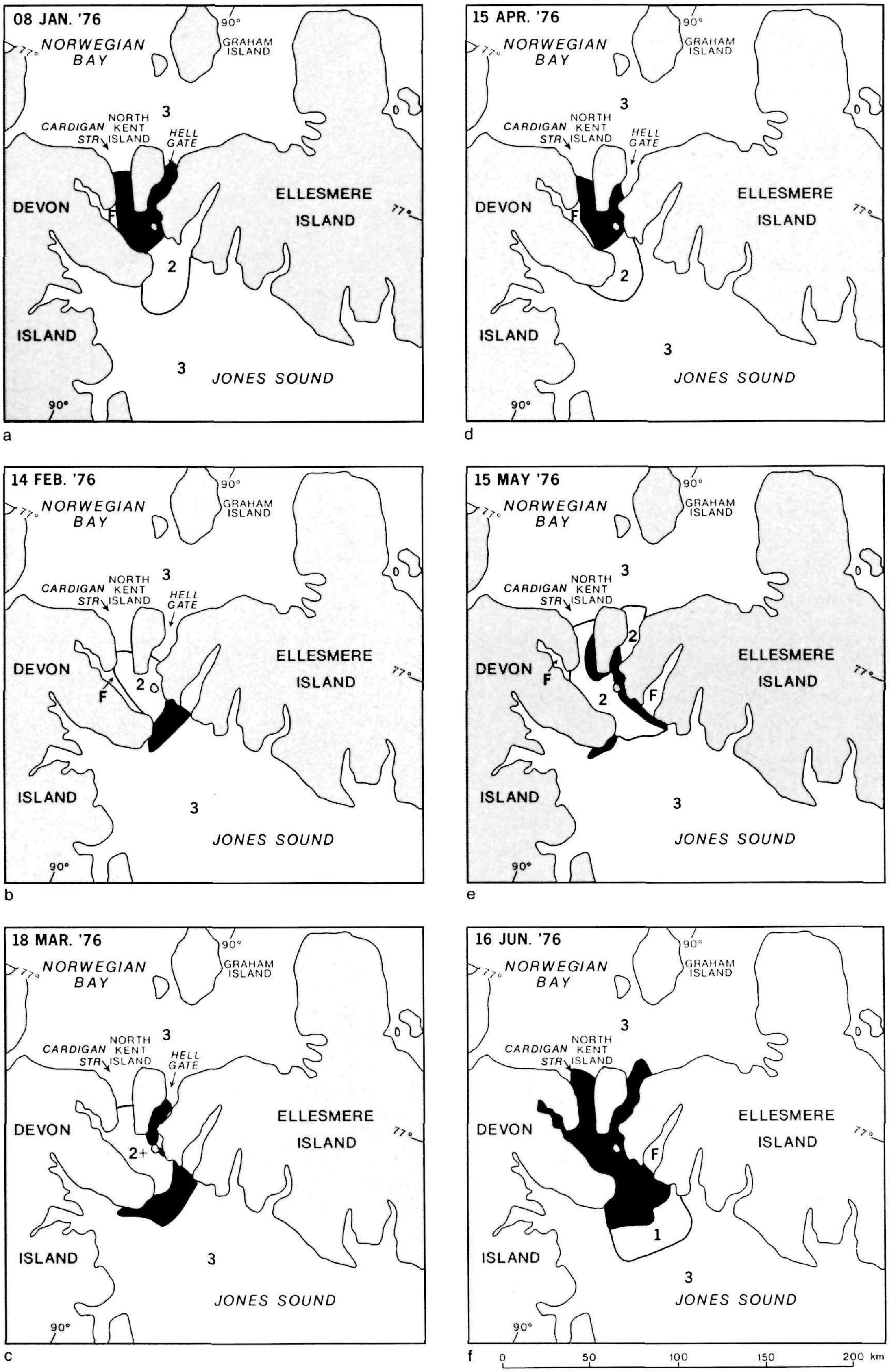
A well-known polynya system occurs in the vicinity of Dundas Island (see frontispiece) and Penny Strait, probably because of the strong currents and predominantly shallow water that prevail throughout the area. Freeze-up usually occurs in this region in late September or early October, with the exception of 1976 when it took place in mid October. Freeze-up occurs first in Penny Strait and the area to the northwest of Cornwallis Island in Queens Channel and McDougall Sound. Wellington Channel and the area around Dundas and Baillie-Hamilton islands may have anywhere from 2/10 to 8/10 ice at this time. Within 2 weeks these latter areas freeze up as well, at which time there is a characteristic alignment of ice (Fig. 11*a*). Although the ice throughout this region is usually composed of annual ice, in 1978 and 1979 northern Wellington Channel did not become free of ice during the summer. Therefore the connection to Lancaster Sound did not occur any further north than approximately Griffin Inlet on Devon Island.

In January (December in 1978), an area of open water appears in Couch Passage between Dundas Island and Baillie-Hamilton Island, or in Pioneer Channel between Dundas Island and Sheills Peninsula on Devon Island (Fig. 11*b*). This feature persists through the winter months (Fig. 11*c*, *d*). At its maximum extent, which usually occurs around the end of April or in early May, the waters between these land masses remain completely open (Fig. 11*e*). With the beginning of break-up, usually in June, Couch Passage and Pioneer Channel tend to clog with ice flowing from Penny Strait, presumably because of the southerly flowing currents in this region (Fig. 2). The shallow depth of the channels and the positions of the islands combine to act as a bottleneck. The jammed ice disappeared in early to mid July in 1976 and 1977, and around the end of July in 1975 and 1978. In 1979, because of the ice conditions, it was not possible to tell when or even if the ice jam disappeared.

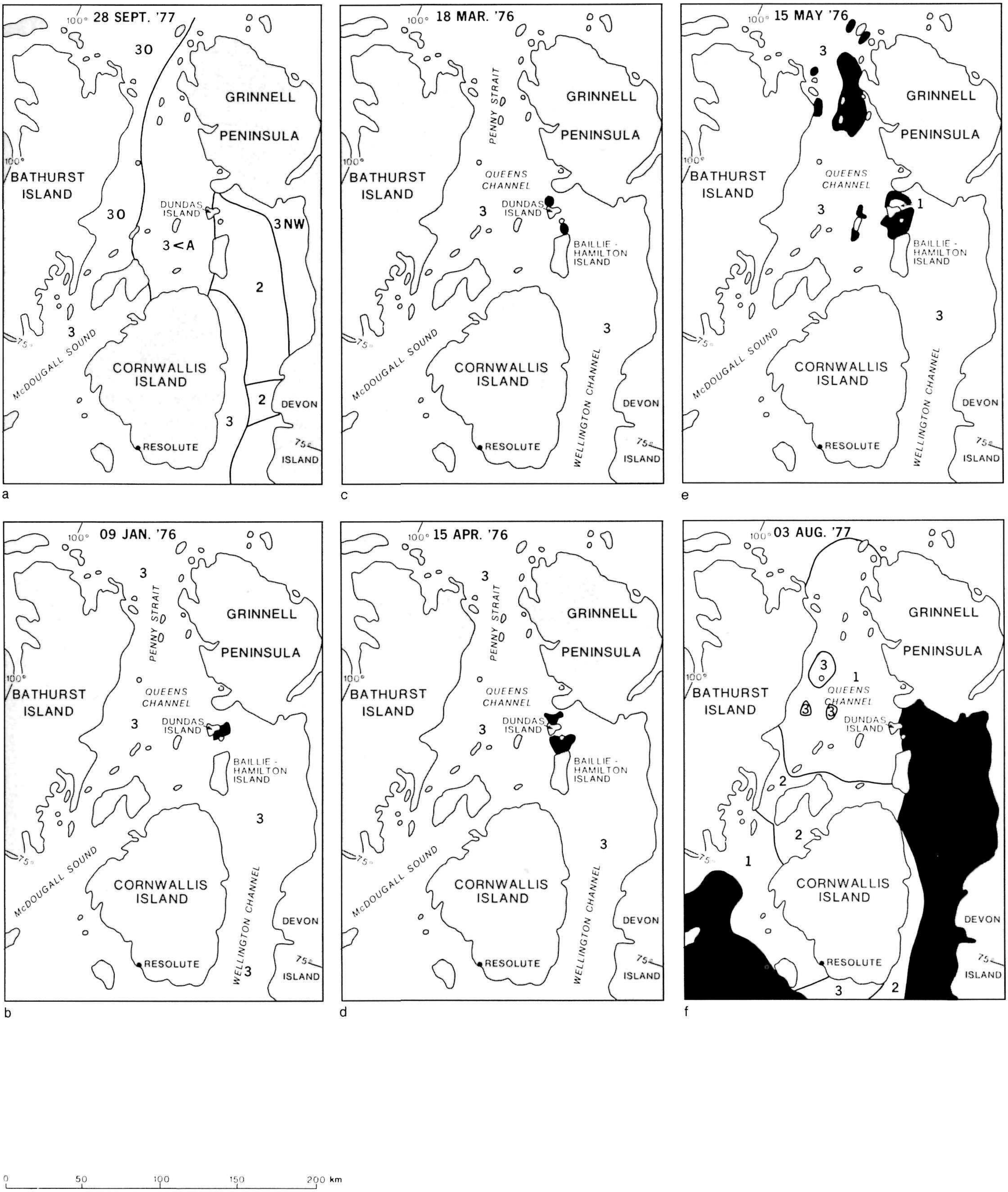
Several small polynyas develop in May or early June along the eastern side of Penny Strait (Fig. 11*e*). Although these polynyas may not open particularly early, they precede break-up and seem to occupy a constant location from year to year. As break-up proceeds through June, the separate patches of open water coalesce until the whole strait is clear of ice (usually by mid June). Finally, by late June to mid July, the open waters of Penny Strait link up with the open water around Dundas Island, although in 1978 the two areas did not unite until the beginning of August. The area around Dundas and Baillie-Hamilton islands joins the open water in Wellington Channel (and hence Lancaster Sound) sometime between mid July to mid August (Fig. 11*f*). In 1978 and 1979, these areas did not join because Wellington Channel remained full of ice as far south as approximately Griffin Inlet.

Southerly flowing currents carry ice from Queens Channel and Penny Strait south through Wellington Channel to Lancaster Sound. McDougall Sound, between Bathurst and Cornwallis islands, was never observed to be completely free of ice in any of the 5 years.

Figures 10a–f
Maps of the Hell Gate – Cardigan Strait polynya, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



Figures 11a–f
Maps of the Queens Channel – Penny Strait polynyas, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



5.11. Arctic Ocean lead system

The Arctic Ocean is covered with pack ice which, under the forces of currents and winds, gradually moves in a clockwise direction. A zone of landfast ice forms along the outer Queen Elizabeth Islands, western Banks Island, and along the mainland coast (Fig. 12). Freeze-up along Banks Island can begin between the first of October (as in 1978) and the first of November (as in 1977), or a week or two later along the mainland coast.

The boundary between the fast ice and the pack ice is commonly marked by a shorelead system which remains relatively constant from year to year, and corresponds to the continental shelf (Fig. 12). The lead system is often continuous from north of Ellef Ringnes Island south to Cape Bathurst on the mainland, and then west past Point Barrow, Alaska. In January 1975 it extended as far north as Robeson Channel, between Ellesmere Island and Greenland.

The lead opens and closes as the pack ice moves; thus it varies in width and continuity. It takes the form of some combination of leads, cracks, and patches of open water (Fig. 12) which in places may stretch up to tens of kilometres wide during winter. For short periods, open water may exist in the lead but, because of the rapid rate of ice formation in winter, there is usually a cover of new ice (Weeks 1978). As stated previously, it was not possible to differentiate new ice from open water on the NOAA imagery, so that all dark areas were mapped as open water. As the lead closes, the new ice is rafted or forced into pressure ridges which can be seen clearly even on NOAA images. From the daily coverage provided by the NOAA imagery, it appears that the pack ice moves in and out quite frequently so that open water and/or new ice are persistent along this shorelead system.

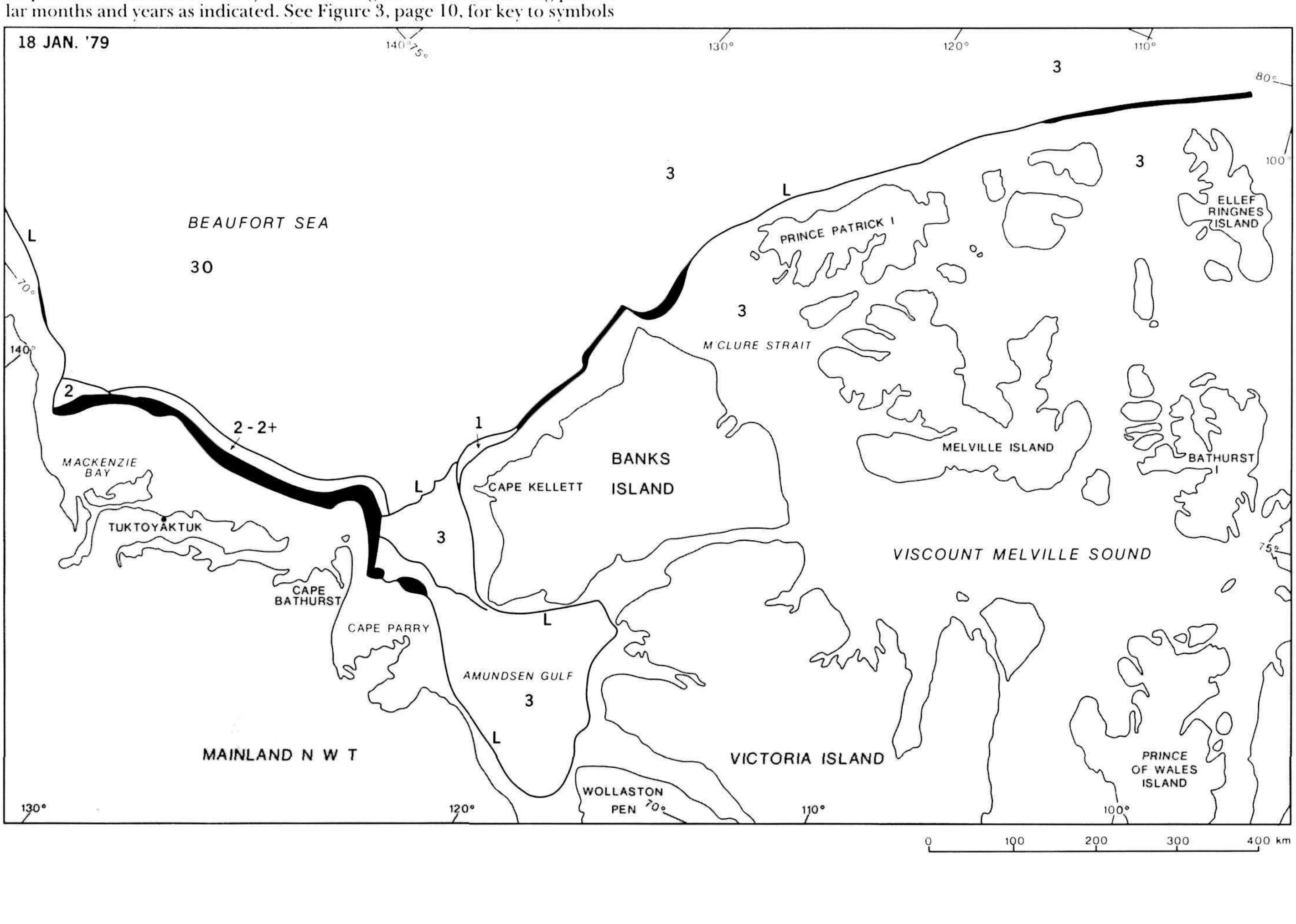
For ease of discussion, we have divided the Arctic Ocean lead system into the following regions: (1) Prince Patrick Island/M'Clure Strait/Banks Island, (2) Cape Bathurst/Amundsen Gulf, and (3) Cape Bathurst to Point Barrow, Alaska.

5.11.1. *Prince Patrick Island*

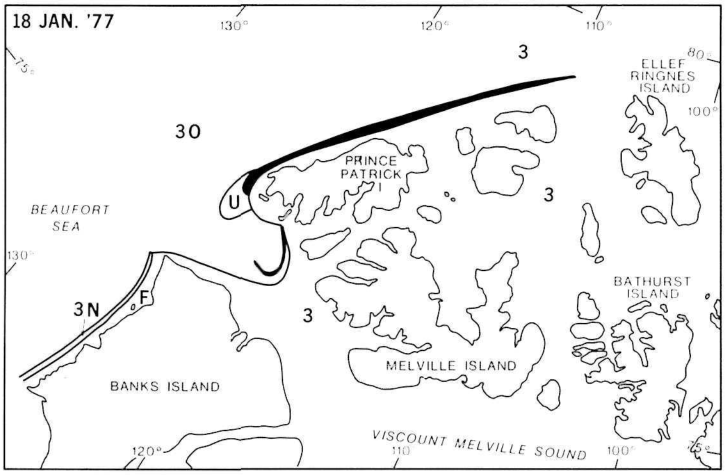
The northwestern coast of Prince Patrick Island (and northwards to Borden and Ellef Ringnes islands) usually remains ice-bound throughout the year. Open water occurred along the Arctic Ocean shorelead as early as mid November in 1975 and 1976, while in other years it occurred sometime in January (e.g. Fig. 13*a*). In 1975, open water remained until early July (although none was present in March, April, and the first half of May). In 1976, it persisted right through until early June, while in 1977 there was open water until early July (except in April). In 1978 there was some open water in February but, because of the combination of heavy cloud and poor or missing images, we have no further data until early June, when there was no open water. In 1979, there was open water until mid June (but no data for February and March because of bad weather).

The maximum extent of open water occurs sometime in the period from April to July, frequently in May (e.g. Fig. 13*b*). At this time, open water is usually continuous from Cape Bathurst to north of Ellef Ringnes Island. By July, with increased mobility of the pack ice, the lead tends to close off and ceases to be a continuous feature. In some years, however, isolated open water can occur after this date: in early July and mid August of 1978, there was open (or semi-open) water between Borden and Ellef Ringnes islands and from

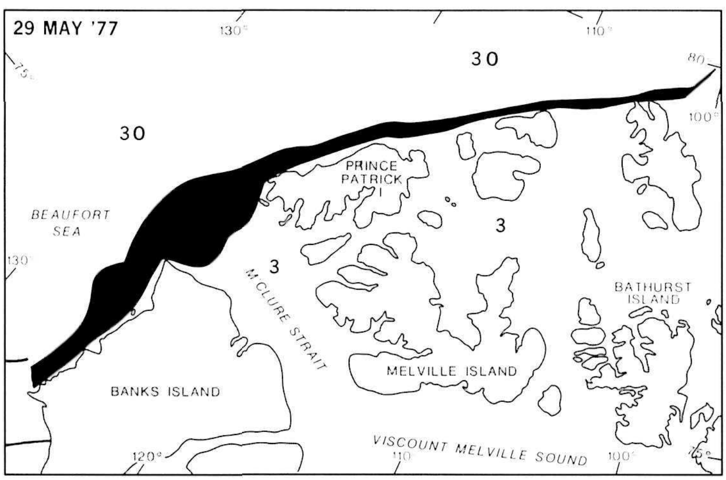
Figure 12
Map of the Arctic Ocean lead system, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



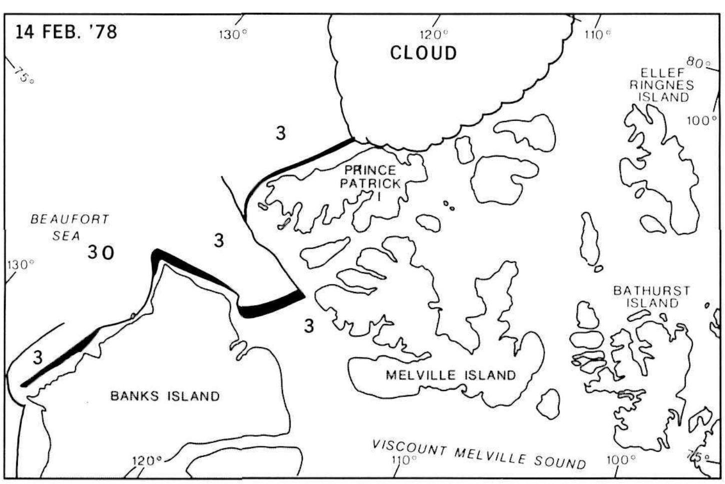
Figures 13a–e
Maps of the Prince Patrick Island lead system, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



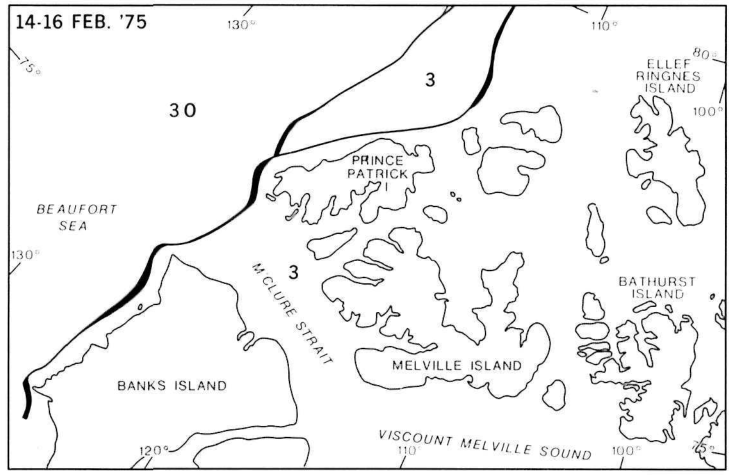
a



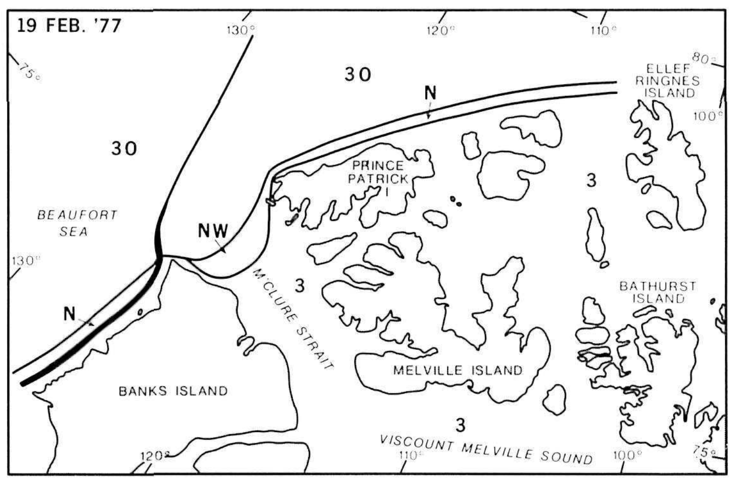
b



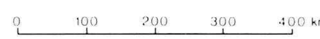
c



d



e



late August to mid September 1978 and in late August 1979 there were various openings offshore between Borden and Prince Patrick islands.

Associated with the Prince Patrick system is an area of open water at the entrance to M'Clure Strait. This is perhaps a shear zone between the Arctic pack ice and the fast ice in the strait. Open water can appear there as early as January (1977, Fig. 13*a*) or February (1975, Fig. 13*d*), and there is usually open water by mid May in most years. In 1978, however, the lead was closed between April and July. Earlier in the year during February, open water occurred in M'Clure Strait near Mercy Bay on Banks Island (Fig. 13*c*); however, the normal position is like that shown in Figure 13*d* and *e*. Open water is generally not present in M'Clure Strait after the beginning of July (although it was in 1977).

Also related to the Prince Patrick system is an opening extending south along the western side of Banks Island. Open water first appeared here at various times ranging from early January in 1977 to late February in 1975 and 1978. Like the Prince Patrick lead, the presence of open water is determined by movements of the pack ice, and it attains its maximum extent between May and July (Fig. 13*b*). In late summer the pack recedes northwestwards, usually leaving the west coast of Banks Island open by early September. Landfast ice starts to form in the north, and the pack moves back toward the shore sometime between mid October and early November (1976, 1977, 1979). In 1975, this occurred in late August/early September, and in 1978 it did not open up in summer to the same extent as it had in other years.

5.11.2. *Cape Bathurst*

Some open water can be found in virtually all months somewhere in western Amundsen Gulf in the area of Cape Bathurst, Cape Parry, and Cape Kellet (Banks Island). Open water can appear as early as sometime in December, although it is not until April that a characteristic form to the polynya appears. Open water appears along the fast-ice boundary, although the current flowing eastwards into Amundsen Gulf may play a role.

Freeze-up occurs in this region sometime between mid October (1975, 1978), early November (1976, 1979) and mid November (1977), and takes 2–3 weeks. The pattern of freeze-up progresses along the coast from the northwest, terminating in Amundsen Gulf. Overall, the ice cover is made up primarily of annual ice. By mid December, a characteristic pattern of cracks and leads starts to develop along the fast-ice boundary, which follows the edge of the continental shelf. This system extends right around Amundsen Gulf (Fig. 14*a*).

During each of the 5 years an open lead developed off the eastern side of Cape Bathurst sometime in January (Fig. 14*a*). This coincided with the appearance of open water just north of Cape Parry in 4 of the 5 years. Open water remains in the general area, in some form, until late May to early June when, characteristically, the area between Cape Bathurst and Cape Kellett opens up to form a disintegration area. Until April, the size, shape, and location of open water is quite variable by month and by year (e.g. Fig. 14*b*). By April in most years, however, the polynya exhibits a more or less typical form (Fig. 14*c*–*f*). With the advance of break-up, the open water between Cape Bathurst and Cape Kellett enlarges into Amundsen Gulf. In addition, open water develops northwards, along Banks Island, and westwards to Mackenzie Bay (see Fig. 14*g*, *h*). The extent to which the shorelead polynya system in the Beaufort Sea is open is mainly dependent upon wind since this influences the movement of the Arctic pack. The coast was open to Mackenzie Bay in all five summers, and as far west as Barter Island in three.

5.11.3. *West of Cape Bathurst*

A recurrent crack and lead system develops between the landfast ice and arctic pack, along the coast west from Cape Bathurst to beyond Point Barrow. According to Marko (1975), "the seaward boundary of landfast ice may usually be identified by its coincidence with a persistent lead (along the Tuktoyaktuk Peninsula) that roughly follows the 30-m depth contour and changes its position very little from year to year." Marko also identifies a transition zone between the landfast ice and pack ice, which includes open water, new ice, and mobile ice. This transition zone is visible on the NOAA imagery.

Freeze-up along the western arctic coast usually occurs first in the area between Mackenzie Bay and Point Barrow sometime between the end of September (as in 1975) and the beginning of November (as in 1977, 1979). In the Cape Bathurst – Mackenzie Bay area, freeze-up occurs roughly 2 weeks later, between mid October (as in 1975) and mid November (as in 1979). West of Point Barrow, freeze-up is usually later still, between the end of October (1975) and mid November (1976, 1979). The crack and lead system along the boundary of the landfast ice usually appears about the middle of November.

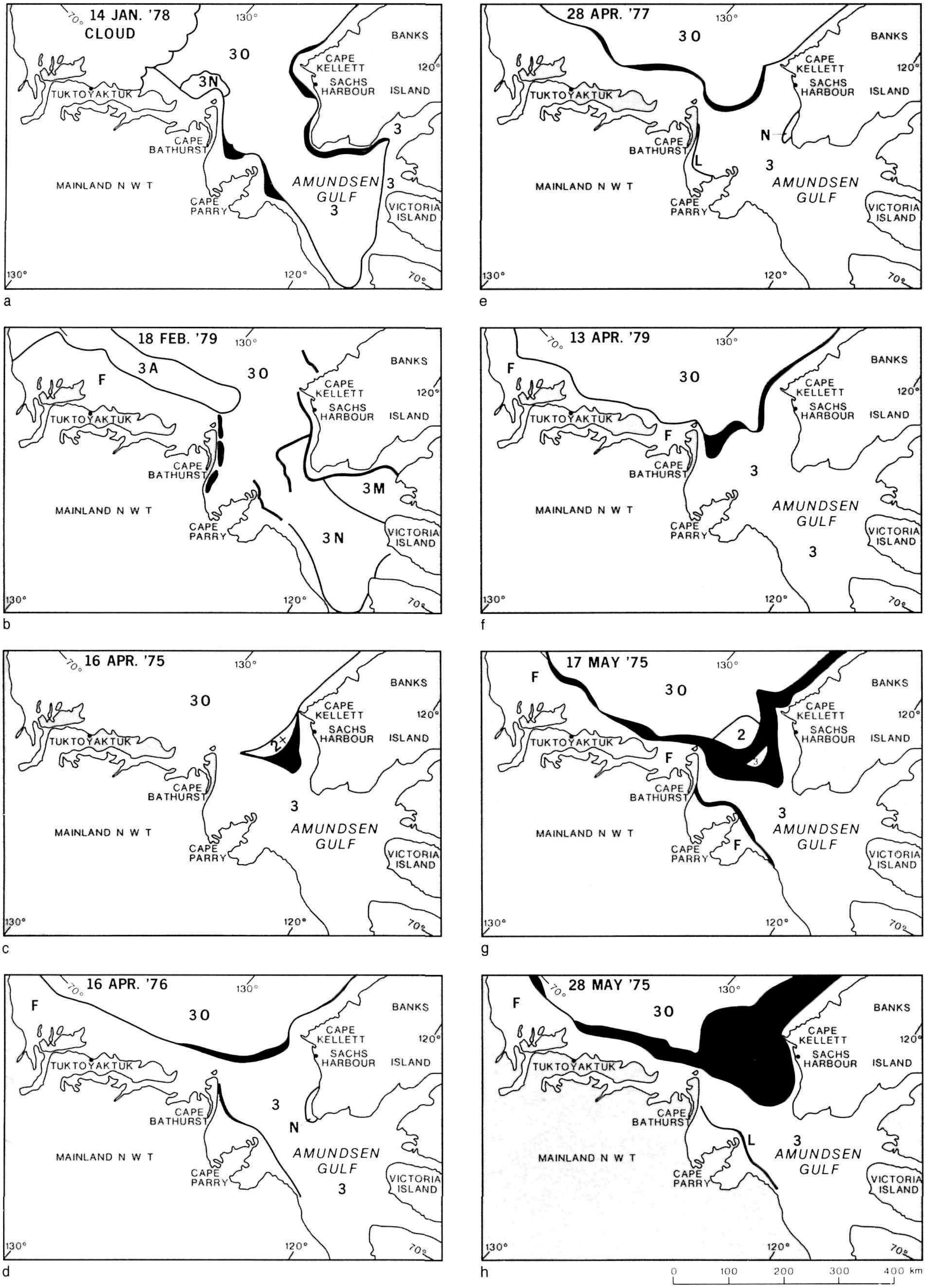
Patches of open water and new ice occur frequently during the winter between Cape Bathurst and Mackenzie Bay (Fig. 15*a*, *b*). As early as November (1976) or December (1975, 1977) open water may appear. Throughout the winter months, openings can be found within this area, but it is not usually until mid May that the open water is continuous from Cape Bathurst to Mackenzie Bay. There was a continuous opening in January 1979, and in 1978 it developed in mid February and remained throughout the winter.

In contrast to the region discussed above, sizeable areas of open water rarely occur between Mackenzie Bay and Point Barrow for any length of time during the winter. The lead along this part of the coast tends to remain closed. In the area west of Point Barrow, however, open water and new ice is evident in most months, but, again, it does not become continuous and extensive until about mid May (Fig. 15*c*).

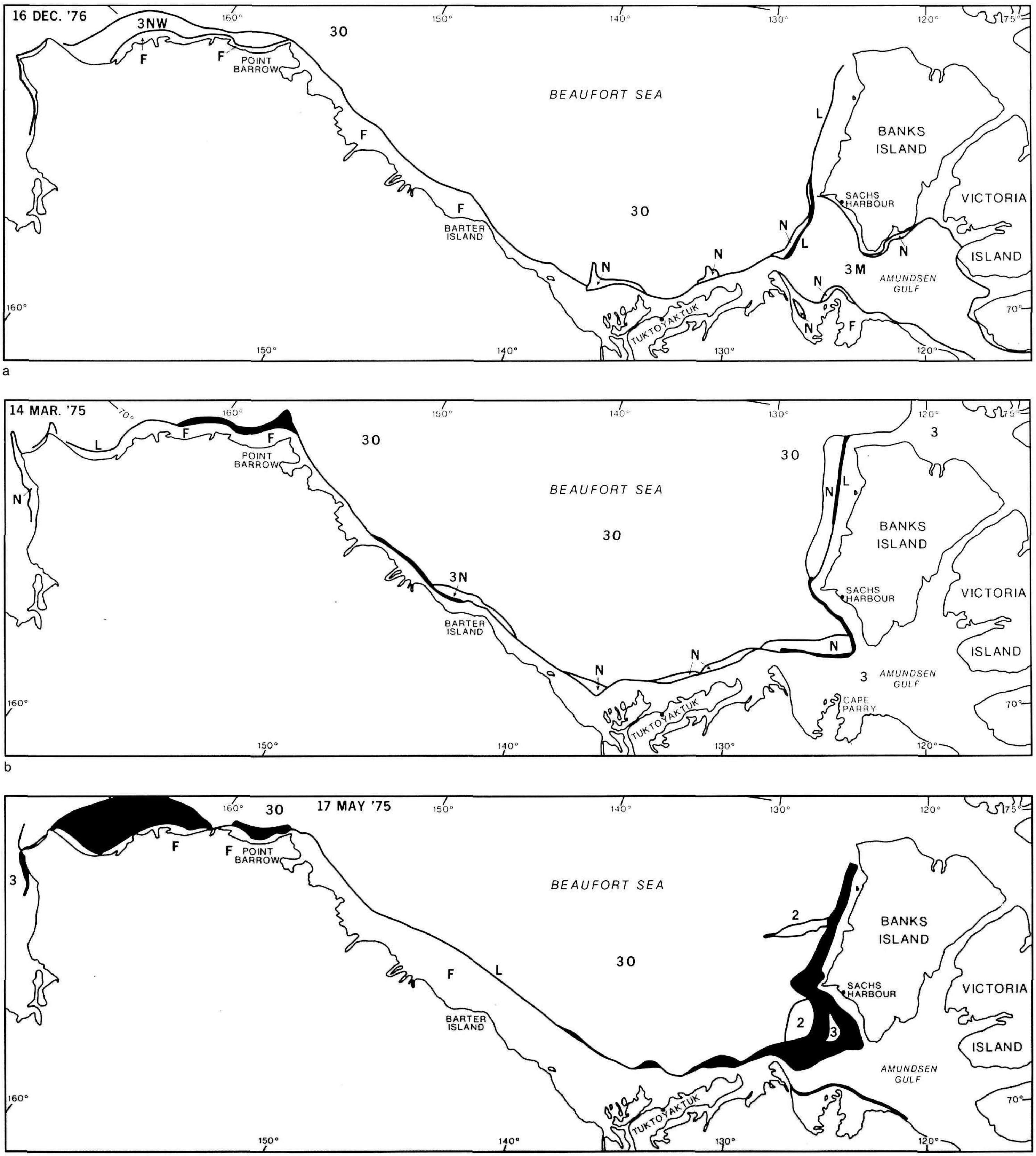
Break-up, which is characterized by progressive widening of the lead system, usually commences in mid June (except mid May in 1979). As break-up progresses, a narrow continuous lead develops along the whole coast from Cape Bathurst to Point Barrow, with the region between Mackenzie Bay and Point Barrow being the last to open. The lead first becomes continuous sometime between mid July and mid August, with the exception of 1975 when the coast remained ice-bound. By the end of September or early October, the lead enlarges to quite an expanse. Off Point Barrow, the open water at the maximum extent was from 60 km (in 1978) to 450 km wide (in 1979).

The reader is referred to the recent paper by Carleton (1980) for a description of the Cape Thompson polynya, off northwestern Alaska.

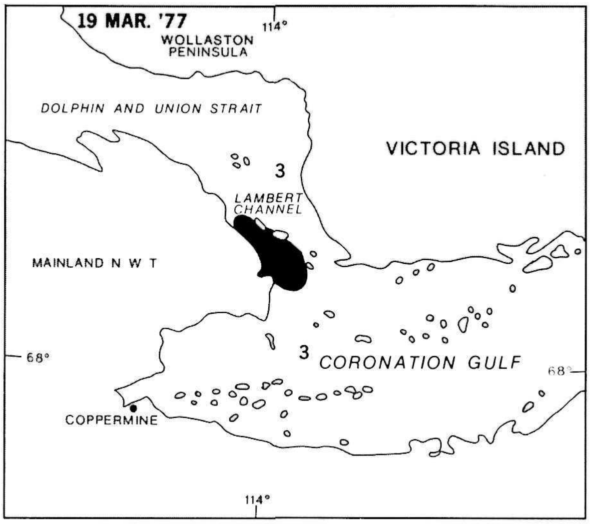
Figures 14a–h
Maps of the Cape Bathurst polynyas and adjoining lead systems, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



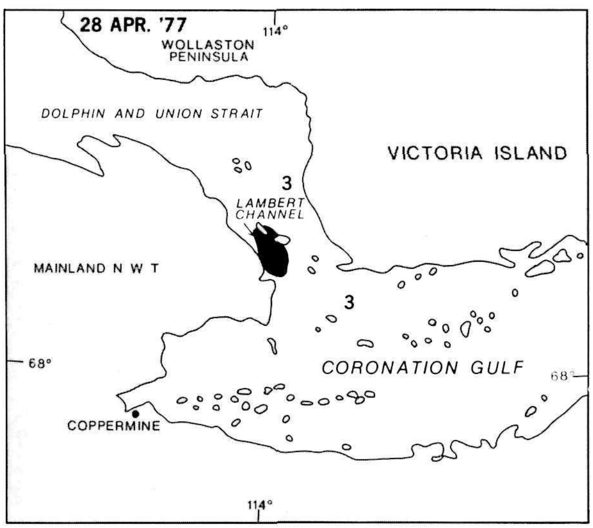
Figures 15a–c
Maps of the lead systems west of Cape Bathurst, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



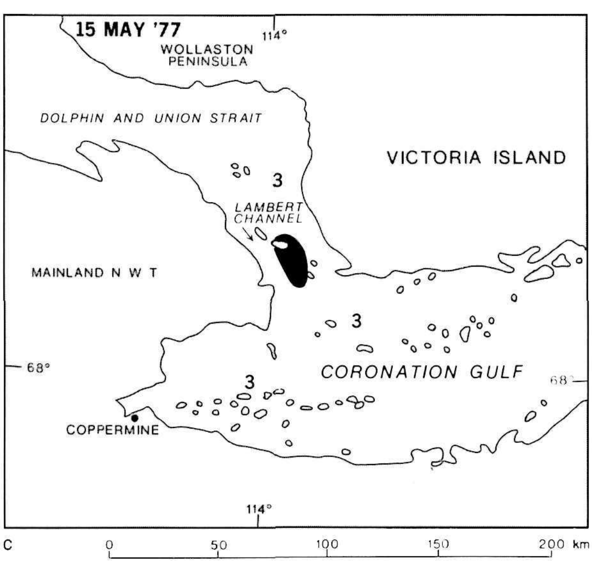
Figures 16a–c
Maps of the Lambert Channel polynya, showing ice conditions during particular months and years as indicated. See Figure 3, page 10, for key to symbols



a



b



c

5.12. Lambert Channel

There is a small polynya in southern Dolphin and Union Strait, between Victoria Island and the mainland. Open water appeared in February in 1978, by mid March in 1977, by mid April in 1979, while in 1976 it did not occur until June. In 1975 it was difficult to determine the earliest date, because of heavy cloud cover. It was, however, open in early July, when surrounding areas were still covered with 10/10 ice. In mid May 1975, there seemed to be open water in the Duke of York Archipelago, in the centre of Coronation Gulf.

Freeze-up begins between mid October and early November in Coronation Gulf and along the mainland coast. Lambert Channel freezes before the eastern side of Dolphin and Union Strait and is usually ice-covered by the end of October or the beginning of November.

Lambert Channel is very shallow in places and contains numerous shoals. Hydrographic charts indicate it has a strong current with heavy tidal rips. Open water usually appears first on the southwestern side of Lambert and Camping islands in Lambert Channel (Fig. 16*a–c*). The polynya typically remains until break-up commences in the first part of July and connects with Amundsen Gulf in mid to late July (1976, 1977) or early August (1975, 1978, 1979).

5.13. Franklin Strait

A small polynya area recurs on the eastern side of Franklin Strait in a group of islands known as the Tasmania Islands (Stirling, this publication, Fig. 1). This polynya is not visible on NOAA imagery, but has been identified on Landsat imagery. It is irregular in shape and approximately 1½–2 km in diameter. Young unstable ice prevails in this area, apparently because of strong currents that pass through the strait. Patches of open water are present by April in some but not all years (R.E. Schweinsburg, pers. commun.).

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Physical causes and biological significance of polynyas and other open water in sea ice

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1. Abstract

Little is known about the biological and physical oceanography of polynyas. Until very recently, these relatively small areas have been largely ignored by physical oceanographers, presumably because physical oceanographers like to study whole oceans or at least inland seas, gulfs, or coastal zones as a whole. Biologists are aware that polynyas and other areas of open water in sea ice are important to seabirds and mammals, and much information has accumulated concerning the species that use them. In contrast, very little is known about the lower levels in the food web upon which the birds and mammals depend, or about the difference between areas of open water during the winter and ice-covered areas in terms of basic biological production.

The literature relevant to the topic has been searched and summarized, with the following results:

1. The most important factor in the formation and maintenance of polynyas and flaw leads is the wind.

2. The constant formation of new ice in polynyas must give rise to an increase in salinity in the surface water, causing vertical exchange of water and the bringing of heat up from deeper layers. This effect has not yet been demonstrated in the field.

3. Many polynyas, especially the smaller ones, are maintained by strong set or tidal currents.

4. Upwelling at glacier faces and shelf ice faces is well known but as yet little studied. This process can maintain open water with a constant supply of planktonic organisms to the surface.

5. Diatom populations developed within the ice itself have been investigated intensively since 1960, but the significance of this production quantitatively is still largely unknown, though probably considerable. The diatoms support an ice-associated fauna consisting of crustacea and other invertebrates, cod (both *Boreogadus* and *Arctogadus*, more commonly the former), and a few species of birds and mammals.

6. The ice-edge ecosystem is clearly most important and ecologically extremely interesting. Although it is not yet understood in detail, there is an exchange of energy along the ice edge between the sub-ice system, the open water, and, at least in coastal regions, the benthos. It is the ice edge rather than the open water of polynyas that appears to be the key to much of the biological significance of these areas.

7. It is suggested that attention should be turned once more to a matter touched upon by research in the 1930s and since abandoned, namely the possible biological effects of water polymers involved in the formation of ice.

2. Résumé

On connaît mal la biologie et l'océanographie physique des polynies. Jusqu'à très récemment, ces étendues relativement petites ont été en grande partie laissées pour compte par les spécialistes de l'océanographie physique sous le prétexte que ceux-ci aiment à étudier des océans entiers ou à tout le moins des mers intérieures, des golfes ou des zones côtières dans leur ensemble. Les biologistes savent que les polynies et autres étendues d'eau libre dans la glace de mer sont importantes pour les oiseaux de mer et les mammifères et ont accumulé beaucoup de renseignements sur les espèces qui les fréquentent. Par ailleurs, on connaît très mal les échelons inférieurs de la chaine trophique dont dépendent les oiseaux et les mammifères ou les différences entre les étendues d'eau libre et les secteurs recouverts de glace quant à la production biologique de base.

On a examiné et résumé la documentation pertinente pour en venir aux conclusions suivantes:

1. Le facteur le plus important quant à la formation et au maintien des polynies est le vent.

2. La formation constante de nouvelle glace dans les polynies doit entraîner une augmentation de la salinité de l'eau de surface qui provoque un brassage vertical et la remontée de chaleur des couches profondes. L'existence de ce processus n'a pas encore été démontrée sur place.

3. Un grand nombre de polynies, en particulier les plus petites, sont maintenues par de forts courants de marée ou de direction définie.

4. La remontée d'eau profonde aux fronts de glaciers et de plates-formes de glace est un phénomène bien connu mais peu étudié. Ce processus peut entretenir un approvisionnement constant en organismes planctoniques à la surface des étendues d'eau libre.

5. Les populations de diatomées formées à l'intérieur des plates-formes de glace mêmes ont fait l'objet d'études intensives depuis 1960, mais leur production est encore mal quantifiée quoique probablement considérable. Les diatomées assurent la subsistance d'une faune associée à la glace et regroupant des crustacés et d'autres invertébrés, la morue (*Boreogadus* et *Arctogadus*, plus souvent la première espèce) ainsi que quelques espèces d'oiseaux et de mammifères.

6. L'écosystème de la lisière des glaces est de toute évidence des plus important et extrêmement intéressant sur le plan de l'écologie. Même si ses caractéristiques détaillées sont encore mal comprises, il existe un échange d'énergie le long de la lisière de glace entre le système sous la glace, l'eau libre et, dans les régions côtières du moins, le benthos. L'importance des polynies en biologie semble reposer en grande

partie sur la lisière des glaces plutôt que sur l'étendue d'eau libre.

7. Il est suggéré de reprendre les recherches sur un sujet abordé au cours des années trente et abandonné depuis: les effets biologiques de "l'hydropolymère" au niveau de la formation de la glace.

3. Introduction

Polynyas vary in size from small "spots" such as the circular hole in the ice of Cambridge Fjord in Baffin Island only 60 to 90 m in diameter (I.M. Dunbar 1958), to very large open water regions such as the North Water (Smith and Rigby, this publication, Fig. 3) in Smith Sound and northern Baffin Bay, some 10^5 km^2 in area (Müller *et al.* 1980). The North Water, described in more detail below, is the largest polynya in Canada and perhaps in the world.

The distribution of polynyas and more important shoreleads in the Canadian Arctic is shown by Stirling (this publication, Fig. 1) and in more detail by Rigby and Smith (this publication, Fig. 1). These maps are no doubt incomplete, for new polynyas are discovered from time to time and several must still be unrecorded. The most important are situated within the three links between the Arctic Ocean and northern Baffin Bay, in Smith, Jones, and Lancaster sounds, in addition to the eastern Beaufort Sea, and the shoreleads of Hudson Bay. Others are in the regions of Hell Gate and Cardigan Strait, Queens Channel and Penny Strait, Amundsen Gulf, Fury and Hecla Strait and northern Foxe Basin, Bellot Strait, Cape Bathurst, Cumberland Sound and Frobisher Bay, and Cambridge Bay and Makinson Inlet along the coastline of Ellesmere Island. The Makinson Inlet polynya was just recently described (Sadler 1974). Offshore winds open up lead systems along the east coast of Baffin Island and along the northwest limits of the Arctic Archipelago. The distribution of polynyas north of Parry Channel is given by Schledermann (1980).

4. Physical causes of polynyas and flaw leads

Kupetskii (1962) and Dunbar and Dunbar (1972) have discussed the history of speculation and research on the causes of open water in winter, and Kupetskii (1959) published an interesting discussion of the causes and effects of polynyas. The subject can best be introduced by describing the mechanism of the North Water.

The North Water was first recorded in 1616 by William Baffin. It was named by the whalers in the 18th or early 19th century, who travelled through these relatively ice-free waters along the West Greenland coast while en route to the Smith Sound open water, which was known to be frequented by the Greenland right whale. Each year the whalers followed the ice break-up along the West Greenland coast, where the ice disappeared first in each season owing to the influence of the comparatively warm West Greenland Current. The earliest recorded entry into the North Water by a sailing vessel is 25 June 1834, the earliest by a steam vessel 3 June 1871, and the estimated average date (for sailing vessels) is the last week in July (I.M. Dunbar 1972*a*). Smith and Rigby (this publication, Fig. 3) show the average monthly extent of the polynya.

Elisha Kent Kane (1853) was so impressed by the expanse of open water that he jumped to the hasty conclusion that he had come to an open polar sea. Matthew Fontaine Maury (1870) supported this open Arctic Ocean theory, and in doing so he produced one of the arguments which have been put forward to explain the formation and maintenance of the North Water.

> There is an under current setting from the Atlantic through Davis's Strait into the Arctic Ocean, and there is a surface current setting out. Observations have pointed out the existence of this under current there, for navigators tell of immense icebergs which they have seen drifting rapidly to the north, and against a strong surface current. These icebergs were high above the water, and their depth below, supposing them to be parallelopipeds, was seven times greater than their height above. No doubt they were drifted by a powerful under current.
>
> Now this under current comes from the south, where it is warm, and the temperature of its waters are perhaps not below 32°; at any rate, they are comparatively warm. There must be a place somewhere in the Arctic seas where this under current ceases to flow north, and begins to flow south as a surface current; for the surface current, though its waters are mixed with the fresh waters of the rivers and of precipitation in the Polar basin, nevertheless bears out vast quantities of salt, which is furnished neither by the rivers nor the rains.

Maury's idea was basically sound. Clearly, most of the upper arctic water layer of the Arctic Ocean is derived ultimately from the Atlantic water below it; but this does not affect the formation of the North Water polynya, which is on a much smaller and more local scale. But the notion of upwelling warm water to explain the phenomenon of the North Water remained and involved the warm water of the West Greenland Current. M.J. Dunbar (1951*a*), Kupetskii (1962), and Nutt (1969) have described the history of this idea. Hamberg (1884) and Mecking (1906) believed that this warm water came to the surface in the North Water area. The work of two 1928 expeditions, however, showed that whether or not West Greenland water entered Smith Sound at depth (and there is evidence that it does), there was no evidence of any upwelling in the North Water area. Although this appears to be true in summer, there is speculation and some evidence that it may not be true during winter. In 1928, there were two expeditions to the North Water, the Danes in the *Godthaab,* and the United States Coastguard expedition in the cutter *Marion* (Riis-Carstensen 1931, 1936; Kiilerich 1933, 1939; Smith 1931). Smith took the view that the North Water was caused simply by the maintenance of a strong southward current:

> It seems...that instead of a warm northward inflow, this persistent polynya in Baffin Bay is maintained by a set in the opposite direction. The fast ice in Smith Sound is so strong that it resists the current, but that formed just to the south is swept away, leaving open water behind it. This explanation is supported, moreover, by the recorded drifts of several ships and ice floes (Smith 1931).

Kiilerich (1933) also called for a strong southward current, but he had a more complex theory. He supposed that during winter the density of the mass of water within Smith Sound must be fairly uniform vertically, that the vertical stability of the water is therefore low, and that a continual vertical exchange of water must occur throughout the winter. He believed that fairly dense surface water from the north was heavier than the Baffin Bay water and the remnant of the West Greenland water which penetrates as far as Smith Sound. Subsequent winter work in the Arctic Ocean does not support this ingenious idea. Nevertheless, Kupetskii (1959, 1962) has recently revived the hypothesis of instability of the water column in winter.

Kupetskii (1962) also proposed, somewhat along the lines of Smith (1931),

> that North Water is an ordinary polynya such as are found in all large ice covered areas and is caused principally by the removal of ice from a leeshore [actually a weather shore—MJD] "by the prevailing winds, in this case, the north and northeast winds. But this ice removal has effects on the hydrological conditions in that, because of the open water, 4.5 times as much ice is formed as would be the case were it not removed. This excessive ice formation causes much deeper vertical convection and his theoretical calculations showed that this convection in certain places may extend to the bottom (quoted from Nutt 1969).

It has been demonstrated that the North Water, like other polynyas of this type, is an ice factory in which new ice is formed constantly (I.M. Dunbar 1972*b*). The "lee" (weather) shore in the case of the North Water is the arch, or ogive curve of ice jammed in the topographic constriction between Greenland and Ellesmere Island (between Pim Island and Cairn Point), which constriction itself leads to an observed increase in wind speed at that point. Smith's 1931 speculation has thus been fully vindicated.

Further apparent confirmation of the wind effect was obtained when, in February 1963, the Ice Island WH-5 blocked Kennedy Channel, and a "second North Water" (to use the term of I.M. Dunbar 1963) formed to the south of it. Both I.M. Dunbar (1963) and Nutt (1969) commented on the similarity between the anomalous development of the open water in 1963 and the regular development of the North Water.

Extending this review, Kupetskii's thesis concerning the formation of polynyas is as follows: (1) polynyas are caused by winds, on the North Water model, (2) the constant ice formation, which leaches out salt to the water below, causes high salinity at the surface, (3) the result is sinking, with vertical exchange of water between the surface and the water below, (4) this vertical exchange, in regions where there is an underlying layer of Atlantic water, reaches down to the warm water, which brings heat to the surface. Similar haline convection is postulated by Foster (1972) and Gordon (1978*a*) for the Antarctic. The heat brought to the surface both adds to the open water and releases heat to the atmosphere. The atmospheric effect does not concern us here, but Kupetskii's (1959) analysis of it is extremely interesting. He classifies winter weather conditions into three categories, depending on the presence or absence of polynyas and the presence or absence of an underlying warmer water layer.

In the light of these concepts, it is possible that the largest polynyas occur only where there is an underlying layer of warmer water. Such a situation exists in the instances of the North Water, the Cape Bathurst polynya southwest of Banks Island, the Baffin Island coastal flaw lead, the Antarctic polynyas and at least some of the northern Russian examples. An exception seems to be the flaw leads on either side of Hudson Bay.

Kupetskii's (1962) study of the North Water describes M.V. Lomonosov as stating as early as 1764 that "the natives near 80° on the northeastern Baffin shores had volunteered the information that the sea is free of ice and that the sea in that locality is quite navigable to sailors." Lomonosov, like Kane a century later, considered the North Water to be part of the supposedly ice free northern ocean. Kupetskii also quotes Petermann (1867) as concluding that the open water was caused by the influx of the warm waters of the West Greenland Current into the region (see Smith and Rigby, this publication, Fig. 2), and he credits Brown (1927) with the first suggestion that the North Water "was first formed under the action of winds, blowing from the icy cap on Greenland and driving off ice from the shores, and then as a result of a rise of warm water from the depths" (Kupetskii 1962). In addition, Kupetskii also points out that Koch (1928) held firmly to the sole agency of the north and northeast winds in the removal of the ice, and that Herdmann (1948), describing a similar polynya in the Antarctic, in Whale Bay in the Ross Sea, came independently to the conclusion that the physical causes were the same as those found for the North Water.

The details of Kupetskii's (1962) calculations of the ice formation and the sinking effect are worth quoting in full (I have made a few small changes in the translation text):

> For the average winter air temperature for the North Water, let us take the average temperature at Pond Inlet because that station...does not undergo the insulating effect of open water. With an average air temperature of −23° for the 24-h period on open water, 3.5 cm of ice is formed, according to the recognized formula of N.N. Zubov. For the entire winter from October to May, with a total of 5520 degree-days of frost, 190 cm of ice develops. But for this very time, 840 cm of ice are formed on the polynya and removed continuously. Thus, the total thickness of ice developing during the winter on the North Water is 840 cm which is 4.5 times greater than the thickness of ice forming under undisturbed conditions.

Again:

> The great amount of ice developing on the polynya causes a pronounced vertical movement in it during the winter. The usual convection associated with this is increased to a significant degree due to the direct cooling of the water and the supplementary repeated salinization with repeated ice formation. The ice is carried off but the salt remains. Hence the depth of winter convection in the North Water is anomalously great. Calculated by N.N. Zubov's method, the amount involved in this process shows that the formation of 3–5 m of ice is necessary for the vertical winter circulation to reach 600 m (to the occurrence of the warm deep water). The greatest penetration of vertical winter circulation to maximum depths of 2000 m takes place only due to cooling, but the warmth of the waters from the depths carried to the surface is sufficient to melt the ice layer to 1.5–2.0 m. Thus, the computation of the amount of ice forming in the polynya and the calculation of the elements of the vertical wind circulation in Baffin Bay support the contention that this circulation in the North Water area penetrates to the bottom and thereby favours, firstly, the removal of warm water from the depths to the surface, secondly, the transformation of these abyssal waters and, thirdly, the formation of the cold benthic waters of the bay.

Kupetskii suggests that:

> The distribution of oxygen may serve as confirmation of the supposed powerful vertical movement of water in the North Water. It is typical that in summer time the oceanographic investigations reveal a high degree of saturation in the northern portion of Baffin Bay. Even at the bottom the oxygen content does not fall below 82% and sometimes it reaches 96%, whereas in more southern regions of the bay (Baffin Bay) at the same depths the oxygen content is very much lower everywhere and does not reach 70%.

These theoretical studies have long caused oceanographers interested in the Arctic to point out the urgency of winter shipboard work in the North Water. Unfortunately, physical oceanographic work in the region has so far been done only in summer [references already given, plus Muench (1971), and Bailey (1957)], when conditions are probably totally different from the winter regime, as strongly suggested by the work recorded here. The North Water, after all, does not exist in the summer; it suffers the fate of one's lap when one stands up. The summer regime is probably quite irrelevant to the mechanics of the North Water, although the reverse is probably not true; that is, the fact that the polynya is open all winter leads to the rapid solar heating of the area in spring, when the surrounding regions are still ice-covered. This is interpreted as the reason for the high surface temperatures (above 5°C) found there in summer (M.J. Dunbar 1951*a*).

Present plans to ship natural gas year-round through the Northwest Passage (the Arctic Pilot Project being the most promising at the moment), if realized, will greatly change the logistic problems of working in the North Water during the winter. So far, the only winter field work in the region has been that of the North Water Project as organized by the late Fritz Müller; a glaciological and climatological enterprise that has already achieved much and promises much more (Müller *et al.* 1980). The work includes air photo surveys and the use of other remote sensing techniques (including the measurement of surface temperatures along set flight paths) that show the relative proportions of open water and ice, and also to some extent the differences between types of ice and snow cover. "The North Water," these authors write, "is not characterized by an open ocean, as a simple interpretation of the name would suggest, but it is an ocean part covered by thin pack ice." The ice is constantly in motion, so that open water appears always in one place or another. Figures 1 and 2 are examples of the ice movements photographed and measured in this work, and give an excellent impression of the whole area (including Jones and Lancaster sounds, where open water is also normal) and of the behaviour of the ice.

Change in the wind can open or close flaw polynyas throughout the winter, especially the smaller ones and the shoreleads. The larger flaw polynyas, such as the North Water, Lancaster Sound, and Jones Sound behave in the same way but their large areas make them less likely to be closed completely at any time. Working in the Bering Sea, Campbell *et al.* (1974) observed ice movements as related to wind pattern between 15 February and 10 March 1973, and reported that "anticyclonic (wind) activity advects the ice southward with strong ice divergence and regular lead and polynya pattern; cyclonic activity advects the ice northward with ice convergence, or slight divergence, and a random lead and polynya pattern."

The largest flaw leads normally found in Canada are in Hudson Bay (Stirling, this publication, Fig. 1). The Hudson Bay lead, seaward of the fast ice, is so wide as to have generated the belief that the whole of the bay, except for the fast ice region along the shore, stayed unfrozen all winter. This was a belief held also for other polar and subpolar regions, such as the Gulf of Bothnia, the Aral Sea, and a large part of the Ross Sea (Lebedev 1968). Zakharov (1967) writes, concerning flaw leads along the Russian arctic coast, "in the spring their size is so impressive that the first investigators formed an impression of a 'non-freezing polar sea'." Lebedev (1968) calculated a maximum size that is to be expected for a wind-generated lead in sea ice, depending on air temperature and wind speed.

In the Hudson Bay instance, the myth of an open bay all winter was dispelled by Hare and Montgomery (1949), who showed that the pattern of air temperatures over the whole region made an open Hudson Bay in winter very improbable. By overflying the area, they demonstrated that in fact the central bay is covered with ice in winter, although there normally exists a large flaw lead seaward of the fast ice on both sides of the bay and extending into northern James Bay. This flaw lead varies in width according to the direction of the wind from "about a mile and a half to 30 or 40 nautical miles" (Hare and Montgomery 1949).

In general, the wind pattern is the most important of the physical causes of polynyas and open water in the flaw zone. Vertical exchange caused by salinification of the surface water consequent upon freezing may play a secondary part, as described above. Possibly a part is also played by upwelling; this is the movement of water to the surface from subsurface depths resulting from the influence of wind or the entrainment effect (characteristic, for instance, of estuaries), or other forces. This term refers to active advection of deeper water, as opposed to the vertical exchange engendered by the formation of denser surface water.

Upwelling was not demonstrated in the North Water in summer, but the winter behaviour of the water has not been studied. The vertical structure of the water of the Nares Channel and Smith Sound region was first investigated by the British Arctic Expedition of 1875–76, from the results of which Moss (1878) identified two layers of water in Nares Strait near the threshold between the Arctic Ocean and Baffin Bay. (For a discussion of this whole matter, see Dunbar *et al.* 1967). An upper layer of Arctic Ocean surface water was found above a lower layer which Moss interpreted as northward-flowing Atlantic (West Greenland) water. The temperature increased from −1.5°C at 37 m to −0.6°C at 210 m, and the salinity (calculated from specific gravity measurements) from 33.35 o/oo to 34.72 o/oo. These measurements were confirmed during the U.S. coastguard cutter *Evergreen* cruise in 1963 (Franceschetti *et al.* 1964), when a lower stratum was found, a little north of the threshold between Kane Basin and Smith Sound; in it temperatures were between −0.07°C and +0.10°C and salinities were from 34.64 o/oo and 34.72 o/oo. Franceschetti *et al.* (1964), Dunbar *et al.* (1967), Muench (1971), and Greisman (1979*a*) all agree that such high salinities are not found in northern Baffin Bay, that this water enters Kane Basin from the Atlantic layer of the Arctic Ocean, not from Baffin Bay, and that there is no evidence of upwelling of this water, or of any Atlantic water, in the North Water area in summer. But the Atlantic layer water from the Arctic Ocean, entering Kane Basin and Smith Sound, is sufficiently close to the underlying Baffin Bay Atlantic layer to mix with it. Greisman (1979*a*) writes:

Figure 1
Northern Baffin Bay, showing movement of the sea ice from 20 March to 1 April 1973 (adapted from Müller 1980)

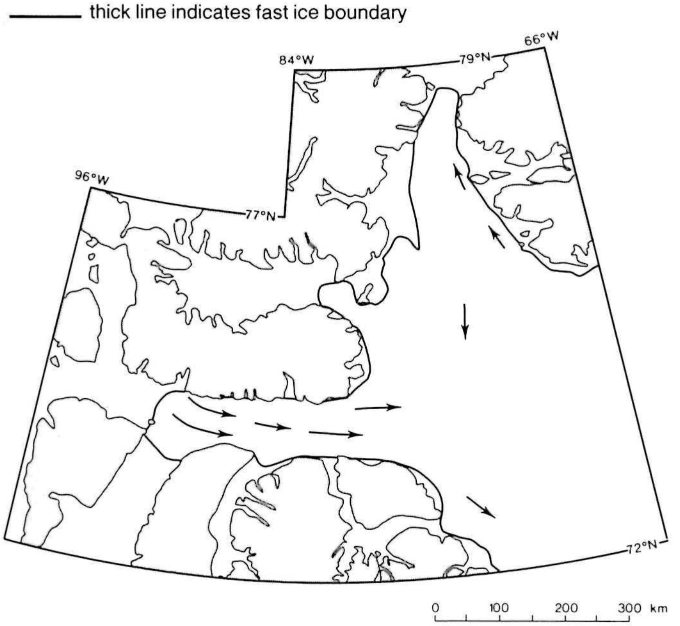
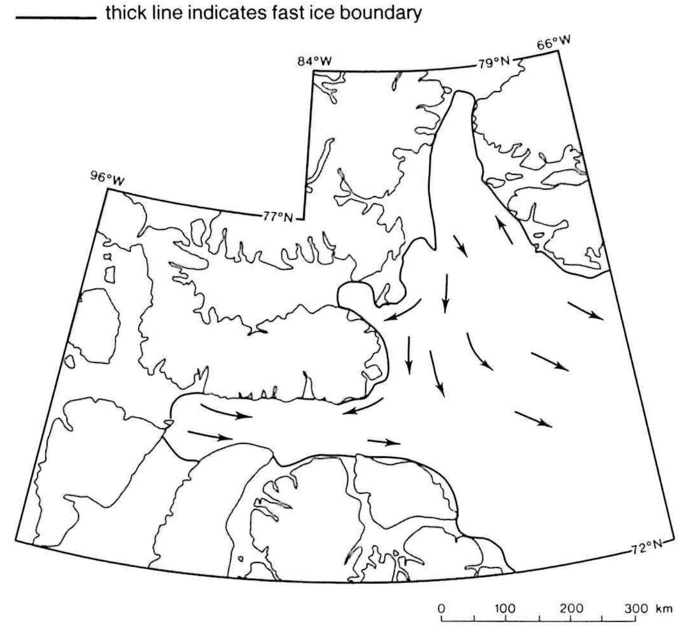


Figure 2
Northern Baffin Bay showing movement of the sea ice from 7 to 20 April 1973 (adapted from Müller 1980)



Mixing between Baffin Bay Atlantic water and inflowing Arctic Ocean (Atlantic) water occurs primarily in the southern Smith Sound region. Of the three channels entering northern Baffin Bay, only Smith Sound has sufficiently deep access to the Arctic Ocean to allow southward flow of Arctic Ocean water dense enough to occur at the same depth as, and therefore mix with, Baffin Bay Atlantic water.

The winter pattern, however, is probably different and has not yet been investigated at all. Buckley *et al.* (1979) demonstrated for the first time, west of Svalbard, the phenomenon of wind-driven upwelling along an ice edge when the wind blows parallel to the ice edge from the west or northwest. Such an effect had been suspected for some time, and probably upwelling of this sort occurs in the North Water in winter along the northern ice edge. There is also the possibility of an estuarine entrainment effect to the south of the Kane Basin – Smith Sound sill, an effect which may also operate in Barrow Strait at the western end of Lancaster Sound, and in Jones Sound, which might also contribute to the open water conditions in those regions. The existence of upwelling, however induced, would also tend to increase the biological productivity.

Of large polynyas such as the North Water, Cape Bathurst polynya, and the eastern Weddell Sea, Weeks (1980) writes categorically: "such polynyas are undoubtedly sites of upwelling."

Upwelling of deep water to the surface, wherever and however it occurs in the sea, is extremely important biologically: Sverdrup (pers. commun.) called it "deep ploughing." The inorganic plant nutrients (phosphates, nitrates, silicates) are formed by the bacterial breakdown of organic matter, the product in turn of living matter. Sinking of the organic detritus results in the formation of the nutrient salts at depths, for the most part, well below the limit of the penetration of light. In order to make these nutrients available to plants in the sunlit (euphotic) zone at the surface, they must be brought back to that upper region. The geography of productivity in oceans is the geography of upwelling, or other vertical instability in the sea.

Ice in sea water is known to cause upwelling for reasons other than the wind effect. Sandstrøm (1919), discussing the results of the Canadian Fisheries Expedition of 1914–15 in the Gulf of St. Lawrence, showed experimentally that melting ice caused an upwelling up the face of the ice and a surface current away from the ice and also a cooling and sinking of water beneath the ice. Hartley and Dunbar (1938) demonstrated upwelling at the sea face of an active ("tidewater") glacier in West Greenland and attributed the upwelling to the entrainment of salt water by a fresh melt-stream originating at the bottom of the glacier, causing an ice-free zone at the glacier face. Such ice-free zones, or "brown zones" (so called because they often carry up silt with the water) have been observed at several glacier faces in Svalbard and in Greenland, and information from the native population indicates that at least some of them stay open all winter.

Interest in these phenomena has been revived by several workers recently. Neshyba (1977) reported on upwelling along the vertical faces of large antarctic icebergs, caused by the melting of ice and the entrainment of salt water. Foldvik and Kvinge (1977) discussed the possibility of upwelling along a floating ice shelf in the Antarctic, caused by the observed supercooling of the water in contact with the underside of the ice and the subsequent release of ice crystals. Such an upwelling would be important, both physically and biologically, in the formation of polynyas. Matthews and Quinlan (1975) found a marked effect of glacial melt on upwelling in an investigation of tidewater glaciers in Muir Inlet, Alaska. Doake (1976) has examined the thermodynamics of the water–ice–salt system. Huppert and Turner (1978), in commenting on Neshyba's (1977) paper, discuss the effects of melting icebergs, and finally Greisman (1979*b*) has attacked the whole problem theoretically, concluding that "the upwelling effect due to melting is strongly dependent upon the temperature elevation of the ice above the freezing point." Greisman supports his conclusion by quoting field work on a glacier in d'Iberville Fjord, Ellesmere Island (Frozen Sea Research Group 1977).

Such upwelling effects at ice faces are all potential polynya-formers and, in the case of the "brown zone" studied by Hartley and Dunbar (1938), a polynya was in fact maintained in summer and apparently, according to local report, also in winter. This glacier, Eqip Sermia, lies in Ata Sound at the northeast corner of the Disko Bay region. Godthaab Fjord, farther south, is also reported to have an open water patch at a glacier (ice-cap) face, and the Greenlanders have told me that in the past this was attributed to a subterranean water channel connecting the head of Godthaab Fjord with Ameralik immediately to the south! These upwelling zones are important locally as feeding areas for seabirds throughout the breeding period, since there is a constant supply of zooplankton to the surface.

Upwelling by other means also appears in the literature in association with polynyas. Gordon (1978*a*, *b*) describes the cyclonic circulation of the Weddell Sea gyre in the Weddell Sea west of the Maud Rise, and concludes that the wind-driven gyre induces surface divergence and upwelling. This acts together with surface freezing and static instability (described above) to cause the frequent occurrence of a large polynya in the centre of the gyre. Szekielda (1974) describes satellite observations of a polynya in the Ross Sea, and states that "infrared measurements and television pictures showed that the polynya is open from July to September (antarctic winter). The large vertical heat diffusion necessary to keep the polynya ice-free might be the result of very intense upwelling and/or volcanic activity." This mention of volcanic activity being possibly involved is the only one I have found in the literature.

The interesting and unique small hole in the ice of Cambridge Fjord, in Baffin Island, has already been mentioned. This tiny polynya appears not to be open all winter, at least not every year, but opens late in the season in March. I.M. Dunbar (1958) concluded that a land–water origin was probable, perhaps either surface or subsurface fresh water under the ice, but more probably underground water from the sea bed. This conclusion turned out to be correct; it seems that leakage of water from an upland lake emerges from the bottom of the fjord, producing the open area (E.L. Lewis, pers. commun.).

Lewis (1979) divides polynyas causally into "convective polynyas" and "latent heat polynyas"; the former involving upwelling, the latter being the type described by Kupetskii (1959, 1962) already discussed, and represented by the North Water.

> Advection and/or convective processes are required to satisfy the energy balance at the surface in polynyas. At one limit is the possibility of the atmospheric thermal demand being met completely by sensible heat associated with upwelling of warmer waters from beneath (convective polynya). At the other extreme is a region of strong currents with the water column mixed from top to bottom and at the freezing point. The thermal demand is then met by phase change, and the resulting frazil ice is deposited elsewhere where the currents slacken (latent heat polynya). This latter possibility is analogous to open water rapids in an otherwise frozen river, with ice dams forming in the pools downstream (Lewis 1979).

The Frozen Sea Research Group of the Institute of Ocean Sciences, Sidney, B.C., is at present working on a polynya of the latent heat type in the Queens Channel area off Cape Collins, Dundas Island (Smith and Rigby, this publication, Fig. 11; see also frontispiece), where the maximum tidal velocity exceeds 2 knots, and "at slack tide slush ice starts to form in the open-water area. The water temperature is very close to freezing and there is an obvious accretion of frazil ice in the surrounding area" (Lewis 1979).

Tidal currents, in all probability, play the dominant role in the maintenance of the polynyas in Frobisher Bay and Cumberland Sound (Stirling, this publication, Fig.1), although no work has been done on either of them. Tides are also postulated by Sadler (1974) in the formation of the polynya he discovered in Makinson Inlet, Ellesmere Island. In this case, as probably also in Frobisher Bay, the shelving of the fjord bottom also plays an important part in concentrating the current. The Makinson Inlet polynya is shown in Figures 3 and 4. Sadler's interpretation, which is based on measurements of temperatures and salinities at four stations, involves the progressive cooling of the water in the basin inside the fjord, landward of the polynya, by the influx of flood-tide water which had been cooled at the surface of the polynya. There would come a point at which the continued cooling effect would cause homothermal conditions with depth in the inner fjord, close to the freezing point, at which time water on the ebb tide, passing through the polynya from the inner basin, would close the polynya by surface freezing. Sadler estimates that this closure would occur in December:

> Until this time the polynya would remain open because of the flow on both flood and ebb tides of water above the freezing point. Once the water in the basin reached an isothermal condition with the temperature at −1.7° C or lower, it might be expected that the very cold waters of the ebb tide would begin to freeze in the polynya. On each flood tide slightly warmer water mixed upwards from the deeper levels of the main inlet would pass through the polynya but the low temperatures of January and February and the large net heat loss due to radiation would probably be sufficient to keep the surface frozen over. With the return of the sun in April, the combination of solar heating and of ablation from below by the slightly warmer inflowing water would be expected to open the polynya sometime before the rest of the ice in the inlet broke up. When the observations were made in the middle of May the polynya was about 2 km long north to south and 1 km wide (Sadler 1974).

Hell Gate and Cardigan Strait (Smith and Rigby, this publication, Fig. 10), being the inlets to Jones Sound from the north, and the entry of Arctic Ocean water, are exposed both to set currents and tidal currents, and the same is no doubt true of Bellot Strait between Boothia Peninsula and Somerset Island (Smith and Rigby, this publication, Fig. 7). Certainly the set transport through Fury and Hecla Strait, which is very large but as yet inadequately measured, is enough to create the polynya there and in northern Foxe Basin.

Besides the wind-induced flaw leads along the shores of Banks Island and in the eastern Beaufort Sea generally, little else is understood about the factors that cause the Cape

Figure 3
The northwest arm of Makinson Inlet, showing the polynya described by Sadler (1974)

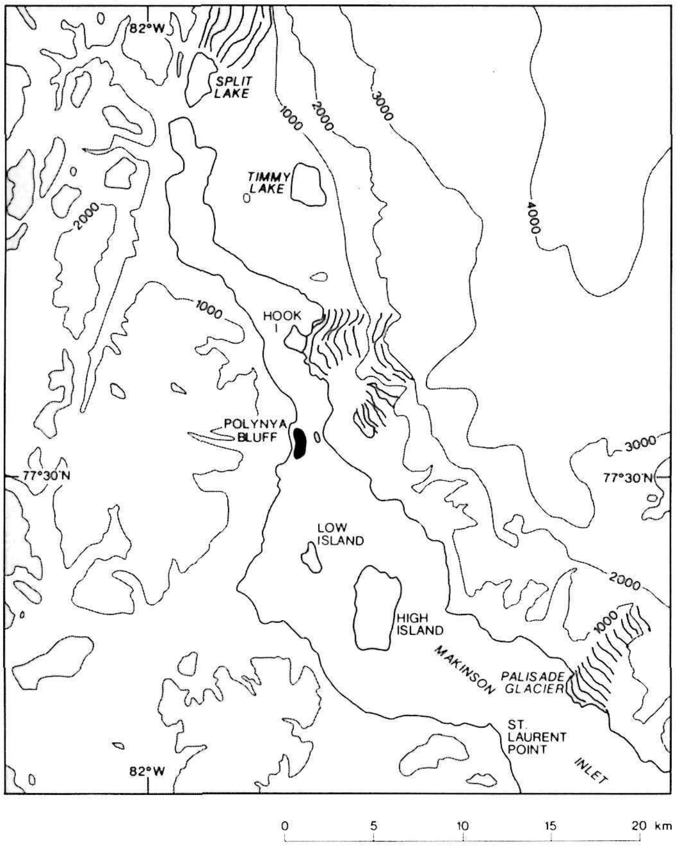
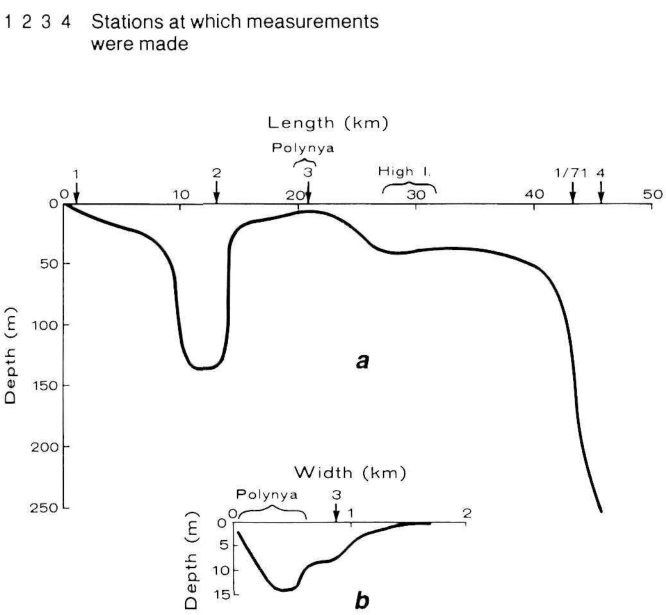


Figure 4
Profiles of the northwest arm of Makinson Inlet (from Sadler 1974): a, longitudinal section; b, transverse section at station 3



Bathurst polynya (Smith and Rigby, this publication, Figs. 12–14). The study by Marko (1975) of the Beaufort Sea ice cover during the years 1973–75 extended from March to October only, so that it is essentially a study of spring break-up and summer conditions. He showed the great annual variation in ice cover and ice behaviour; 1973 and 1975 being in his estimation close to the extreme of open, or light ice conditions while 1974 was close to the extreme closed condition. So far as the spring break-up is concerned, Marko reported "a systematic eastward progression of north–south leads" as an early step in the break-up process, and concluded that "the close association of the individual steps in the progression with easterly wind alignments suggested the over-riding importance to a given ice configuration of the immediately preceding and contemporary atmosphere pressure patterns." In other words, wind was the causative factor.

Marko (1975) and Marko and Thomson (1977) have an interesting suggestion concerning the long spatially regular rectilinear leads observed by satellite and aircraft in the Arctic Ocean, well known to arctic glaciologists. In 1966 Treshnikov (pers. commun.) described a discussion with colleagues in an aircraft over the Arctic Ocean concerning these long straight leads that was overheard by one of the young technicians on board, who remarked that it was a pretty poor bunch of scientists who couldn't figure that one out. On being asked to explain, he said "well, the earth is round, isn't it? But the ice is flat, so it has to crack." Marko (1975) has a more ordinary but no less interesting suggestion that the leads "are produced by current shears in the surface water layer associated with propagating planetary waves," the ice acting as a semi-brittle material. The concept is based on the analogy of rock mechanics, and in a later paper (Marko and Thomson 1977) the possible importance of surface water waves is played down in favour of the possibility that the observed patterns are examples of "massive scale strike-slip faulting."

5. Biological effects and significance of polynyas, leads, and ice edges

Both the presence and the absence of sea ice in the north have special biological significance. Sea ice supports a surprisingly intense primary production within the ice itself, consisting principally of diatoms; this forms the basis for the maintenance of an important ecosystem. Ice edges are regions of special biological activity. Ice provides a solid substrate used by certain mammals. Ice fosters upwelling, with all its significance in terms of production and transport. On the other side of the coin (absence of ice in winter), polynyas and other open water provide refugia for some sea mammals in winter and for migrant seabirds in spring and fall. They are regions in which plankton production normally begins earlier in the year than in ice-covered areas, and therefore areas in which one would expect differences at all levels (zooplanktonic, nektonic, and benthonic) as compared with regions normally completely covered by ice in winter, or indeed in summer. These effects, of ice and non-ice, are interconnected ecologically, so that it seems best to consider the biological relevance in terms of the broader concept of "ice and life" rather than in the narrower compass of open water in winter.

5.1. Ice biota

There is now a considerable body of literature on the phenomenon of the growth of flora, mainly diatoms, in sea ice. For summaries of this literature, see Horner (1976, 1977) and Grainger (1977, 1979), and for recent coverage of, and additions to, the subject, Alexander (1980) and Dunbar and Acreman (1980). The growth of diatoms and other micro-organisms in sea ice has been observed for well over a century, somewhat sporadically, and has been studied intensively since 1960. The most intense growth apparently begins in late winter or early spring, many weeks before the normal phytoplankton bloom in the water, and is concentrated in a few centimetres at the bottom of the ice. There are local, regional, and temporal differences in the composition and intensity of the diatom growth, and also in the associated fauna that, together with the diatoms, make up this special ice-associated ecosystem. There is still a great deal to be learned about this system, but it is possible that the total primary production within the ice in the Arctic Ocean is as high as one quarter of the total primary production in the Arctic Ocean (ice diatoms plus planktonic production). Alexander (1974), estimating the total annual primary production of the Beaufort Sea inshore area to be about 10 g carbon per metre squared, considered algal production in the ice to be about 5 g, or one half of the total. This estimate did not include the benthic primary production, which is much higher in shallow water than is the planktonic production. This applied to the nearshore areas only; for offshore and oceanic regions of the Arctic Ocean we are at present only able to guess at the proportional importance of the ice algae. We have some information (Dunbar and Acreman 1980) on the difference between the intensity of growth in arctic sea ice as opposed to the growth in the Gulf of St. Lawrence, the arctic growth being between one and two orders of numbers higher than in the Gulf of St. Lawrence. All in all, the algal growth within the ice in the Arctic is by no means insignificant. It supports a fauna, the key element of which seems to be the arctic cod, *Boreogadus saida,* which plays a vital role in the total marine ecology in high latitudes.

The extent to which algal growth in the ice influences the spring phytoplankton bloom in the water is still controversial, but it is probable that this process is one of the important links between the ice-covered ecosystem and the open-water ecosystem, the zone of contact being the region of the ice edge. This is the subject of the following paragraph from Alexander (1980):

> Information on the contribution of organisms in the ice to seeding the phytoplankton community is contradictory. There could be reasons for the variability in this respect. Hasle (1969), who recorded maximum diatom standing crop of 2 to 3 $\times$ 10^6 cells per litre near to pack ice, said that, although epontic (within ice) diatoms contribute a major component of the phytoplankton, some ice algae are not dominant in the phytoplankton. In our work in the Chukchi Sea, we have not found ice algae in the phytoplankton, and have concluded that their residence time in the water is very short. Saito and Taniguchi (1978) suggest that in the Bering and Chukchi Seas cells from the ice form a significant portion of the plankton. Hameedi (1978) came to a similar conclusion for the Chukchi Sea. In the Arctic the duration of the ice algae bloom is relatively short (six weeks), whereas in the Antarctic, organisms continue to be associated with floating ice throughout the entire summer. This probably explains why in Antarctic waters bands of algae are found in the center of ice cores — they were probably produced in the fall as the ice was reforming. This is confirmed by the observations of Hoshiai (1977).

Associated with this algal growth in sea ice is a fauna that to some extent seems to form a separate ecosystem, but also maintains open energy exchange with adjacent open water communities, the under-ice planktonic system, and, in shallow water, with the benthos. In my description of this fauna, I have included what is known of the antarctic equivalent, for the general ecological interest of the differences and similarities between the two polar regions.

The arctic "cryofauna" is described by Barnard (1959), Mohr (1963, 1969), Mohr and Geiger (1968), Baker and Wong (1968), Andriashev (1967, 1968, 1970), Tencati and Geiger (1968), Horner (1972), Horner and Alexander (1972), Welch and Kalff (1975), Buchanan *et al.* (1977), Green and Steele (1975), George (1977), Alexander (1980), and Dunbar and Acreman (1980). Several amphipod species have been recorded as ice fauna, the most abundant being *Gammarus wilkitzkii* and *Onisimus (Pseudalibrotus) nanseni. Apherusa glacialis* has been found abundantly in the stomachs of Arctic cod immediately under the ice and in holes in ice. Nematodes, not identified further, are recorded as being very abundant by Alexander (1980). Harpacticoid copepods are recorded by Dunbar and Acreman (1980). Both the polar cods *(Boreogadus saida* and *Arctogadus glacialis)*—there is confusion in the literature about which vulgar name belongs to which Linnean name—are common, particularly the former. Andriashev (1970) has the following vivid paragraph:

> Everybody who has sailed in the Arctic seas, especially aboard ice-breakers, will probably recall the following trivial picture. Astern of the ice-breaker are dozens of kittiwakes *(Rissa tridactyla).* From time to time they throw themselves down, picking small dark-silvery fishes from the surface of the ice. This is the polar cod *(Boreogadus saida)* or "saika" in Russian. These observations, though naive enough, are quite reliable. The very fact of the polar cod's presence on the surface of over-turned pieces of ice shows that before the passage of the ship it was under or in the lower surface of the ice.

For the Antarctic, where the cryophilic fauna appears to have been less investigated than in the Arctic, information is available from Andriashev (1967, 1968, 1970), Knox (1970), Rakusa-Suszcewski (1972), and Whitaker (1977). The amphipods, which dominate the fauna as they do in the north, are represented by *Orchomenopsis (Orchomenella)* sp. *(chilensis?)* and *Paramoera (Bovallia) walkeri,* the former being described as being found in very large numbers. Calanoid copepods *(Calanus propinquus* and *C. acutus)* are described by Andriashev as rare in this fauna, but there is one cyclopoid of the genus *Oithona* and three harpacticoids, *Tisbe, Harpacticus* and *Dactylopodia,* not identified to species. Two euphausiids, *Euphausia superba* and *E. crystallorophias,* are included and two polychaete worms of the genera *Harmothoë* and *Pionosyllis.* Fishes are represented by three nototheniids, *Trematopus borchgrevinki, T. nicolai,* and *T. newnesi.* Andriashev (1970) calls these fishes "cryopelagic": defined as "fishes which actively swim in midwater (in coastal zones or in the open sea), but during their life cycles are associated in some way or other with drifting of fast ice."

The two faunas are presented in summary in Table 1. They form an interesting pattern of ecological convergence and systematic allopatric speciation, and there is one factor, the presence of the euphausiids in the antarctic group, which is exceptional and apparently special to the Antarctic. To some extent, the fauna is essentially a substrate fauna, formed of species which belong to normally benthonic fami-

Table 1
Fauna associated with ice diatoms

Arctic	Antarctic
Amphipoda:	Amphipoda:
Gammarus wilkitzkii	*Orchomenella (Orchomenopsis)* sp.
Gammarus setosus	*Paramoera (Bolvallia) walkeri*
Onisimus nanseni	*Pontogeneia antarctica*
Onisimus litoralis	*Cheiromedon femoratus*
Apherusa glacialis	
Eusirus holmii	Copepoda:
Gammaracanthus loricatus	*Calanus propinquus, C. acutus (rare)*
	Oithona sp.
Copepoda:	*Tisbe* sp., *Harpacticus* sp.
Microsetella sp.	*Dactylopodia* sp.
Ostracoda:	Euphausiacea:
Paradoxostoma rostratum	*Euphausia crystallorophias*
(commensal with *Gammarus*	*Euphausia superba? ?*
and *Gammaracanthus*	
	Polychaeta:
Polychaeta:	*Harmothoë* sp.
(larvae)	*Pionosyllis* sp.
Nematodes:	Pisces:
Unidentified	*Trematomus borchgrevinki*
	Trematomus nicolai
Pisces:	*Trematomus newnesi*
Boreogadus saida	
Arctogadus glacialis	
(also ciliates, heliozoans)	

lies or genera, thus the sub-ice substrate may be looked upon as ecologically analogous to the sea floor, an upside-down floor or "ceiling." This applies to *Gammarus wilkitzkii* and perhaps also *Pseudalibrotus nanseni*; the latter, however, like *P. glacialis*, is also common in the plankton. It applies also to the harpacticoid copepoda, found in both polar regions, to the amphipods *Gammaracanthus loricatus* and *Orchomenella*, and the polychaete worms and nematodes. But it does not apply to *Apherusa glacialis* in the north nor to the euphausiids in the south, all three of which are planktonic.

The euphausiids are of special interest. *Euphausia crystallorophias* is recorded as common among ice floes and immediately beneath the ice, although Andriashev (1968) writes "What the connections of *Euphausia crystallorophias* with the ice community are, is not known exactly, as with the abundant Calanoids (*Calanus propinquus, C. acutus* and others)." It is not clear whether these species feed on the in-ice diatoms or upon planktonic flora. As for the most abundant of the krill species in the Antarctic, *Euphausia superba*, the question of its abundance in the ice zone as opposed to the pelagic zone has been exhaustively examined by Marr (1964), but Marr was writing at the time when the in-ice biota in the Antarctic was only just beginning to attract attention, and he makes no mention of it at all. He concludes that *E. superba* is a species of both the ice-free water and of the pack-ice zone, but there is no information on whether or not it takes part in the ice-diatom-grazing community.

Nevertheless, the presence of the euphausiid species in the antarctic pack-ice is significant, in view of the almost complete absence of euphausiids or comparable numbers of any equivalent pelagic large Crustacea, such as *Parathemisto* (M.J. Dunbar 1964), in the Arctic Ocean. The significance of course involves the great difference between the primary biological productivity of the two regions, the Antarctic being among the most productive marine regions of the world, the Arctic among the poorest. This means that production in the sea ice in the Arctic, which has been estimated to be between 10 and 30% of the total primary production in the Arctic Ocean, is much more important for the arctic regime than it is for the Antarctic, where the planktonic production is very high. There is not sufficient planktonic production in the Arctic Ocean (as distinct from the peripheral northern seas in which the conditions are quite different) to support large planktonic herbivorous populations; whereas the in-ice production is concentrated enough spatially to support a specialized ecosystem.

The seasonal variation in ice cover in the Antarctic is much greater than in the Arctic, owing to the persistence of most of the Arctic Ocean pack ice throughout the summer. The seasonal variation in the Antarctic is enormous and resembles not that of the Arctic Ocean but rather that of peripheral northern seas such as Baffin Bay, Hudson Bay, Bering Sea, and Barents Sea, which are ice free for a period in summer; all of which support large populations of pelagic herbivorous and carnivorous Crustacea, including euphausiids and hyperiid Amphipoda, and a much higher level of primary organic production than does the Arctic Ocean.

Within the northern hemisphere, there is an interesting difference between the ice diatoms themselves, in the northern waters (arctic regions and Hudson Bay) and in the most southerly extension of winter sea ice, namely the Gulf of St. Lawrence. The ice diatoms in localities in northern Canada, including Hudson Bay, have been found to be almost entirely (97%) composed of pennate species, most of them benthonic in habit, whereas those of the Gulf of St. Lawrence are about 43% centric forms, planktonic in habit (Dunbar and Acreman 1980). This difference is most probably related to the much shorter annual period of ice cover in the gulf than in the northern localities sampled but we have no information from the Antarctic concerning composition of the diatom ice flora in the antarctic ice, as regionally distributed, the peripheral parts of which have a much shorter seasonal life than the proximal sea ice closer to the antarctic continent.

As for the fishes, the antarctic Nototheniids replace the northern Gadids. In the Arctic, the polar cod and the arctic cod are present in the sub-ice community in all stages of their life cycle, so far as we know, but in the Antarctic the Nototheniids invade this community only as young (fingerlings, or fry). The Nototheniids have no swim-bladder; the Gadids do. No doubt in relation to this difference, the Antarctic fishes in the sea-ice zone cling to the ice by the use of their wide ventral fins (Andriashev 1970), whereas the Gadids in the north swim freely in the sub-ice zone and between the floes. The two groups belong to different orders, the Gadiformes and the Perciformes, but superficially in appearance and in certain characteristics, such as resistence to freezing and in sensory mechanisms, they have come to resemble each other. Both groups are predominantly benthonic in habit — like the diatoms and the amphipods, they are substrate dwellers. In the arctic cod the mouth is oblique, opening forwards and upwards, suggesting adaptation to under-ice feeding. The other fishes, the seals and the birds which form part of the wider ecosystems in the two polar regions, consist of different species in the two areas, with very few exceptions. It is not therefore surprising that the same rule applies to the lower levels of the ecosystem and to the specialized ice-associated community. But it is nevertheless worthwhile to go into the details of the differences, since they underline the meaning of that much overloaded term "bipolarity."

5.2. The ice-edge ecosystem

To my knowledge there have been no measurements of the rate of primary production in polynyas and few in flaw leads. Bursa (1963), working at Point Barrow, writes that

Life activities begin to accelerate about two months earlier in leads than in the ice-covered areas. Direct exposure to sunlight and contact with air may favour phototactic migration of flagellates from under-ice darkness. These movements attract zooplankton and larger animals, including pteropods and medusae, which swarm in the leads.

Bursa (1961) demonstrated the sudden release of phytoplankton that occurs when the ice melts during the month of June near Igloolik. Unfortunately this work, done during the "Calanus" wintering expedition of 1955–56 (Grainger 1959), did not extend to the polynya to the east of Igloolik in northern Foxe Basin (Smith and Rigby, this publication, Fig. 9).

There seems, however, to be something more involved here than the simple disappearance of ice and the illumination of the open water. This is strongly suggested by the repeated observation that it is at the ice edge, rather than away from the ice, that the greatest activity takes place. This has been a general observation made by many biologists and navigators. As the most recent example, this time accompanied by actual measurements, the work of Alexander and Cooney (1979) serves most excellently. Alexander (1980) also wrote a summary:

> The ice front in the Bering Sea is associated with a high stock of secondary and higher producers (Irving *et al.* 1970), which suggests a highly active system. One of the earlier measurements of primary productivity in the ice edge area showed a rate of 89.2 mg C/m²/day [89.2 mg/m² of carbon daily] at the ice front, although only one such station was sampled (McRoy and Goering 1974). In our recent Bering Sea work, we found the most intense primary production to occur at the ice edge just prior to break-up (Alexander and Cooney 1979). Three years coverage during the critical spring period as well as comparative data from other times of the year have given us a rather detailed picture of the seasonal cycle and as a result we have been able to estimate the relative contribution from this spring ice edge regime compared with the remainder of the year on the S.E. Bering Sea shelf.

Alexander and Cooney found that the ice-edge bloom extends away from the ice to a distance of 50 to 80 km. Figure 5 is taken from their paper, showing the highest production rate and chlorophyll concentration "within the ice margin," a lower rate outside the ice and the lowest some miles away from the ice.

Hart (1942) recorded high ice-edge blooms in the Antarctic. Ivanov (1964), also in the Antarctic, observed the most intense bloom along the ice edge, and concluded that it was the result of the liberation of algae grown in the ice. As has been pointed out above, that is still controversial, but possibly important.

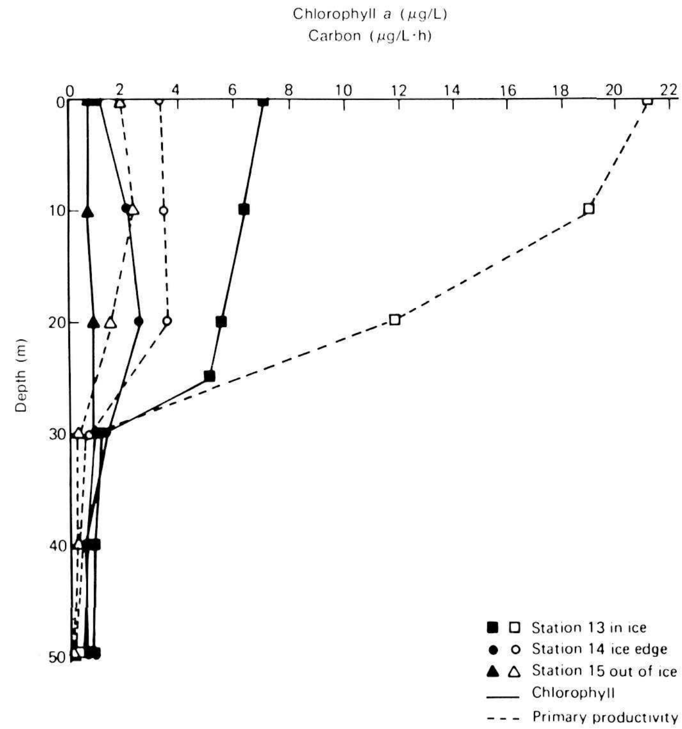
There does not appear to be any evidence of upwelling along the ice edge, in these researches, as a possible source of nutrients in large supply. The work of Alexander and Cooney (1979) offers no such possibility in terms of the salinity structure, and Hasle (1969) observed that the surface water at the ice edge (Antarctic) had a much lower salinity than the layers below.

It is tempting, and possibly useful, to revive once more the possibility of the involvement of the structure of the water itself in this context, in particular the concentration of water polymers, trihydrols, tetrahydrols, and so on. This has been suggested in the polar context by Bogorov (1939), Laktionov (1940), and M.J. Dunbar (1951*a*, 1977), and it is apparently also in the minds of other researchers (e.g. Buinitsky 1971, 1977), although these latter have not expressed themselves specifically in terms of water polymers. To quote from M.J. Dunbar (1977),

> Buinitsky's paper revives interest in some almost forgotten work in the 1930s, when very interesting experiments were done by Barnes (1932), Barnes and Jahn (1933), and by Harvey (1933), all showing that water recently melted from ice had a decidedly stimulating effect on the growth and multiplication of plant cells (*Spirogyra, Euglena, Nitszchia*). In the case of *Euglena*, for instance, Barnes and Jahn found that the average increase in the number of cells in the condensed steam water, in experiments of ten to sixteen days' duration, was 32%, while the increase in the ice water culture was 105%. The effect was also observed in cultures of *Bacterium coli* (Hegarty and Rahn 1934). The possible importance of these results for students of life in polar seas was pointed out by Barnes and Jahn (1934) and later by Dunbar (1951*b*).

At that time it was suggested that polymerized water molecules (trihydrol, etc.) were factors conditioning the observed differences between the effects of ice melt-water and condensed steam-water, but more

Figure 5
Primary productivity and chlorophyll depth profiles at stations within the ice margin, outside the ice, and away from the ice in the Bering Sea (from Alexander 1980)



recent physico-chemical advances in the study of water and ice structure banished the polymers from the scene, and interest in the "Barnes effect" lapsed somewhat. The results of those experiments, however, still stand, and moreover now that we have considerable knowledge of the development of plant cells in high concentrations within the ice itself and in very close association with ice, it becomes necessary to pursue the problem further. In this respect the statement by Buinitsky, in this present volume, is particularly interesting. He writes: "This peculiar feature of sea ice as an environment for microscopic organisms is conditioned, first, by the high nutrient content in the brine pockets and cavities in which the organisms live, and second, by the fact that, *as is known*, the brine is in a quasi-crystalline state and acts as a strong biological stimulant. It is also possible that in the fine capillaries of sea ice the ordinary water is transformed into the recently discovered modification know as "Water II." The biological properties of this new type of water have not yet been studied, but what is already known about it suggests that it influences living organisms favorably.

This may be altogether too speculative for general scientific acceptance, but it would be worth attacking the problem once more, both in the field and experimentally, with the help of appropriate physical chemists.

Fishes are undoubtedly important in the ice-edge ecosystem, particularly the arctic cod (*Boreogadus*) but also the polar cod (*Arctogadus*). McAllister (1975) suggests that ice-associated fishes may use the under-ice habitat on account of the defence it offers against predation by birds. Holmquist (1958) found young sand launces (*Ammodytes dubius*) hiding in cavities in the ice. Bain and Sekerak (1978) made a special study of *Boreogadus*, including the use of scuba diving. They write

> Despite numerous reports in the literature of a close relationship between Arctic cod and ice, repeated under-ice observations at various localities in the spring and early summer of 1977 revealed few cod near the undersurface of the ice.

It is possible that the presence of the divers themselves caused the departure of most of the cod that might have been there, but it is more probable, as Bain and Sekerak point out, that because *Boreogadus* is known to be a shoaling fish, widely separated schools might be missed entirely by observers. It is also known that the distribution of the cod in time, as well as in space, is highly patchy. The Barrier Island (Simpson Lagoon) study (LGL Ltd., unpubl.) on the Alaskan coast found almost no *Boreogadus* one season and several million the following year. It is also possible that the patchiness is caused by the distribution of ice diatoms. The evidence of the presence of arctic cod in the vicinity of the ice edge comes convincingly from the study of bird stomachs, especially murres. Bain and Sekerak (1978) suggest that the cod concentrate near the interface between ice and open water, where the murres also concentrate:

> Observations of feeding birds and analysis of their stomach contents show that in June 1976 a minimum of 1.4 million Arctic cod, and probably closer to ten times that number, were consumed by murres along the ice-edges between Griffith and Beechey islands in a 33-day period (Bradstreet 1977).

Bradstreet estimated that murres consumed 17 660 arctic cod daily per linear kilometre of ice edge in the middle of Wellington Channel. The murres are often observed to dive beneath the ice and cod are constantly observed in ice cracks, again strongly suggesting that the ice edge may be the favoured habitat of this species.

Fishing for the cod with gill nets gave very poor results (Bain and Sekerak 1978), for some reason. Nevertheless, *Boreogadus* has been fished successfully, at least experimentally, by both the Norwegians and the Russians, who are exploiting the arctic cod as a commercial species.

Sekerak and Richardson (1978) have brought together much useful information and observations on the ice-edge ecosystem, summarizing several recent studies including those of Bain *et al.* (1977), Bradstreet (1977), and Bradstreet and Finley (1977). Figure 6, taken from that paper, summarizes the important relations between sea birds and ice-edge aquatic fauna, and emphasizes, once again, the significance of *Boreogadus*. Drawing from a number of recent studies, these authors also describe the importance of ice edges to certain sea mammals, notably narwhal, white whale (beluga), and polar bear, which concentrate along ice edges in spring.

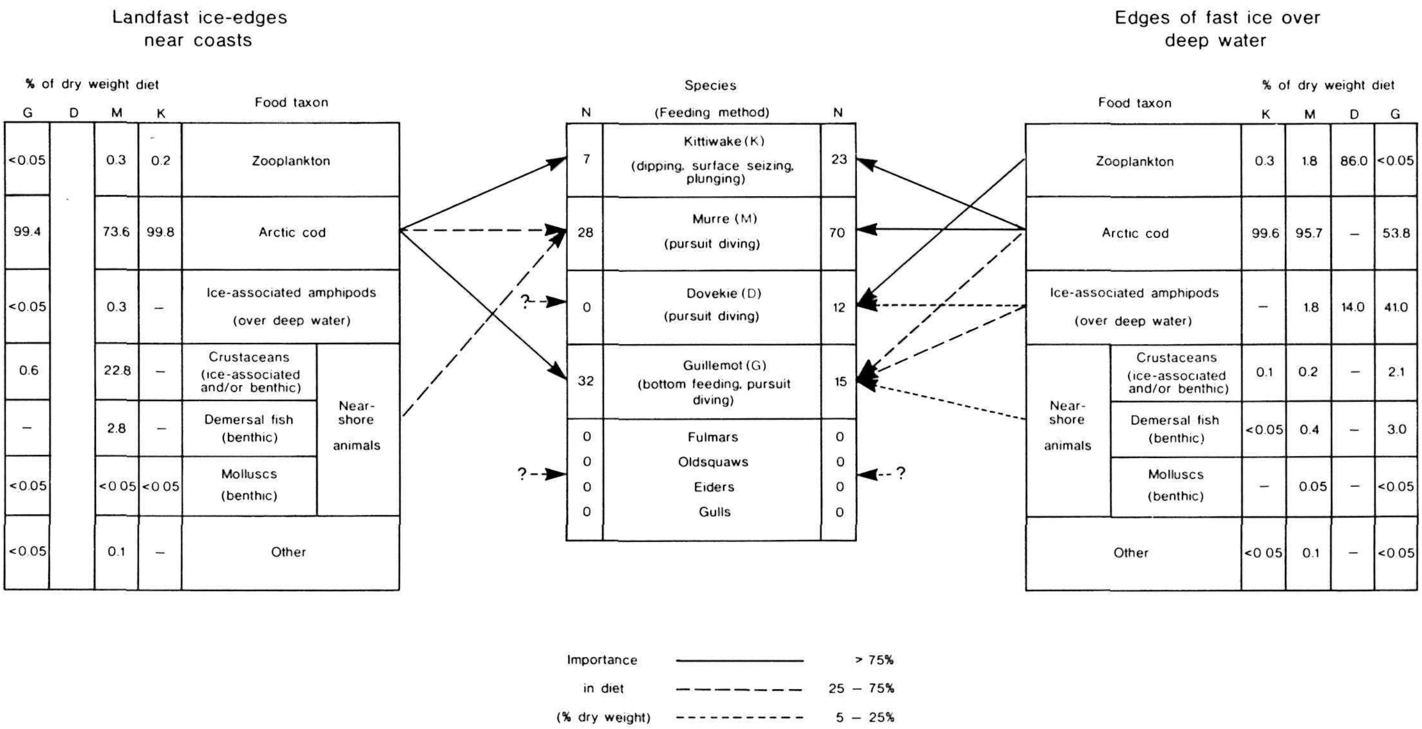
Ice edges are clearly extremely important ecologically. It appears to be the ice edge, rather than the ice-covered region or open water, that has the highest significance in terms of productivity and concentration of living organisms. The causes of the high primary productivity are not clear, although suggestions in the literature have been mentioned above. Possibly the fact that the ice edge is the zone of contact between the ice cover and the open water is itself important — a region that borrows from both systems in a synergistic manner. Certainly there are important links between the two, which exchange back and forth across the ice-edge zone. These ecological links are, for instance, the ice diatoms, the Crustacea that feed directly upon them but are also found outside the ice-covered and ice-edge zones, and *Boreogadus*.

We should focus great research attention on the ice-edge ecosystem. There are new things to be discovered there. Speaking as an interested non-biologist, Weeks (1980) had this to say about the biological regimes in the seasonal sea ice zone:

> Biological regimes rarely fail to amaze one with their diversity. Invariably, when they have been well studied, the maze that one perceived at first impression is replaced by a highly ordered system in which everything has its place. At the present time, the biology of the seasonal sea ice zone is at the state where we are beginning to see glimpses of order in the maze. The difficulty is that the ice biota, the central character in the play, reads a different script than those to which we are accustomed. Therefore, it is risky to anticipate its behavior from studies of other non-ice related regimes. Clearly, however, we are dealing with a rich, diverse, and well-ordered biological system that can, in certain circumstances, show an extremely high productivity.

One point is becoming clear: because of the ice-edge effect, areas in which polynyas and flaw leads are recurrent may be more important biologically than either ice-covered areas or areas of open water, especially in the winter and early spring.

Figure 6
Food web relationships of some seabirds along ice edges in Barrow Strait during June and early July 1976 (pre-hatching period) (from Bradstreet 1977)



6. Vulnerability of polynyas and flaw leads

No work at all has been done on this problem, and there is nothing in the literature that is relevant to it. There has been some study of the behaviour of oil in ice-covered waters, and a great deal of speculation about it, but that is not relevant to polynyas or leads as such. Put another way, the present knowledge of oil in sea water, world-wide, on the one hand, and of oil in sea-ice regions on the other, applies to polynyas and leads as it does to any other marine environment, and it is not the intention here to rehearse or summarize the literature on oil hazards in the sea in general or in northern waters in particular. The same is true of the possibility of pollution from mine-tailings, or any other form of chemical pollution.

In view of the apparent importance of the ice edge to biological production and populations, it is difficult to escape the conclusion that an increase in the linear extent of ice-edge conditions could be beneficial, rather than the reverse. This would obviously have its greatest effect in spring and summer rather than in the winter.

7. Research needed

The research needs can be simply and briefly listed. It is always a little invidious to give research requirements an order of priority, because so many things (cost, available logistics, availability of scientists, and so on) have to be taken into consideration. In the following, nevertheless, I have given some attention to priority or urgency, from my own point of view.

1. North Water in winter; physical and biological research. What is the water structure in winter? Do Kupetskii's ideas apply to the North Water? What is the timing of the spring phytoplankton bloom? Is the benthos different from the benthos of the rest of Baffin Bay?

2. Physical and biological studies of other polynyas, each for itself. What causes each one? What is their biological significance? Does the annual biological cycle in them differ from the cycle in open water?

3. *Boreogadus saida* and *Arctogadus glacialis*. Remarkably little is known about these two cods, and their importance under the ice, as part of the ice biota ecosystem, along the ice edge, and in open water.

4. The ice-edge ecosystem. This involves exercise in ecological theory as well as a great deal of field work. What are the links between the ice-edge and the adjacent systems under the ice, in the open water, and the benthos? What are the numbers involved, in terms of energy exchange?

5. Ice biota ecosystem. There is much to be learnt about the dynamics and the distribution of this system. Why are there local and regional differences? How far from land are the ice diatoms found? How is the diatom population reseeded each year? What is the relation between the ice diatoms and the diatoms of the spring phytoplankton bloom? To what extent can it be considered to be a substrate system, or upsidedown benthonic community? What is its quantitative significance in the total arctic marine budget?

6. Benthos. Nothing is known about the benthos below polynyas. One would expect differences in these regions from the benthos growth, and perhaps diversity, outside polynya and flaw lead regions. Kupetskii (1962) wrote

In conclusion one might say that the benthos in the North Water region, according to its species composition, is very close to the benthos of the Novosibirsk shallows where the Great Siberian polynia is located (Gorbunov 1946). And this once again emphasizes the identical nature of the hydrological processes originating in the two regions remote from each other.

There is not much known about the benthos of the North Water now, and in 1946 there must have been almost nothing known. The quotation calls for investigation.

7. Oil in polynyas and leads. Would polynyas and leads act as oil pools, or points of concentration of spilled oil? Or would most of it be trapped in the unevennesses of the underside of the adjacent ice? How would the presence of oil affect productivity in leads?

8. The use of polynyas and leads in winter by indigenous people. There is probably a great deal of readily available information, but it would be relevant and useful to have a definite study and statement on it.

9. The possible relevance of the water molecular structure to primary production and the association of high productivity with the ice edge; the possible significance of the polymerization of the water molecule in the formation of ice.

10. The development of equipment and techniques for field work on polynyas in winter will need some research in itself. Not least of the problems is that of suitable vessels, for which large polynyas such as the North Water present special challenges. There will be high risk of ice deposition on rigging and superstructure, which would make the use of ordinary hulls, including icebreakers, perhaps inappropriate. In the days of the North Water Project (Arctic Institute) I recommended that attention be given to ocean-going tugs, suitably converted. These are low-profile vessels, sturdy and tough. Sealer types might also be useful. Also highly desirable would be a well in the ship's bottom for sampling of all kinds. This has disadvantages in ordinary day-to-day sailing, but would be almost a necessity in the conditions to be faced in winter in the North Water.

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Walruses hauled out on the ice edge at small recurring polynya at Dundas Island (photo: I. Stirling)

Subadult bearded seal near the Cape Bathurst polynya (photo: I. Stirling)

Marine mammals

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1. Abstract

Polynyas appear to play a critical role in the survival of many viable populations of marine mammals in the Canadian Arctic. The role of each area, and the extent to which it may be used, can vary greatly between species, seasons, and individual polynyas. This paper reviews the use of major polynya areas in the Canadian Arctic by each species. Important, and possibly critical, aspects have been identified. Most polynya areas are threatened with extensive disturbance and possible pollution as a result of offshore petrochemical exploration and year-round shipping activities. However, we cannot evaluate the effects of such disruptions because we have an inadequate understanding of the ecological significance of these areas to marine mammals. Considerable research is needed to ensure that the necessary data are available upon which decisions relating to the conservation of marine mammals in polynya areas can be based.

2. Résumé

Les polynies semblent conditionner la survie de nombreuses populations viables de mammifères marins de l'Arctique canadien. Chaque polynie joue un rôle dont la nature et l'importance varient considérablement selon l'espèce, la saison et la nappe d'eau elle-même. Le présent document examine l'utilisation que chaque espèce fait des principales polynies de l'Arctique canadien; on y détermine les aspects importants, voire cruciaux, de cette question. Le transport maritime permanent et les travaux d'exploration pétrolière en mer risquent de perturber considérablement et même de polluer la plupart des polynies. Or, il nous est impossible d'évaluer les effets de ces dérangements car nous connaissons mal le rôle que jouent les polynies pour les mammifères marins. Il faudra donc effectuer une recherche considérable pour recueillir les données voulues permettant de prendre des décisions au sujet de la protection des mammifères marins dans les polynies.

3. Introduction

In terms of their use by marine mammals, there are three types of polynyas in the Canadian Arctic. The large and unique North Water, smaller recurring polynyas close to shore or in inter-island channels (e.g. Penny Strait), and shorelead (or shear zone) polynya systems such as those in Hudson Bay or the Beaufort Sea (Stirling, this publication, Fig. 1). The biological significance of each type of polynya may vary greatly between seasons, between species of marine mammals and, to an unknown extent, between areas. In some regions, marine mammals continue to feed in polynya areas during the summer after break-up. In some areas at least, the factors that help to create a polynya in the first place may also make that area more biologically productive. Thus, the purpose of this paper will be to review the available literature on the use of polynyas by marine mammals in the Canadian Arctic, attempt to evaluate their biological importance to marine mammals, identify critical gaps in our knowledge, and examine the possible detrimental effects of different types of disturbance. In this discussion, we will consider the polar bear as a marine mammal because it depends on the marine ecosystem for its sustenance.

4. Use of polynyas by marine mammal species

4.1. Ringed seal *(Phoca hispida)*

The ringed seal is the most abundant and ubiquitous species of marine mammal in the Arctic. The preferred winter and spring habitat of the adult breeding population is the fast ice of bays, coastlines, and solidly frozen inter-island channels (McLaren 1958). During winter, adult ringed seals maintain breathing holes by abrading the ice with the heavy claws of their foreflippers (Smith and Stirling 1975). Generally, these breathing holes are established along cracks that were the last to freeze in the fall. Agonistic behaviour of the adults tends to exclude subadult seals from such areas, thus restricting them to the less stable ice of offshore areas, shore-leads, and polynyas. In this way, the difficulties associated with maintaining breathing holes are at least partially alleviated for subadult seals. In general, quantitative data are not available with which to rigorously test this hypothesis but several lines of evidence in both the eastern and western Arctic suggest this is a correct interpretation.

Analysis of the age structure of seals killed by Inuit hunters in the fast-ice areas during the early spring invariably shows a preponderance of adult seals (Smith 1973). In contrast, seals killed by polar bears along lead systems and in unstable offshore ice tend to be predominantly adolescents (Stirling and McEwan 1975; Stirling and Archibald 1977; Smith 1980). In most Inuit villages in which seals are hunted extensively, the presence of a new lead or patch of open water during the winter is widely recognized as a good place to hunt ringed seals because of their local abundance (and accessibility). Similarly, when new leads in the offshore ice begin to freeze over, the young ice becomes perforated with an abundance of new breathing holes, indicating relatively high local concentrations of seals (Fig. 1).

From early March to late May of 1971, the Inuit hunters from Holman (in Amundsen Gulf) took 1570 ringed seals from the floe edge on the eastern border of the Cape

Bathurst polynya which, in that year, remained open throughout the winter. Sixty percent of those seals were subadults, indicating fairly strongly the importance of the polynya to the subadult ringed seals of that population. These results also indicate that the adult ringed seals occupying the fast-ice areas along the shore tended to remain under the fast ice and were actively excluding subadults (T.G. Smith, unpubl. data). Strong evidence of territoriality in this species has recently been documented by the observation of site tenacity during the early period of hauling-out and the strong possibility of site fidelity between years (Finley 1979; Smith and Hammill 1980). There is limited evidence that some ringed seals breed offshore (Koski and Davis 1979), but the relative importance of pack-ice breeding, when compared to the density observed in the landfast ice, probably is not great.

Dispersal of young prior to break-up may occur along lead systems but this has not been studied. During the open water period, ringed seals appear to disperse pelagically throughout arctic waters, although an association with ice floes has been noted (T.G. Smith, unpubl. data). Fall concentrations of ringed seals feeding pelagically have been documented (T.G. Smith, unpubl. data). However their relationship, if any, to former polynya areas is unknown.

Overall it appears that polynyas are most significant to ringed seals in providing overwintering areas for subadults. In some areas, polynyas may also support a small part of the breeding population during the winter.

4.2. Bearded seal *(Erignathus barbatus)*

The bearded seal occurs throughout the Arctic, but its distribution is much more patchy than that of the ringed seal and its ecological requirements are less understood. The preferred habitat of the adult breeding population appears to be areas of moving ice interspersed with open water less than 100 m in depth (Burns 1967; Davis *et al.* 1975; Stirling *et al.* 1977*a*). Like ringed seals, bearded seals are also capable of maintaining their own breathing holes by abrading the ice with the claws of their foreflippers (Vibe 1950; Stirling 1977) (Fig. 2). In the western Arctic, male bearded seals have been recorded vocalizing under water in an area of annual ice more than 400 km from the closest open leads (Stirling and Smith 1977). It is not known if spatial segregation of age classes occurs at any season. In general, however, bearded seals are more abundant in areas where open water occurs continuously or at least periodically. Consequently, since bearded seals have no known obligative migrations, it is apparent even from the somewhat sketchy data available, that the winter distribution of bearded seals in the Canadian Arctic could for the most part be superimposed over the distribution of polynya areas.

4.3. Walrus *(Odobenus rosmarus rosmarus)*

In the Canadian Arctic, Atlantic walruses overwinter in areas of pack ice where the water is shallow and the ice is thin enough that they can break it with their heads in order to maintain breathing holes. Icebergs which ground in these shallow areas are rocked back and forth by water currents and winds, creating a border of weaker broken ice. Walruses utilize these points extensively to maintain breathing holes through the winter (Fig. 3).

Figure 1
Ringed seal breathing holes in a refrozen lead (photo: I. Stirling)

Because of the limiting effect of ice thickness, the winter distribution of walruses tends to be limited to the larger water bodies, such as Baffin Bay or Davis Strait, where the ice is less stable. Nevertheless, the importance of polynya areas, notably in Foxe Basin and to a lesser degree in areas such as Penny Strait or Hell Gate (Smith and Rigby, this publication, Figs. 9–11) is emphasized by the fact that variable numbers of individuals overwinter there each year. Although occasional individual walruses have been recorded overwintering away from the larger and more reliable polynyas (Stirling 1974*a*; Kiliaan and Stirling 1978), this is not common enough to be of consequence to the population. The extent to which the breeding and non-breeding portions of walrus populations may segregate during the winter is not well understood.

Almost all populations of walruses probably have local seasonal movements or migrations, although the details may not be known for each area. When the first cracks form in the ice in the spring, walruses tend to move along them to new feeding sites. In some cases, annual variations may enlarge the existing polynya areas in which walruses overwinter, thus allowing them to extend their feeding area. The presence of leads early in the year provides walruses with an essential lane of access to new areas.

Figure 2
Breathing hole in the sea ice being maintained by bearded seals. Note the scratch marks in the ice (photo: I. Stirling)

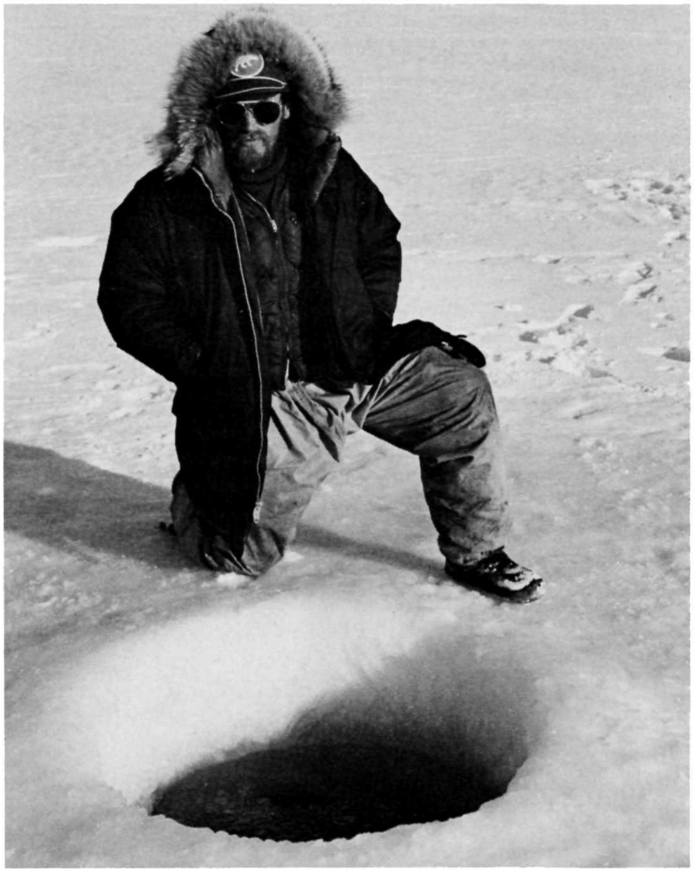

Figure 3
A typical walrus breathing hole at the edge of a small piece of multiyear ice frozen into the annual ice (photo: I. Stirling)

4.4. Other species of seals

No other species of seals are abundant during the winter in polynya areas in the Canadian Arctic, although small but undetermined numbers of harbour seals *(Phoca vitulina)* may overwinter in the shoreleads and river mouths of Hudson Bay (Mansfield 1967*a*). During summer, small numbers of harbour seals occur in Hudson Bay, usually associated with the estuarine feeding habitat. Periodic occurrences have been reported from southeastern Baffin Island and the Beaufort Sea.

Occurrences of hooded seals *(Cystophora cristata)* in polynya areas at any season are sufficiently rare that the species can be omitted from further discussion.

Winter use of polynyas by harp seals *(Pagophilus groenlandicus)* is negligible although a few may winter in the Frobisher Bay or Cumberland Sound polynyas (Stirling, this publication, Fig. 1). In the summer, however, large numbers of harp seals migrate to former polynya areas in Hudson Bay, Baffin Bay, Lancaster Sound and adjacent water bodies to feed (Sergeant 1965, 1976). During this period, harp seals may use shoreleads as migration routes.

4.5. White whales or beluga *(Delphinapterus leucas)*

White whales are capable of breaking a certain amount of young ice with their backs in order to breathe (Fig. 4) but they are essentially dependent upon areas where open water is maintained by natural conditions. In Canada, most white whales appear to winter in areas of drifting pack ice, even if this necessitates long seasonal migrations (Fraker 1979; Davis *et al.* 1980). However, in areas such as Foxe Basin (Sergeant 1973) and possibly James Bay (Jonkel 1969), they appear to overwinter in localized polynya areas as is apparently more common in the Soviet Arctic (Kleinenberg *et al.* 1964).

The importance of leads, particularly shorelead polynya systems, as spring migration routes to feeding and calving sites in areas such as the Beaufort Sea and Lancaster Sound cannot be overstated. Even after break-up, some of the former polynya areas in both the eastern and western Arctic appear to be important as feeding areas.

4.6. Narwhal *(Monodon monoceros)*

In Canada, narwhals are found mainly in the eastern and high Arctic, although a limited number enter northern Hudson Bay during the summer (Mansfield *et al.* 1975*a*). Like white whales, they are capable of breaking young ice with their backs in order to breathe, but they are essentially dependent upon areas where open water occurs naturally. Most narwhals appear to overwinter in the more southerly open pack ice areas of Davis Strait, keeping to deeper and more open water than white whales (Vibe 1967; Kapel 1975, 1977). Narwhals do not appear to overwinter in significant numbers in polynyas in Canadian waters.

In the spring, narwhals migrate through shorelead polynya systems into Lancaster Sound and, to a lesser degree, Hudson Strait (Mansfield *et al.* 1975*a*). They continue to penetrate new leads into fast-ice areas as break-up proceeds. Although leads are critical to narwhals as migration routes, they appear to use the shallower water polynya areas for feeding less than white whales. After break-up, and throughout the rest of the year, they feed extensively in deep waters, some of which are former polynya areas.

Figure 4
White whales making breathing holes in young ice (photo: J. Lentfer)

4.7. Bowhead *(Balaena mysticetus)*

Bowhead whales are more similar to white whales than narwhals in their use of polynyas. Both the eastern and western Arctic populations appear to winter in the more southerly open pack areas of Davis Strait and the Bering Sea respectively. In the spring, both populations are dependent upon shoreleads as migration routes to major feeding areas in polynyas prior to break-up (Fiscus and Marquette 1975; Fraker 1979). During the summer, they continue to feed to a significant degree in former polynya areas. Bowheads appear to leave the former polynya areas in the fall for their overwintering areas prior to freeze-up (Fraker *et al.* 1978).

4.8. Polar bear *(Ursus maritimus)*

In this discussion, polar bears are considered marine mammals, because they live on and feed from the sea for as much of the year as possible, moving onto land only for maternity denning or when compelled by complete melting of the sea ice. These bears tend to be facultative migrants. The size of individual home ranges probably varies between areas, depending on the extent to which environmental factors force them to move seasonally. Polar bears prey mainly upon ringed seals and, to a lesser degree, on bearded seals (Stirling and Archibald 1977). Polar bears appear to be more abundant in polynya areas and along shoreleads, probably because the densities of seals are greater and they are more accessible. For example, between March and June in the Beaufort Sea from 1971 through 1975, 87% of the sightings of polar bears were made adjacent to floe edges or in unstable areas of 9/10 or 10/10 ice cover with intermittent patches of young ice (Stirling *et al.* 1975). A similar pattern has been observed in other areas of the Arctic but the data have not yet been quantified (I. Stirling, unpubl. data).

In a preliminary study, Stirling and Archibald (1977) found that the majority of seals found killed by polar bears were subadults or young of the year although the exact proportions varied with both habitats and areas. Two-thirds (10/15) of the ringed seals killed in the pack ice or along the floe edge were subadults. The concentrations of polar bears around polynya areas and leads is probably also related to higher densities of subadult ringed seals which may be less experienced at avoiding predators. Smith (1980), in a study of polar bear predation in both the eastern and western Canadian Arctic, concluded that polar bears usually killed adolescent ringed seals and that perhaps seals in unstable ice, such as that found near polynyas, might be easier for bears to hunt.

Although polar bears subsist primarily on seals, they also eat other materials such as kelp. Polar bears have often been observed eating kelp that has been washed up on the beach (Russell 1975), and there are several reports of polar bears actively diving for and feeding upon kelp during the open water period of the summer and fall (Lønø 1970; Russell 1975; Stirling 1974*b*). In some polynya areas where the water is shallow, such as along the coast of southeast Baffin Island, the kelp fronds lie against the underside of the ice and up into seal breathing holes. Polar bears feed on these plants extensively throughout the winter (Fig 5). The nutritive significance of kelp to polar bears is unknown but it appears that access to this resource during the winter is limited to some polynya areas.

Figure 5
Kelp pulled out of a seal hole onto the ice by feeding polar bears (photo: I. Stirling)

5. Marine mammal use of major polynyas

In the following section, we review the use of the major polynya areas of the Canadian Arctic by the different species of marine mammals. Important or possibly critical aspects will be identified to the extent that the available data permit. However, because so little work has been done on ecological relationships, much of the interpretation will have to be based on qualitative rather than quantitative data.

5.1. Cape Bathurst polynya and adjoining shorelead systems (Smith and Rigby, this publication, Figs. 12, 14, and 15)

The white whale and bowhead populations of the western Arctic migrate long distances each spring along shoreleads from the Bering Sea in order to reach their feeding grounds in the Cape Bathurst polynya (Sergeant and Hoek 1974; Fraker 1979). The western Arctic white whale population totals ca. 4000–6000 (Sergeant and Hoek 1974; Fraker 1977), and the most recent estimate of the number of bowheads passing east along the north coast of Alaska is 2264 (Braham *et al.* 1979).

The main use of the leads along the coast of Banks Island occurs in May and June when the whales are migrating to the Cape Bathurst area. By migrating 1–2 months ahead of break-up, the whales are able to feed longer in the Cape Bathurst polynya before migrating westward into the Mackenzie River delta to feed. The white whales apparently give birth to their calves there as well. Even so, substantial numbers of both species have been known to remain in the area around Cape Bathurst for to 2–3 months during the open water period, instead of moving westward (Fraker 1979). Sightings of bowheads, made by whalers around the turn of the century, indicate that a similar pattern of distribution existed then as well (Townsend 1935; Sergeant and Hoek 1974).

The Cape Bathurst polynya and its adjoining leads are used by large numbers of seals, particularly subadult ringed seals and adult bearded seals (Stirling *et al.* 1977*a*; T.G. Smith, unpubl. data). These seals appear to concentrate there because of the reliable occurrence of open water or young ice throughout the winter. Extensive local movements along these lead systems probably occur during the winter in response to short-term changes in ice conditions and food availability but this has not been studied. Although there are no quantitative comparative data, it appears that most bearded seal pups are born along the shorelead polynya system adjoining the Cape Bathurst polynya, while most ringed seal pups are born in the fast-ice areas in eastern Amundsen Gulf and along the coastlines of Banks Island and the mainland (Smith and Stirling 1975; Stirling and Smith 1977). During the fall, substantial but unquantified numbers of subadult ringed seals migrate west along the mainland coast, mostly in open water but using shoreleads as necessary (Usher 1970; Stirling *et al.* 1977*a*). Although it is not known where they go, or what proportion of their cohorts these animals represent, one seal branded in the eastern Beaufort Sea was recovered at Icy Cape in Siberia (Smith 1976). Whether or not these animals return in the spring has not been determined. However, if they do, they almost certainly travel along the shorelead polynya system that parallels the mainland coast from the Chukchi Sea to Amundsen Gulf.

Because seals concentrate in these areas, and consequently may be more accessible to predators, the Cape Bathurst and associated polynyas are also very important feeding sites for polar bears (*Ursus maritimus*) (Stirling *et al.* 1975). In the western Canadian Arctic, the population of polar bears ranges between about 1500 and 1800 animals (DeMaster *et al.* 1980). The Cape Bathurst polynya and associated shoreleads probably comprise the most important feeding area for polar bears through winter and spring (Stirling *et al.* 1975).

In contrast to the aforementioned species, walruses very rarely visit the Cape Bathurst polynya or its adjoining lead systems. Although some discrepancies exist in the literature regarding the historical distribution and abundance of walruses in the southeastern Beaufort Sea (MacFarlane 1905; Fay 1957), at the present time only the occasional walrus strays into this region, usually in the summer (Mansfield 1959; Harington 1966; Usher 1966). However, there is at least one record in which a walrus was presumed to have overwintered in a lead just 50 km west of the northwestern tip of Banks Island (Stirling 1974*a*). Although these open water areas may be used for overwintering by walruses to a greater extent than previously recorded, the total use is probably not significant.

Narwhals, killer whales (*Orcinus orca*), harp, harbour, and hooded seals, northern fur seals (*Callorhinus ursinus*), and possibly ribbon seals (*Phoca fasciata*) have all been reported in the Cape Bathurst polynya and its adjoining leads, but such occurrences are rare (Anderson 1937; Dunbar 1949; Radvanyi 1960; Usher 1966; Mansfield *et al.* 1975*b*; Smith 1977).

5.2. North Water (Smith and Rigby, this publication, Figs. 3 and 5)

The North Water is of significance to more species of marine mammals than any other polynya in the Canadian Arctic. At one time, it was thought that substantial numbers of whales of all species probably overwintered in the North Water but preliminary data collected by Finley and Renaud (1980) in late winter did not support this hypothesis. They estimated that about 500 white whales, or about 5% of the estimated population of 8000 – 10 000 in Lancaster Sound (Sergeant and Brodie 1975), overwintered in the North Water in 1978 and 1979. Of an estimated summer population which may be less than 10 000 (Davis *et al.* 1980), only one group of 12 narwhals was seen in 1979 and no bowheads were observed in either year. During spring, white whales, narwhals, and bowheads migrate north from their apparent overwintering area in Davis Strait. The whales travel along the shorelead polynyas of eastern Baffin Bay to feed in the North Water and penetrate the first cracks and open water in Lancaster Sound, Jones Sound, and associated water bodies (Webb 1976; Sergeant and Hay 1978; Koski and Davis 1979). It has been estimated that a third of the white whales and 85% of the narwhals that inhabit North American waters enter Lancaster Sound during summer (Smiley and Milne 1979). Thus, the North Water is a vitally important spring and summer feeding area for all species of whales.

As spring and early summer progress, white whales and narwhals utilize new leads as soon as possible to penetrate further into Lancaster Sound, Prince Regent Inlet, and eventually Bellot Strait. Narwhals and bowheads in particular continue to feed throughout the summer in Lancaster Sound and Navy Board Inlet. During the fall, when the white whales begin to migrate out of the High Arctic, they continue to feed extensively in eastern Lancaster Sound, particularly in the vicinity of southeastern Devon Island. The same feeding pattern has been documented with seabirds (Nettleship 1974; Johnson *et al.* 1976; Nettleship and Gaston 1977). These observations tend to suggest that some of the currents and upwellings that help to create the recurrent polynya situated in eastern Lancaster Sound are also mixing nutrients and enriching the area biologically, thus making it important for feeding by higher vertebrates.

The walrus population of the eastern Arctic also uses the North Water on both a seasonal and year-round basis. Small numbers apparently winter in the Thule District and several hundred may winter in Canadian waters each year along the eastern coast of Devon Island and the southeastern coast of Ellesmere Island (see review by Davis *et al.* 1980). However, the majority of walruses using the polynya belong to a large migratory population which moves into the North Water during the spring from its wintering grounds in Davis Strait (Vibe 1967; Loughrey 1959). Some herds then travel north into Kane Basin, while the majority migrate into Lancaster and Jones sounds where they feed throughout the summer. There are no reliable population estimates.

Ringed seals and bearded seals are abundant throughout the North Water area although no quantitative estimates have been made of their distribution or numbers. Underwater tape recordings made along the floe edge in Lancaster Sound, south of Maxwell Bay, during April 1980 indicated that bearded seals were abundant (I. Stirling, unpubl. data) although it is not yet possible to relate vocalization rates to absolute numbers.

The importance of the North Water and associated polynyas in Jones and Lancaster sounds as a highly productive feeding area for marine mammals is emphasized by the large numbers of harp seals that migrate to that area to feed during the summer (Vibe 1950; Sergeant 1965; Finley and Johnston 1977; Koski and Davis 1979). Harp seals arrive in June and July and some remain to feed as late as October before returning to their wintering area in southern Davis Strait.

A substantial population of polar bears resides adjacent to the Canadian side of the North Water and the polynyas of Jones and Lancaster sounds. A minimum estimate of the size of this population is 1700 (Stirling *et al.* 1978). These bears move east to hunt adjacent to the floe edge in the winter and spring, after which they move westwards as break-up continues through early summer. Substantial numbers of polar bears also occur during early summer on the floe ice in eastern Baffin Bay (Koski and Davis 1979) but quantitative information on their distribution and movements are not yet available. During spring, the greatest densities of polar bears recorded in the area to date have been recorded along the southern and southeastern coast of Devon Island (Stirling *et al.* 1978; Koski and Davis 1979). Even though ringed and bearded seals are difficult to observe at this time of year, the presence of high densities of polar bears probably indicates the presence of relatively high densities of these seals. Considering the importance of southeastern Devon Island to feeding whales and seabirds later in the summer, the high densities of polar bears reported in this area are probably further evidence of a high degree of biological productivity there.

5.3. Penny Strait and Queens Channel (Smith and Rigby, this publication, Fig. 11)

The polynyas in Penny Strait and Queens Channel occur over fairly shallow water and appear to be particularly significant to overwintering walruses. Because walruses tend to stay in the water where they are not readily visible during March or April when there is enough light to conduct aerial surveys, it is difficult to obtain quantitative data. Data available to date, based on sightings, indicate that the size of the overwintering population may vary (Bissett 1967; Davis *et al.* 1978; Kiliaan and Stirling 1978). Davis *et al.* (1975) estimated that 200–300 wintered in the vicinity of eastern Jones Sound and Penny Strait in 1976 and 1977. In April 1980, an aerial survey coordinated with extensive underwater recording was conducted in Penny Strait and Queens Channel. Although only about 50 walruses were sighted, underwater vocalizations were numerous, often occurring in areas where no animals were visible. This indicated that many more animals were present than were actually visible. Subjectively, it was estimated that upwards of 300 walruses may have wintered in that area in winter 1979–80 (I. Stirling, unpubl. data).

During summer, walruses feed extensively throughout the area and in McDougall Sound and Wellington Channel. Davis *et al.* (1978) estimated a summer population of 1000 in 1976 and 1977. An unknown number of these animals may also move back and forth between Hell Gate and Penny Strait. Thus, on the basis of the preliminary data, it appears that the Penny Strait and Queens Channel area may be the most important overwintering area for walruses in the Canadian High Arctic outside the North Water.

Bearded seals are also particularly abundant in these polynyas, and the area is of particular significance to a sizeable overwintering population. Underwater recordings have indicated one of the highest rates of vocalization recorded anywhere in the Arctic, and numbers of bearded seal calls decrease rapidly as one moves away from the polynyas (I. Stirling, unpubl. data). Thus, although bearded seals are not readily visible during much of the year, they are clearly abundant in these polynyas on a year-round basis.

No quantitative data are available on ringed seal numbers in Penny Strait or Queens Channel, but from subjective observations it appears they are probably abundant. Subadult animals probably predominate there.

Polar bears are locally abundant in Penny Strait and Queens Channel (Stirling *et al.* 1978), probably because of the substantial numbers of seals that reside there. Next to Lancaster Sound, these polynya areas probably represent one of the most important feeding areas for polar bears in the High Arctic.

White whales, narwhals, bowheads, and harp seals also migrate into the Penny Strait and Queens Channel area during the summer months (Macpherson 1963; Davis *et al.* 1980). The Penny Strait polynyas provide suitable summer habitat for small numbers of narwhals, while the Queens Channel polynyas support small numbers of bowheads (Davis *et al.* 1980). Harp seals have been observed throughout the entire area (Davis *et al.* 1980).

5.4. Hell Gate and Cardigan Strait (Smith and Rigby, this publication, Fig. 10)

Variable numbers of walruses winter in this small but reliable polynya each year. Kiliaan and Stirling (1978) reported 100 walruses in May 1972 while Davis *et al.* (1978) reported 200–300 in winter 1977 in eastern Jones Sound and Penny Strait. In April 1980, only one walrus was observed in the Hell Gate area (I. Stirling, unpubl. data). However, as discussed earlier, aerial surveys in cold weather are unreliable for counting walruses. Consequently, the count can be regarded only as a minimum estimate. As leads form into Jones Sound in late spring, walruses migrate into the Hell Gate area. Throughout summer, they feed both in Fram Sound and in the shallow water north of North Kent Island. Clearly, the area is important to walruses as an overwintering area, a summer feeding area, and as a seasonal migration route to other areas.

Ringed and bearded seals are abundant in the area but no quantitative data are available. Polar bears occur regularly around this polynya through winter and spring in variable numbers (Riewe 1977; Kiliaan *et al.* 1978). We suspect the area surrounding this polynya is an important feeding area for polar bears but there are no quantitative data available. The polar bears in this region are part of the same subpopulation that occurs in Lancaster Sound, Barrow Strait, and in the area of Penny Strait and Queens Channel (Stirling *et al.* 1978).

Harington (1963) reported that narwhals feed in the Hell Gate – Cardigan Strait polynya during summer but no other observations seem to be available. In general, however, this does not appear to be a particularly important area for any species of whales.

5.5. Bellot Strait (Smith and Rigby, this publication, Fig. 7)

High densities of ringed seals have been recorded in the vicinity of the Bellot Strait polynya during June and July (Finley 1976; I. Stirling, unpubl. data). Although no data are available on the numbers of seals present during winter, the reported summer densities probably indicate a substantial year-round population. Bearded seals occur in this area as well and, we suspect, may be abundant. The suggestion that large numbers of seals are present on a year-round basis is supported by the fact that polar bears are extremely abundant in both the summer and winter, particularly to the southeast (Tasmania Islands) and southwest (Brentford Bay) of the entrances to Bellot Strait (Davis *et al.* 1975; Finley 1976; Stirling *et al.* 1978). The polar bears in the area appear to be relatively discrete from those of Lancaster Sound and an estimation of the size of this subpopulation is about 1100 (Stirling *et al.* 1978).

Historically, the area around Bellot Strait was part of the bowhead whaling grounds (Davis *et al.* 1980). Bones of bowhead whales used in traditional fashion in houses from the Inuit Thule culture are also abundant along the east coast of Somerset Island, from Bellot Strait to Creswell Bay. These artifacts also indicate long time use of this area by this species. At present, bowheads still use the area during the summer months although sightings of whales are much less frequent there than in Lancaster Sound. Nonetheless, the Bellot Strait area may be of moderate importance to bowheads.

During summer, small numbers of narwhals feed in Bellot Strait and use the area as a passage to feeding areas to the west (Finley and Johnston 1977; Sergeant and Hay 1978). They have been sighted as early in the summer as 24 July and as late into the fall as 4 September (Finley and Johnston 1977). Small numbers of belugas, walruses, and harp seals appear to summer in the polynya as well (Loughrey 1959; Finley and Johnston 1977). Approximately 2000 narwhals were sighted near Savage Point on eastern Prince of Wales Island on 30 July 1980. From the ice conditions, it was apparent these whales had passed through Bellot Strait (T.G. Smith, unpubl. data).

5.6. Fury and Hecla Strait and northern Foxe Basin (Smith and Rigby, this publication, Fig. 9)

The Fury and Hecla Strait polynya and the numerous smaller polynyas in northern Foxe Basin support high densities of walruses, bearded seals, and ringed seals on a year-round basis (Manning 1943; Loughrey 1959; Anders 1965; Mansfield 1967*b*). Unlike the walrus and bearded seal populations, use of this polynya by ringed seals during the winter is dominated largely by subadult seals (Bradley 1970). However, throughout the rest of the year this area is probably used by all age classes.

This whole region appears to be a relatively important summering area for bowhead whales and an ice-free travel corridor for animals migrating eastwards through the strait during the fall (Mansfield 1971). White whales and narwhals also summer and migrate through Hecla and Fury Strait, although such movements do not appear to be critically important (Parry 1835; Sergeant 1962; Anders 1965; Mansfield *et al.* 1975*a*).

Polar bears appear to be abundant throughout Foxe Basin but no quantitative data are available.

5.7. Roes Welcome Sound polynya (Stirling, this publication, Fig. 1)

The Roes Welcome Sound polynya is an important wintering area for white whales, walruses, and harbour seals (Mansfield 1958; Mansfield 1967*a*; Sergeant 1973). In addition, it is an important summer feeding area for narwhals and bowheads (Ross 1974; Mansfield *et al.* 1975*a*).

Most or perhaps all of the whales that summer along the western coast of Hudson Bay winter in the Roes Welcome Sound polynya, although the exact numbers are not known (Sergeant 1973). The population of white whales in western Hudson Bay is estimated at 10 000 (Sergeant 1973). During summer, many of these whales move south and concentrate between the Nelson River estuary and the Manitoba – Northwest Territories boundary (Sergeant and Brodie 1969), although some appear to summer in the vicinity of the polynya (Manning 1943).

In winter, walruses also tend to concentrate primarily in the polynya. After break-up, some walruses remain in the area while many others migrate to northeastern Coats Island and southeastern Southampton Island (Degerbøl and Freuchen 1935; Mansfield 1968).

Bowheads reside in the Roes Welcome Sound polynya from approximately mid May to mid September each year (Ross 1974). Although the current distribution of this population appears to be similar to what it was in the past, the present population size is much reduced from its historic numbers. Most of the bowhead population is believed to leave Hudson Bay late in fall. Occasionally, however, some whales may overwinter in the polynya (Low 1906; Degerbøl and Freuchen 1935; Ross 1974). Narwhals use this open-water area in a similar manner to bowheads except that they probably never winter in Hudson Bay (Mitchell and Reeves 1980). During summer, small numbers of harp seals also feed in Roes Welcome Sound (Sutton and Hamilton 1932; Manning 1943).

Polar bears and bearded seals are permanent residents of the Roes Welcome Sound polynya (Sutton and Hamilton 1932; Manning 1943). The ringed seal is another permanent resident of northwestern Hudson Bay, where it is reported to occur in moderate numbers, although its distribution and abundance in this polynya have not yet been determined (McLaren 1958). Killer whales and hooded seals have not been reported in Roes Welcome Sound.

5.8. Frobisher Bay and Cumberland Sound polynyas (Stirling, this publication, Fig. 1)

Moderate numbers of bearded seals reside in the Frobisher Bay and Cumberland Sound polynyas on a year-round basis (Smith *et al.* 1979). These two southeastern Baffin Island polynyas also support moderate densities of polar bears, and low to moderate densities of ringed seals (Smith *et al.* 1979; Stirling *et al.* 1980). Varying numbers of walruses occur in both areas throughout the year, in addition to relatively abundant numbers of harp seals during the summer and fall, and possibly small numbers during the winter and spring (Anders *et al.* 1967; MacLaren-Marex Inc. 1979; Smith *et al.* 1979). Bowheads appear to concentrate in the Cumberland Sound polynya during the fall, winter, and early spring

(Brown 1868; Anderson 1934; Koski and Davis 1979), while killer whales are common during summer (Kumlien 1879). The Cumberland Sound polynya also provides an important ice-free route for white whales travelling to feeding sites at the head of the sound shortly after break-up (Anderson 1934; Sergeant and Brodie 1975). The Frobisher Bay polynya, on the other hand, provides these whales with an important wintering area (MacLaren Marex Inc. 1979).

The Cumberland Sound polynya receives occasional visits from narwhals, hooded seals, and harbour seals, whereas the latter two species, in addition to killer whales, are unknown in the Frobisher Bay polynya (Kumlien 1879; Soper 1928; Anders *et al.* 1967; MacLaren Marex Inc. 1979). The bottlenose whale *(Hyperoodon ampullatus)* is a constant spring and summer occupant in the area near Frobisher Bay and Resolution Island (Lindsey 1911; Mitchell and Kozicki 1975).

5.9. Eastern and western Hudson Bay (Stirling, this publication, Fig. 1)

White whales, polar bears, bearded seals, and harbour seals reside year-round in the vicinity of the western Hudson Bay shorelead system (Doan and Douglas 1953; Sergeant 1968; Mansfield *et al.* 1975*b*; Stirling *et al.* 1977*b*.). White whales have also been reported overwintering in the persistent leads of James Bay (Jonkel 1969). In addition to hunting along the lead systems that parallel the eastern and western coastlines of Hudson Bay, some polar bears may winter along open water areas at the confluence of James and Hudson bays (Jonkel *et al.* 1976). The western Hudson Bay and Belcher Islands leads are also important summer feeding areas for undetermined numbers of harp seals (Sergeant 1965; Mansfield 1968, 1970).

The coastal shorelead of northwestern Hudson Bay, from approximately Eskimo Point to Roes Welcome Sound, appears to support higher density resident populations of ringed seals (Smith 1975) and walruses than other sections of these shoreleads. However, local concentrations of walruses also occur in the shoreleads surrounding the Ottawa, Sleeper, and Belcher islands (Loughrey 1959; Mansfield 1958; McLaren 1958). Small numbers of sightings of bowheads and killer whales have been made in the Hudson Bay shoreleads (Low 1906; Sergeant 1968; Ross 1974). Although small numbers of narwhals and hooded seals visit Hudson Bay, it is not clear how much they use these lead systems (Mansfield 1968; Sergeant 1968; Mansfield *et al.* 1975*a*; Mitchell and Reeves 1980).

5.10. Eastern Baffin Island (Stirling, this publication, Fig. 1)

The fjords along the east coast of Baffin Island support particularly high densities of breeding ringed seals (McLaren 1958; Smith 1973). Since subadult ringed seals appear to disperse further offshore during winter (McLaren 1958), it is probable that the shorelead polynya system is of particular importance to that segment of the population. Bearded seals are also common in this region, and breed along the whole of the polynya and into the offshore pack ice (Koski and Davis 1979; Smith *et al.* 1979).

During winter and spring, the preferred hunting habitat of polar bears consists of the band of landfast ice adjacent to the coastline. Along the east coast of Baffin Island, this band is fairly narrow in most places compared to other areas of the Arctic (Smith 1980; Stirling *et al.* 1980). Consequently, hunting polar bears are especially dense on the landfast ice and nearshore pack ice along these shoreleads.

Historically, walruses were abundant at Scott Inlet, and hauled out and calved at Padlei and on three islands off the mouth of the Clyde River (Degerbøl and Freuchen 1935; Mansfield 1958). Today only Padlei still supports a "large resident breeding population" (Mansfield 1958). It is likely that the once abundant walruses were severely depleted during the whaling era, and then were further displaced during the recent centralization of the Inuit into villages and construction of the DEW line. Overall, the eastern coast of Baffin Island supports only small numbers of harbour seals although in the past this species may once have been more common in the vicinity of Cumberland Sound (Anders *et al.* 1967; Mansfield 1967*a*). It appears the shoreleads of eastern Baffin Island are of little importance to these two species.

The eastern Baffin shoreleads provide access between summer and winter ranges for several marine mammal species. Harp seals utilize the northeastern coast of Baffin Island as their principle migration route into Jones and Lancaster sounds, at least during the early part of the summer (Koski and Davis 1979). A large portion of the population also migrates south from the High Arctic in the fall to their wintering grounds via these same shoreleads (Koski and Davis 1979). However, there is no mention in the literature regarding the distance which the seals travel down the coastline of the island. Recent aerial surveys have confirmed that narwhals and bowheads also use the eastern Baffin Island lead system as a major migration route during the fall, from Pond Inlet to Cumberland Sound (Koski and Davis 1979).

5.11. Southern Baffin Island (Stirling, this publication, Fig. 1).

Little data has been collected on the distribution and abundance of marine mammals in Hudson Strait and the shorelead systems of southern Baffin Island. Walruses migrate westwards along the southern coast of Hudson Strait in the early summer (Degerbøl and Freuchen 1935) and return in the fall along the northern edge (Loughrey 1959). Some walruses apparently overwinter in the strait in open water areas. Historically, this species was hunted year-round at these locations (Kemp 1975). Variable numbers of walruses may winter in the relatively ice-free waters of the leads surrounding the Nottingham and Salisbury islands, North Bay, and the Middle Savage Islands from October to May, but detailed information is not available (Mansfield 1958).

Ringed seals breed in the fast ice of the bays along southern Baffin Island although subadult seals probably concentrate along the shoreleads during winter and spring. Degerbøl and Freuchen (1935) suggested that ringed seals may migrate along these leads between a summering area at the west end of Hudson Strait and a wintering area in White Strait north of Big Island, but this is speculative and no more recent data are available. Polar bears also utilize the shorelead habitat to a significant extent during winter and spring.

White whales use the southern Baffin Island lead system as a migratory route during spring and fall, and it is possible that small numbers winter there as well (Sergeant 1973). Stephansson (1975) also reported a small number of white whales in the shoreleads west of Lake Harbour in January 1975.

Varying numbers of narwhals, killer whales, bowheads, and harp seals migrate through Hudson Strait during spring and fall but the extent to which these species actually use the shoreleads is not known (Low 1906; Sutton and Hamilton 1932; Mansfield 1968; Sergeant 1968; Banfield 1974; Mansfield *et al.* 1975*a*).

5.12. Entrapments or *savssats*

Savssat is the Greenlandic word for an entrapment of whales, usually narwhals or white whales, in which the animals are confined in patches of open water during the fall or winter. The penchant of these species for feeding in leads and small openings in the ice makes them vulnerable to remaining in localized patches of open water until the surrounding areas are frozen up and escape is apparently impossible. As the remaining open water freezes over, the animals probably eventually die.

Savssats appear to occur on an accidental basis. The largest recorded entrapments have been reported from Greenland. Brown (1868) reported an entrapment of several hundred narwhals and white whales, while Porsild (1918) recorded one in Disko Bay during the winter of 1914–15 in which about 1000 narwhals were killed by Greenlanders and many more were shot but not retrieved.

Entrapments occur in the Canadian Arctic as well but they are apparently less common than in Greenland, possibly because of the migration patterns of the narwhals and white whales (Hay 1980). Freeman (1968), Hay (1980), and Stirling (1980) all report instances of entrapments in Canadian waters.

6. The importance of polynyas to marine mammals

From the foregoing sections, it is clear that polynya areas in the Canadian Arctic are used extensively by marine mammals. However, it is difficult to assess accurately how critical each polynya is to the survival of viable regional populations of marine mammals because many data are not available. For the most part, this is because the necessary studies have not been conducted. However, the results of some relevant research have not been analysed and published. There is also considerable variability in how each polynya and type of polynya is used by each species of marine mammal on a seasonal and regional basis.

One useful approach is to ask what would happen if the polynya was not there? Obviously this is impossible to evaluate on an experimental basis, but by examining the consequences of natural seasonal variation, some useful insights can be gained. For example, the influence of rapidly changing ice conditions on the availability of open water, and consequently on populations of seals and polar bears, has been observed in the western Arctic (Stirling *et al.* 1976, 1977*b*). Apparently in response to severe ice conditions in the Beaufort Sea during winter 1973–74, and to a lesser degree in winter 1974–75, numbers of ringed and bearded seals dropped by about 50% and productivity by about 90%. Concomitantly, numbers and productivity of polar bears declined markedly because of the reduction in the abundance of their prey species. The changes in ice conditions could have affected the seals in two ways. Firstly, because of the heavy and compressed ice, it may simply have been more difficult for seals to maintain their breathing holes. Secondly, if the ice was thicker in spring 1974 and contained fewer cracks and leads, less sunlight may have penetrated into the sea to stimulate primary production. At best, the Beaufort Sea appears to have a fairly low level of primary and secondary production and a relatively uncomplicated food chain. Consequently, changes at the lower trophic levels could have rapid and significant effects on higher organisms. Thus, in this case at least, it appeared that the timing and reliability of occurrence of a particular polynya was critical to some of the resident marine mammals. If the shoreleads of the western Arctic or Hudson Bay ceased opening during winter and spring, the effects on marine mammals would be devastating. Local populations that depend on polynyas for their overwintering survival, such as the walruses and bearded seals in the area of Penny Strait and Queens Channel, would probably be eliminated if the polynyas ceased to exist. While we recognize that such major physical changes seem unlikely in the foreseeable future, the results might be similar if man's activities resulted in large-scale disruptions to polynyas or the lower organisms of the food chain that reside there.

In looking toward the future, it appears particularly relevant to identify some of the critical areas that need to be studied relative to marine mammals and polynyas. One of the most important questions to evaluate is whether it is just the presence of open water that is important, or if the processes that create the polynya in the first place also stimulate greater productivity in the area. The answers probably vary regionally but, in at least two areas, there is some suggestion that the polynya areas may be biologically richer (and thus more important as feeding areas) than adjacent waters. Fraker (1979) has noted the continued feeding of both white whales and bowheads in the Cape Bathurst polynya after break-up, when the whales' movements are not restricted by ice. He has speculated that the area may be enriched by the mixing of waters from the Beaufort Sea, Prince of Wales Strait, Dolphin and Union Strait, and the Mackenzie River. In addition, he queried whether a high level of solar radiation resulting from a long season of exposure on the dark open waters of the polynya may result in an increased primary productivity. At present, the answers are unknown. As reported earlier, a similar situation exists in eastern Lancaster Sound near the southeastern corner of Devon Island, where marine mammals are particularly abundant in almost all seasons. Curiously, although upwelling and subsequent nutrient enrichment has often been suggested to explain the biological richness of eastern Lancaster Sound, even this most basic aspect has not yet been demonstrated scientifically.

Another factor related to the productivity of polynya areas is the undetermined but possibly critical role of the ice edge (Dunbar, this publication). Recent studies by Buckley *et al.* (1979) have suggested that the physical force of wind moving from the ice onto the water may set up a current away from the ice which stimulates localized upwelling and nutrient enrichment. Alexander and Cooney (1979) found that in the Bering Sea the most intense primary production occurred at the ice edge just prior to break-up. Dunbar (this publication) has identified the ice edge as one of the most critical areas to be studied. Because it is the ice edges that delineate polynyas, what goes on there biologically may be as important to the marine mammals that migrate, feed, and overwinter in polynyas as the presence of open water.

More site-specific and species-specific studies need to be conducted to quantitatively determine the age and sex structure of species migrating, overwintering, or feeding during the summer in particular areas. What is the importance of a polynya to the maintenance of a viable population of a particular species? How much could this vary between areas? For example, along southeastern Baffin Island or in the western Arctic, most ringed seal productivity takes place in the deep fjords and bays. However, in the High Arctic, preliminary surveys of ringed seal birth lairs and underwater recordings indicate that few seals are present in the bays during winter, possibly because the snow cover is inadequate to facilitate construction of haul-out and birth lairs (T.G. Smith and I. Stirling, unpubl. data). In contrast, birth lairs appear to be more abundant in the snow drifts that accumulate along the pressure ridges in the inter-island channels (Smith *et al.* 1979; T.G. Smith and I. Stirling, unpubl. data). Consequently, the rough ice adjacent to polynya areas may be of greater importance to breeding ringed seals in the High Arctic than in other areas. Similarly, the possible effects of polynyas on local precipitation during winter, and whether or not this in turn might improve conditions for ringed seal pupping are unknown.

7. Potential threats to marine mammals in polynyas

As a result of human activities, the potential threats to marine mammals in polynya areas appear to be threefold: pollution, physical disturbances, and hunting.

7.1. Pollution

Oil and gas exploration and eventual production is proceeding on an enormous scale in the Canadian Arctic. Despite the extensive research that is being conducted, and the great care that is taken during these operations, oil spills and blowouts can, and in all probability will, occur. The concern, as expressed by Milne and Herlinveaux (1979) is that "We do not have the capability to contain or clear up oil that may be spilled in the north." Because of the dangers ice presents to drilling operations and marine transport of petroleum, relatively ice-free areas such as non-linear polynyas and shoreleads are utilized whenever possible. Although oil spills are much less likely to happen in these areas, mishaps can still occur. In addition, oil is likely to appear in open water areas because, during a blowout, the rising oil may concentrate in cracks, leads, and polynyas in the vicinity, although it also spreads to some extent in a thin layer under ice floes (Pimlott *et al.* 1976; Milne and Herlinveaux 1979). Cold ambient temperatures and the confining effects of surrounding ice are believed to account for the surface layers of 2.5 mm or more that oils can attain in leads during the spring and summer (Milne 1978). The risk of a blowout continuing under the ice through the winter after an accident in the fall is ever-present.

Oil affects marine mammals both directly and indirectly. In an investigation in which the effects of oil on ringed seals were examined, it was concluded that direct contact with oil can result in severe temporary or permanent eye damage, and the death of seals which had been stressed previously by poor nutritional condition (Geraci and Smith 1976). Oil fouling can also have a serious effect on ringed seal pups prior to weaning (Geraci and Smith 1976). Recent studies on the toxicological, pathological, and temperature effects of crude oil on polar bears indicate oil fouling will cause severe cold stress (Øritsland *et al.* 1980). It was also observed that when a polar bear comes into physical contact with crude oil, it licks the oil from its coat with such intensity and for so long that the oil has a serious internal effect. The final results of this study are not yet available, but it is clear that oil spills have the potential for causing severe damage to polar bear populations.

Studies are also being conducted on the effects of oil on small cetaceans but no results are available to date.

Oil spills may have serious effects on some species of marine invertebrates upon which marine mammals are ultimately dependent. A number of short-term toxicity tests involving oil concentrations similar to those encountered in the vicinity of a spill have been conducted on various species of marine invertebrates. At least in the short term, some species appear to suffer high mortality while others appear unaltered. Unfortunately, "the long term ecological consequences of the resulting reduction in species diversity is uncertain" (Percy 1975). In addition to reduction in species diversity and within species numbers, arctic marine mammals may also be affected by bio-accumulations of the heavy metals contained in crude oil. The concentrations that may accumulate in mammals feeding upon lower life forms that reside in an oil-polluted environment may be toxic.

In 1975, Percy reported that "few Arctic marine oil spills have been studied in sufficient detail and over a long enough duration to realistically assess environmental impacts." Although a number of studies have been conducted on experimental spills since that time, the present studies are still operated on a relatively short-term or inadequate long-term basis. Data concerning the spread of oil and weathering in polynyas and its subsequent effects on marine mammals are non-existent. In addition, pre-spill baseline data on polynyas is poor, consequently the ability to assess the environmental impacts of oil in these areas is further complicated. Nonetheless, oil appears to concentrate in polynyas and leads to a similar if not greater extent than surrounding areas. Limited data also suggest that oil may have detrimental effects on species coming into contact with it. An oil spill or blowout in a polynya area could be particularly devastating to species with restricted winter distribution if the availability of undisturbed polynyas for feeding and breathing was critical to their continued survival.

7.2. Year-round ship traffic

In 1977, Petro-Canada and its partners announced a proposal to ship liquid natural gas (LNG) in large icebreaking carriers from Melville Island to southern markets on a year-round basis. Dome Petroleum may make similar use of the Northwest Passage to move oil from the Beaufort Sea to eastern markets. Ore from the Arvik mine on Little Cornwallis Island will use a similar route though possibly not on a year-round basis. The planned shipping route will be along the Greenland coast, across Baffin Bay, and through Lancaster Sound, Barrow Strait, and Viscount Melville Sound to southeastern Melville Island. For much of the year, a large portion of the route is completely ice-covered. Thus, maximum use will be made of polynyas and shoreleads because that will reduce shipping time and minimize the risk of damage or spills.

Although the LNG cargo, if ignited, will burn and probably have only a small localized effect, the ships will be carrying 10 000 or more tonnes of fuel, which could cause a serious spill if the carrier was badly damaged (Smiley and Milne 1979).

The noise levels associated with LNG traffic may also seriously disrupt animals using these areas. Although estimates of the noise levels produced by icebreaking LNG cariers are not available, in considering this problem Møhl (1980) made extrapolations using calculations based on data from World War II cruisers. The results indicated that if LNG tankers pass by marine mammals at a distance of less than 100 km, communication could be highly impaired or totally blocked between animals more than 100 m apart. In this study, Møhl suggested that the noise levels generated by LNG carriers may also result in temporary or possibly permanent hearing damage, and nausea induced by infra-sound. During the winter, species that utilize polynyas may be severely restricted in the alternatives they have for escaping hazardous disturbances that may occur in these open-water areas. In an effort to avoid the noise from LNG carriers, marine mammals may react in a way that possibly could prove fatal. The Canadian Arctic Resources Committee has projected that by the turn of the century, 2000 passages will be made through the Northwest Passage each year. If this number is accurate, the potential for detrimental effects from noise upon marine mammals could be significant.

The penchant of narwhals and white whales for entering small leads and patches of open water has been well documented, as has the regularity with which they become entrapped. Some biologists are concerned that whales may follow icebreakers away from polynya areas during the winter only to become restricted to unnatural isolated patches of open water left in the wake of ships and subsequently perish.

7.3. Hunting

Ever since indigenous man inhabited the Arctic, there has been an association between settlements and polynyas, probably because of the local abundance of marine mammals that occur in these areas (Schledermann 1980). The greater vulnerability of marine mammals to hunters while migrating through or breathing in the leads adjacent to polynyas has also probably influenced this relationship.

In recent years, the number of Inuit hunters has increased dramatically, as has the technology of the equipment with which they hunt. One of the unfortunate results has been that some populations have been heavily hunted, and considerable waste has occurred when marine mammals have been killed for their ivory (Land 1977). It is clear that human utilization of marine mammals in polynya areas is as great a potential threat as industrial activities, although it should be the easiest to ameliorate through modification of management practices.

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The biological significance of polynyas to arctic colonial seabirds

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1. Abstract

Recurring polynyas, leads, and other open-water areas are important to populations of seabirds wintering in the Canadian Low Arctic: along southeast Baffin Island, and in Hudson Strait and Hudson Bay. Polynyas at high latitudes, north of approximately 70°N, are used by only a small number of wintering birds, mainly Ross' Gulls (*Rhodostethia rosea*) in the Arctic Ocean and Black Guillemots (*Cepphus grylle*) farther south. The bulk of the high arctic seabird population moves to the west Greenland polynya or farther south to winter. However, recurring polynyas are extremely important in both the High and Low Arctic when the birds return in the spring. Open water gives the birds early access to the breeding site; it also allows an earlier zooplankton bloom than in adjacent, ice-covered waters. There is a clear association between the breeding locations of the highly colonial seabird species and the presence of recurring polynyas in both the North American and European Arctics. With one apparent exception (the Black Guillemot colony at Skruis Point, Jones Sound), there are no major seabird colonies in the Canadian Arctic that are not adjacent to recurring polynyas. Where polynyas occur and major colonies are absent these open-water areas are either too small or too distant from the floe edge, or they are adjacent to coasts lacking suitable nesting habitat for cliff-breeding seabirds.

2. Résumé

Les polynies, chenaux et autres étendues d'eau libre récurrentes sont importants pour les populations d'oiseaux de mer qui hivernent dans le Bas-Arctique canadien, c'est-à-dire le long du sud-est de l'île Baffin, dans le détroit d'Hudson et dans la baie d'Hudson. Les polynies situées à des latitudes plus élevées (au nord de 70 °N approximativement) ne sont fréquentées que par de petits nombres d'oiseaux qui hivernent et principalement par la mouette rosée (*Rhodostethia rosea*) dans l'océan Arctique et le guillemot noir (*Cepphus grylle*) plus au sud. La plus grande partie de la population d'oiseaux de mer du Grand Nord migre vers la polynie de l'ouest du Groenland ou plus loin vers le sud pour y hiverner. Les polynies récurrentes du Haut et du Bas-Arctique sont toutefois extrêmement importantes lors du retour des oiseaux au printemps. Les étendues d'eau libre permettent aux oiseaux d'arriver tôt dans les aires de reproduction; elles permettent également une apparition plus hâtive du zooplancton que dans les eaux avoisinantes recouvertes de glace. Il existe une relation très nette entre les aires de reproduction des espèces très coloniales d'oiseaux de mer et l'existence de polynies récurrentes dans l'Arctique, tant du coté de l'Amérique du Nord que du côté de l'Europe. Apparemment, sauf dans le cas d'une exception partielle (la colonie de guillemots noirs de la pointe Skruis dans le détroit de Jones), il n'existe pas de colonies importantes d'oiseaux de mer qui ne sont pas adjacentes à des polynies récurrentes dans l'Arctique canadien. Aux endroits où il y a des polynies et où il n'y a pas de colonies importantes, les étendues d'eau libre sont soit trop petites, soit trop éloignées de la limite de la banquise flottante ou bien situées le long de côtes où il n'existe pas d'aires de nidification convenables aux oiseaux de mer qui se reproduisent sur les falaises.

3. Introduction

In terms of their importance to seabirds, there are three main types of recurring polynyas in the Canadian Arctic: areas of year-round open water, areas which may freeze during the coldest portions of some winters but are the first to open in the spring, and an area we have termed the west Greenland polynya. The latter area lies along the west coast of Greenland north to about 70°N (Fig. 1). Although it is not a true polynya because it is open to the Labrador Sea on its southern end, we have included it because of its enormous importance to seabirds.

In the discussion that follows, we base our comments on the catalogue of polynyas in the Canadian Arctic compiled by Schledermann (1980), Stirling (1980), Dunbar (this publication), and Smith and Rigby (this publication) supplemented by data on ice cover from various ice atlases (Anon. 1955, 1958; Swithinbank 1960; Lindsay 1975, 1977).

In general, most arctic seabirds rapidly migrate southwards as soon as the breeding season is over, away from the vicinity of their colonies. After this initial exodus, the speed of migration varies from species to species, but the birds continue to move south as the winter ice begins to form. For those species that do not leave the Arctic altogether, polynyas and temporary openings in the ice are obviously important as the only areas of open water in which the birds can feed. Their importance probably lies in the access they provide to the epontic (under ice) fauna surrounding it, such as arctic cod (*Boreogadus saida*) and the gammarid amphipods (*Onesimus glacialis* and *Apherusa glacialis*) (Bradstreet 1977; Bradstreet and Finley 1977; Sekerak and Richardson 1978; Bradstreet 1980; Dunbar, this publication). It is possible that this ice-edge fauna is especially rich in the larger polynyas. Wind-induced upwelling can occur along the edges of pack-ice (Salomonsen 1972; Buckley *et al.* 1979); this may bring nutrients up to enhance the local productivity much as upwellings do in coastal zones (e.g. Cushing 1971). Polynyas are also important as feeding areas when the seabirds return to breed, early in the spring. The availability of food at that time is especially crucial for females as the energetic costs of producing eggs are high. Consequently, the birds require a food source close to the breeding site (e.g.Birkhead and Nettleship 1981*a;* Gaston and Nettleship 1981).

Polynyas may also be important in spring by allowing early access to the breeding site, since seabirds are often reluctant to fly across extensive stretches of unbroken ice (Salomonsen 1951; Belopol'skii 1961; Uspenskii 1958; Løvenskiold 1964). In general, the absence of open water can considerably delay the arrival of many seabird species at their colonies in spring. During years in which the ice persists, many seabird species become concentrated along the floe edge at the point of open water nearest the colony until break-up. The timing of break-up has a normal annual variation of up to 3–4 weeks, and there is enough flexibility in the timing of the birds' breeding season to allow them to cope with this. Longer delays, however, can reduce breeding success (Salomonsen 1951; Nettleship *et al.* 1980). There are clearly advantages in breeding close to a predictable recurring polynya, and most arctic seabird colonies are so situated (see sec. 5 and Fig. 1). Stonehouse (1967) documented a similar relationship between the distribution of polynyas and penguin colonies in the Antarctic.

The presence of open water close to the colony in spring may have the added advantage of denying access to the site by ground predators, especially arctic foxes *(Alopex lagopus).* The most vulnerable species are those which nest on islands on flattish ground or slopes, as opposed to cliffs, such as Dovekies *(Alle alle),* Black Guillemots *(Cepphus grylle),* and some gulls and terns.

Finally, the presence of a polynya near a colony in the spring may have significant influences later in the summer, long after all the other ice has broken up. In the Arctic, as elsewhere, phytoplankton is the basis of the marine food web. The spring bloom cannot begin until the surface is free of ice and solar radiation can penetrate into the water column and trigger photosynthesis. Therefore, the phytoplankton bloom in the Arctic begins earliest in polynyas and other areas of open water, as does the zooplankton bloom which succeeds it. For example, Pavshtiks (1968) found that in Davis Strait the zooplankton bloom occurs in July in the west Greenland polynya, in August in the middle of the strait, and in September along the ice-bound coast of Baffin Island. In most species of seabirds breeding in the Canadian Arctic and Greenland, the young hatch in the latter part of July or early August (Salomonsen 1951; Nettleship 1977; Nettleship *et al.* 1980; Birkhead and Nettleship 1981*b*; Gaston and Nettleship 1981). This timing is presumably geared to the period when the maximum amount of food is available for feeding the young (e.g. Lack 1968). The parents then have a short period in which to fledge their young before the arctic summer ends in late August or early September. A July zooplankton bloom would allow 4–6 weeks for chick-rearing. But an August or September bloom would be too late for most seabird species to rear young successfully. This is particularly crucial for species which feed on fish and the larger crustaceans, whose annual population increase comes even later than that of the zooplankton on which they graze.

At different times, all of these facets of the polynya environment are important to seabirds, as the following examples show.

4. Seabirds and polynyas in winter

Research which would determine the extent to which seabirds use polynyas in winter has been restricted by darkness and difficulty of access. Darkness may also hinder foraging by whatever birds remain in high-latitude polynyas, though little is known about the ability of northern seabirds to feed in the dark. Since small numbers regularly winter at high latitudes, some species are evidently able to forage efficiently enough to at least meet their energy requirements for maintenance. In general, however, the exodus of seabirds from northern Baffin Bay and the North Water area is virtually complete by the end of September (Salomonsen 1951, 1967; Johnson *et al.* 1976; Nettleship and Gaston 1978; McLaren and Renaud 1979; Nettleship *et al.* 1980; R.G.B. Brown, unpubl. data). The rapidity of the exodus suggests that the North Water is not an attractive wintering area for most seabirds in the Canadian Arctic.

Only two species do not follow this pattern. Almost the entire population of Ross' Gull *(Rhodostethia rosea)* breeds in northeast Siberia, and migrates east along the north coast of Alaska in September and October (Fisher and Lockley 1954; Gabrielson and Lincoln 1959; Løvenskiold 1964; Divoky 1976). Ross' Gulls apparently winter in the Arctic Ocean, where they presumably feed in temporary leads in the ice, or in polynyas if they exist there.

Banding returns from west Greenland show that adult Black Guillemots move south, but only for a relatively short distance (Salomonsen 1967). For example, birds from the Upernavik District move approximately 100 km south to Umanak, Umanak birds move a similar distance south to Disko and Egedesminde, and so on in a series of population displacements down the coast. The northernmost birds are regularly seen in leads at the ice edge. Birds of the year, by contrast, disperse *northwards* immediately after they fledge. Presumably, it is these birds which have been reported in small numbers throughout the winter in polynyas and other open water areas in the Smith Sound region (Fig. 1) (Hayes 1867; MacMillan 1918). Occasionally, Black Guillemots have also been recorded at other high arctic locations: Port Bowen and Fury Point (Prince Regent Inlet/Lancaster Sound — Smith and Rigby, this publication, Fig. 6) in winter 1824–25 and February 1833, respectively (Ross 1826, 1835); Hell Gate and Cardigan Strait (Jones Sound — Smith and Rigby, this publication, Fig. 10) in March 1900 (Sverdrup 1904); and as far north as near Thank God Harbour (Robeson Channel) in February–March 1872 (Davis 1876) and elsewhere in that region in winter (see Feilden 1877; Nares 1878; Greely 1888). However, despite frequent casual sightings of small numbers of Black Guillemots, most seabirds from the High Arctic move southwards and winter in large numbers along the ice-free coasts of southwest Greenland (Salomonsen 1951, 1967; Renaud and Bradstreet 1980).

By contrast, the west Greenland polynya is extremely important, as the migration patterns of various populations of Thick-billed Murres *(Uria lomvia)* so clearly show (Tuck 1961; Salomonsen 1967; Gaston 1980). Upon completion of breeding, murres from Lancaster Sound and northwest Greenland immediately migrate to the waters off the west Greenland coast at approximately 70°N. Most of the Greenland birds and some at least from Lancaster Sound later move on to Newfoundland waters. Birds from the European Arctic (Svalbard, Novaya Zemlya, and the Murman coast) reach southwest Greenland in November, presumably after following the ice edge in the Greenland Sea and Denmark Strait southwestwards from their breeding areas. Hudson

Strait birds go directly to the Labrador coast and on later to Newfoundland, but some at least migrate back in spring via west Greenland.

Banding returns (Salomonsen 1967) have shown that west Greenland is also an important wintering area for Svalbard Dovekies, and for the west Greenland populations of Great Cormorants *(Phalacrocorax carbo)*, and Great Black-backed *(Larus marinus)*, Iceland *(L. g. glaucoides)*, and Glaucous gulls *(L. hyperboreus)*. The greater importance of the west Greenland polynya, compared to ice-free areas farther north, is presumably due to its larger geographical extent and more southerly location. In addition, because it is open at its southern end, seabirds from European populations can enter later in the winter.

In contrast to the High Arctic, there are numerous observations of seabirds wintering in low arctic polynyas and other open-water areas, from southeast Baffin Island west through Hudson Strait to Foxe Basin and Hudson Bay. Several species remain all winter in Hudson Bay and Strait in polynyas and patches of open water among the pack-ice (Stirling, this publication, Fig. 1). and move south only when unusually severe weather causes the water to freeze over (Sutton 1932; Manning 1949). In the Southampton and Coats islands area, Thick-billed Murres "...may be found at the floe throughout the dead of winter" and can be seen in substantial numbers every month of the year wherever there is open water (Sutton 1932). Low (1906) simply states that the murre "remains in the open water of Hudson Bay throughout the winter" and Sutton (1932) records that they

> do not move much to the southward during the coldest months. Only when the winter is very severe, do they have to move to the south in finding open water, where food may be obtained. It is a matter of common knowledge among the Aivilikmuit that the channel between Coats and Southampton practically never freezes, even during years when Frozen Strait to the north is frozen shut.

Tuck (1961) notes that Hudson Strait is kept open by strong tides, and quotes a report that "murres have been quite common along the floe-edge this winter" off Lake Harbour in 1953.

Like the murres, Black Guillemots also winter in open-water areas in Hudson Bay, Hudson Strait, and Foxe Basin (Smith and Rigby, this publication, Fig. 9). They are abundant along ice edges from January to April. At the floe-edge near Native Point, Black Guillemots "swarmed about the open pools among the loose floe-ice, being so numerous as almost to cover the surface of the water. When the sun shone, many of the birds climbed out on the ice, basking on their bellies" (Sutton 1932). Of 17 birds collected at the time of this observation, all were in good condition with fat deposits, their stomachs filled with crustaceans — indicating the amount of food available in this polynya.

Glaucous Gulls also overwinter in the Hudson Bay/Strait area in limited numbers. They have been recorded in late fall, mid winter, and early spring in open-water areas, often associated with Black Guillemots and the occasional Thick-billed Murre. Dovekies are irregular winter residents and are most often seen in small numbers from late September to March (Sutton 1932). Farther north, near Igloolik, most species leave by mid September, and only Black Guillemots were seen at the floe-edge during winter 1955–56 (Ellis and Evans 1960). Guillemots were also the only winter residents in the Cumberland Sound region of Baffin Island in 1877–78 (Tyson 1879).

We conclude, therefore, that recurring polynyas, leads, and other open-water areas in the Canadian Arctic are most important to populations of seabirds wintering in the low arctic regions of southeast Baffin Island, Hudson Strait, and Hudson Bay. Polynyas at high latitudes, north of about 70°N, are used by only a small number of birds, mostly Ross' Gulls in the Arctic Ocean, and small numbers of Black Guillemots farther south. The bulk of the breeding populations of all species moves to the west Greenland polynya or farther south to spend the winter.

However, the recurring polynyas in both the High and Low Arctic become critical when the birds return in the spring. The timing of the spring influx of seabirds into the north is known to be linked to the appearance or presence of polynyas and patches of open water near the breeding sites in the arctic regions both of Canada and Europe (Belopol'skii 1961; Uspenskii 1958; Tuck 1961; Bianki 1967; Gaston and Nettleship 1981). For example, Johnson *et al.* (1976) found Dovekies very abundant at the ice edge and among loose drift ice at the eastern entrance to Lancaster Sound (Smith and Rigby, this publication, Fig. 5) in the latter half of May 1976. These birds were apparently en route to the large colonies in the Thule District of northwest Greenland. Johnson *et al.* estimated that as many as 1.5 million birds were present. A later survey in an adjacent area during the same period in 1978 put the numbers at a minimum of 6 million birds (McLaren and Renaud 1979). Freuchen and Salomonsen (1958) estimated that the Dovekie population of the Thule District was in the order of 30 million birds. Clearly, a significant proportion of this population visits the ice edge at the entrance to Lancaster Sound each spring. It may be that the entire population of Thule District Dovekies is either spread around the whole perimeter of the North Water at this time of year, or is at the edge of the west Greenland polynya on its way to the North Water polynya, which is obviously an extremely important feeding area for Dovekies at the start of the breeding season.

5. Seabirds and polynyas in the breeding season

The immediate importance to seabirds of open water near the breeding site is shown by what happens in abnormal years when the ice fails to break up. In summer 1978, for example, the polynya at the eastern end of Lancaster Sound (Smith and Rigby, this publication, Fig. 5) did not develop. The result was a disastrous breeding season for seabirds (Nettleship *et al.* 1980). On Prince Leopold Island only 10–20% of the species which feed at the surface [Northern Fulmars *(Fulmarus glacialis)*, Black-legged Kittiwakes *(Rissa tridactyla)*, and Glaucous Gulls] attempted to breed. The numbers of the two diving species, Thick-billed Murres and Black Guillemots, which attempted to breed were nearly normal, but both species started late and as a result there was high chick mortality, both before and after fledging. The murres, for example, laid their eggs 3 weeks later than normal and suffered both smaller eggs and chicks and reduced chick-feeding rates (Nettleship *et al.* 1980). These three points are all evidence of a reduced food supply, either because the prey was inaccessible under the ice, or because the heavy ice prevented the spring plankton bloom from developing. Similarly, Kartaschev (1960) found that Thick-billed Murres on the Murman coast had a reduced breeding success in a year when break-up was late. Salomonsen (1951) reported a similar occurrence in the Thule District when Dovekies failed to breed in a year when the ice failed to break up and their nesting slopes remained snow covered all summer.

More generally, there is a very good correlation between the siting of arctic seabird colonies and the presence of recurring polynyas. Figure 1 illustrates this for the Northern Fulmar and Thick-billed Murre. All the colonies of these two species in arctic Canada and west Greenland are on coasts adjacent either to recurring polynyas, or to waters covered with unconsolidated pack-ice during the winter. There is a species difference, however. The murres breed close to areas where there is open water early in the season. Fulmars seem to make use of sites that they can reach by crossing unconsolidated pack-ice, and where an adjacent polynya (as at Cape Vera, near the Hell Gate and Cardigan Strait polynya — Smith and Rigby, this publication, Fig. 10) or extensive shoreleads (Buchan Gulf, Scott Inlet, Fig. 1) will develop as the season progresses. This discrepancy may well reflect differences in their food requirements later in the summer, when the chicks hatch. The murres feed on fish while fulmars take both fish and zooplankton (Bradstreet 1980; Gaston and Nettleship 1981). Because the annual increase in fish numbers follows that of zooplankton, the murres might well need the earlier start to the annual plankton cycle that occurs in fully open waters.

The variation in selection of breeding sites probably reflects differences in flight behaviour. Fulmars have an energetically economical gliding flight, and carry a small body weight relative to their wing area; murres (as well as Dovekies and Black Guillemots) have an energetically expensive flapping flight — a necessary consequence of their adaptation to diving — and a heavy body relative to their wing area (Warham 1977). Both species have great difficulty in taking off from a flat surface such as an ice floe, or from water obstructed by pack-ice. Given the reduced range imposed by its flapping flight, it seems clear that it would be more hazardous for a murre to attempt to fly across unconsolidated pack ice than it would be for a fulmar. The same considerations influence the distances from the colonies which the two species are able to travel to forage for food. Even so, there are still limits on fulmars. Figure 1 shows that none breed along the east coast of Baffin Island between Scott Inlet and Cape Searle, despite the presence of apparently suitable nesting habitat. This is precisely the stretch of coast along which the pack ice is consolidated against the land-fast ice so that no shorelead exists until late summer or early fall. However, there are hundreds of very small colonies of Glaucous Gulls and other *Larus* spp. there, usually 10–20 pairs in each. These colonies are sited on capes and headlands adjacent to very small patches of open water caused by melt runoff from snow and ice fields (D.N. Nettleship, unpubl. data).

Similar species arrangements occur elsewhere. The east coast of Greenland is ice-bound except for a recurring polynya at Scoresby Sound, and unconsolidated pack ice off Kron Prins Christians Land in the far northeast. Thick-billed Murres breed only at Scoresby Sound, and Northern Fulmars breed there and in Kron Prins Christians Land, while Glaucous Gulls breed along the whole coast (Salomonsen 1979). Again, there are no fulmar colonies west of Devon Island in the zone of consolidated ice cover in winter (Fig. 1). There are, however, three small Black-legged Kittiwake colonies: Washington Point (Baillie-Hamilton Island), Separation Point (eastern Cornwallis Island), and Browne Island (Nettleship 1974; Brown *et al.* 1975). The first is adjacent to the polynyas in Queens Channel (Smith and Rigby, this publication, Fig. 11) while the ice atlases (Anon 1955, 1958; Swithinbank 1960; Lindsay 1975, 1977) indicate that the other two may be near recurrent shorelead polynyas.

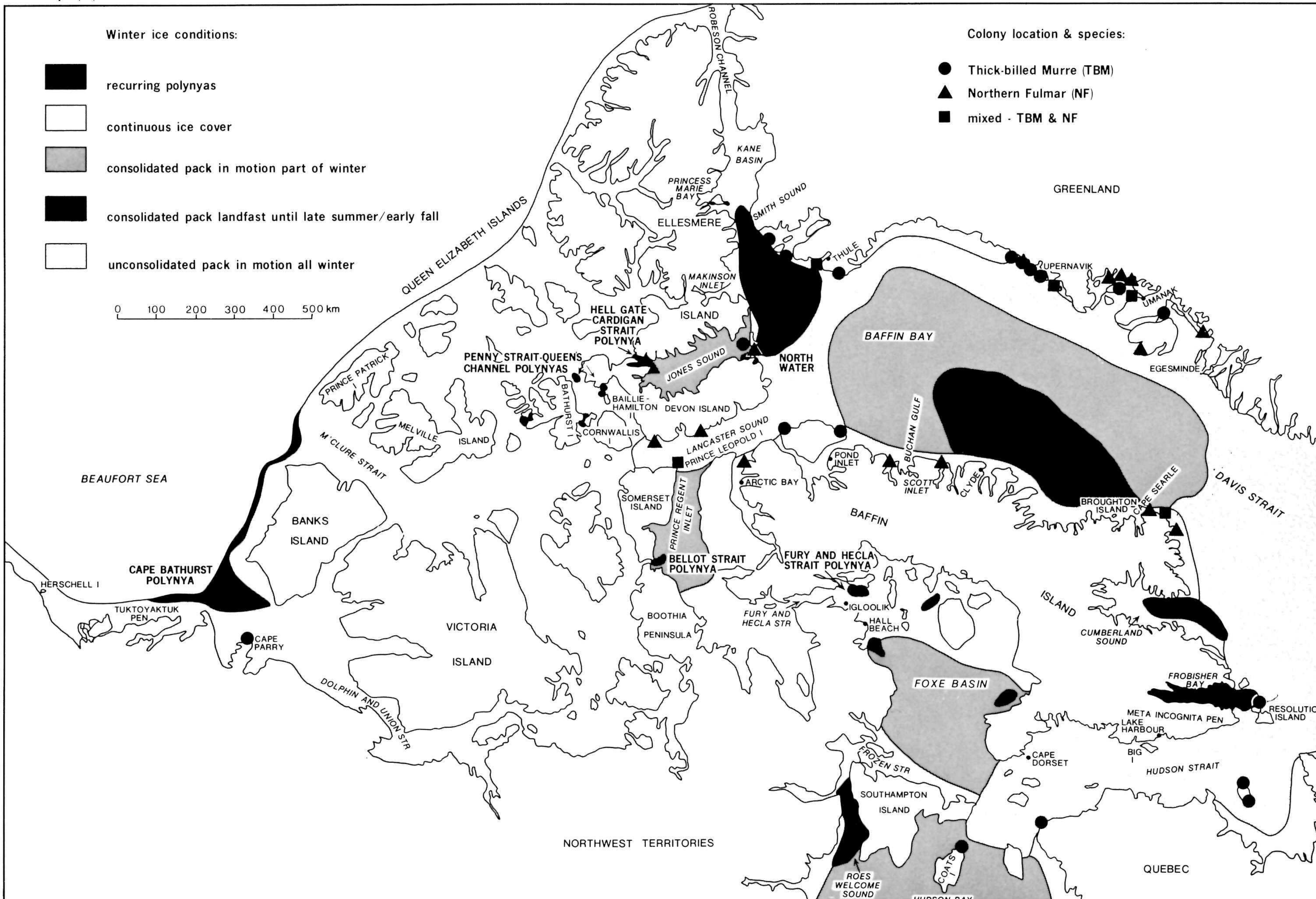
Evidently, gulls can exploit polynyas that fulmars and murres cannot reach. Gulls, like fulmars, have an energetically economical flight, but unlike fulmars they have no difficulty in taking off from flat or confined surfaces. Their greater agility not only reduces the hazards of crossing consolidated pack-ice, but also allows the gulls to exploit very small patches of open water in the consolidated zone, such as the small polynyas west of Devon Island (Smith and Rigby, this publication, Fig. 11), or the small patches of open water along the central Baffin Island coast.

Finally, Figure 1 shows that there is a single small Thick-billed Murre colony composed of approximately 300 pairs in the western Canadian Arctic at Cape Parry. This colony is situated adjacent to the large Cape Bathurst polynya (Smith and Rigby, this publication, Figs. 14 and 15). T.W. Barry (quoted by Stirling 1980) has suggested that until recently this polynya was nearer to Cape Parry. If the apparent shift is real, it will be interesting to see what effect it will have on this small isolated population of murres, given the limitations in the species' flight range as outlined above.

The breeding range of the Dovekie also illustrates the importance of polynyas to a high arctic seabird. Over the whole Arctic, all major Dovekie colonies are beside waters that either never freeze over completely (Thule District, West Spitsbergen, Jan Mayen, as well as the minor colonies in west Greenland, Bear Island, and northern Iceland), or that are more or less ice-free by the time the chicks hatch in July (Scoresby Sound, northern Novaya Zemlya, Franz Josef Land, Severnaya Zemlya) (Salomonsen 1951; Fisher and Lockley 1954; Salomonsen 1967; Demente'ev and Gladkov 1968; Norderhaug *et al.* 1977. See also Anon. 1958). The distribution of Ivory Gulls *(Pagophila eburnea)* in Canada makes the same point on a smaller scale. There are three known breeding areas: Seymour Island, north of Bathurst Island (Nettleship and Smith 1975; MacDonald 1976); nunataks in the ice cap in southeast Ellesmere Island (Frisch and Morgan 1979); and Princess Marie Bay, in the Bache Peninsula area of eastern Ellesmere Island (R. Burton, pers. commun.). All three breeding sites are close to small polynyas. Seymour Island is in the middle of a polynya. It is a flat site, and arctic foxes cause serious damage to the colony if the polynya is late in forming in the spring because they can reach the colony across the ice. The Ellesmere nunataks and Princess Marie Bay colonies are close to the Makinson Inlet and Flagler Bay polynyas respectively (Stirling, this publication, Fig. 1). Both sites are also close to the North Water. Finally, the very small Ross' Gull colony in Penny Strait (Smith and Rigby, this publication, Fig. 11) is situated adjacent to the polynya there, though not actually in it, and the nests are therefore often robbed by polar bears *(Ursus maritimus)* (MacDonald 1979 and pers. commun.)

We know of only one major seabird colony in the Canadian Arctic that may not be associated with a polynya. Black Guillemots are normally only a weakly colonial species, nevertheless there are exceptionally large colonies at the western end of Jones Sound: 2000–3000 pairs on North Kent Island, about 5000 pairs on Calf Island, and about 10 000 pairs (the biggest colony in North America) at Skruis Point (Nettleship 1974; Brown *et al.* 1975). The first two are situated in the Hell Gate and Cardigan Strait polynya (Smith and Rigby, this publication, Fig. 10). Skruis Point, however, is surrounded by consolidated pack ice until the beginning of August; until then, the nearest open water is the Hell Gate and Cardigan Strait polynya, approximately 50 km away (Lindsay 1975, 1977). The limitations in alcid flight range suggest that it is unlikely that the birds could be travelling to the polynya to feed. On the other hand, so large a colony of diving birds could hardly survive without access to a substan-

Figure 1
Distribution of Thick-billed Murre and Northern Fulmar colonies in arctic Canada and west Greenland, in relation to winter ice conditions and occurrence of polynyas



tial body of open water. This apparent anomaly should be investigated further.

With this exception, then, all major seabird colonies are close to recurring polynyas. However, several of the polynyas listed by Schledermann (1980) and Stirling (1980) (see also Fig. 1) do not appear to have major seabird colonies associated with them. Cumberland Sound is the most conspicuous example. However, the structure of the cliffs along the coast and on islands in the sound is such that there are no suitable ledges for the birds to nest on. The shores of Foxe Basin (Smith and Rigby, this publication, Fig. 9), Fury and Hecla Strait, Dolphin and Union straits, Roes Welcome Sound, and Bellot Strait (Smith and Rigby, this publication, Fig. 7) are too low-lying for cliff-nesting birds. This is true of Frobisher Bay as well, though this polynya has an offshore colony associated with it — the Thick-billed Murre site on 'Hantzsch' Island (61°55'N, 65°00'W) in the Resolution Island group. We have no information on the small polynyas at Alexander and Karluk Brooman. It is quite likely that there are, in fact, small colonies of Arctic Terns (*Sterna paradisaea*), Black Guillemots, and *Larus* gulls breeding at these sites — species that nest on flat ground and have a wide distribution in the Arctic (e.g. Ellis and Evans 1960; Godfrey 1966). Except for Cumberland Sound, however, these polynyas are a considerable distance from coasts with suitable nesting habitat for colonial, cliff-breeding seabirds. Even if they are productive, there would be little advantage to a non-breeding seabird in making a considerable detour to feed there, when suitable polynyas exist much closer to its breeding site.

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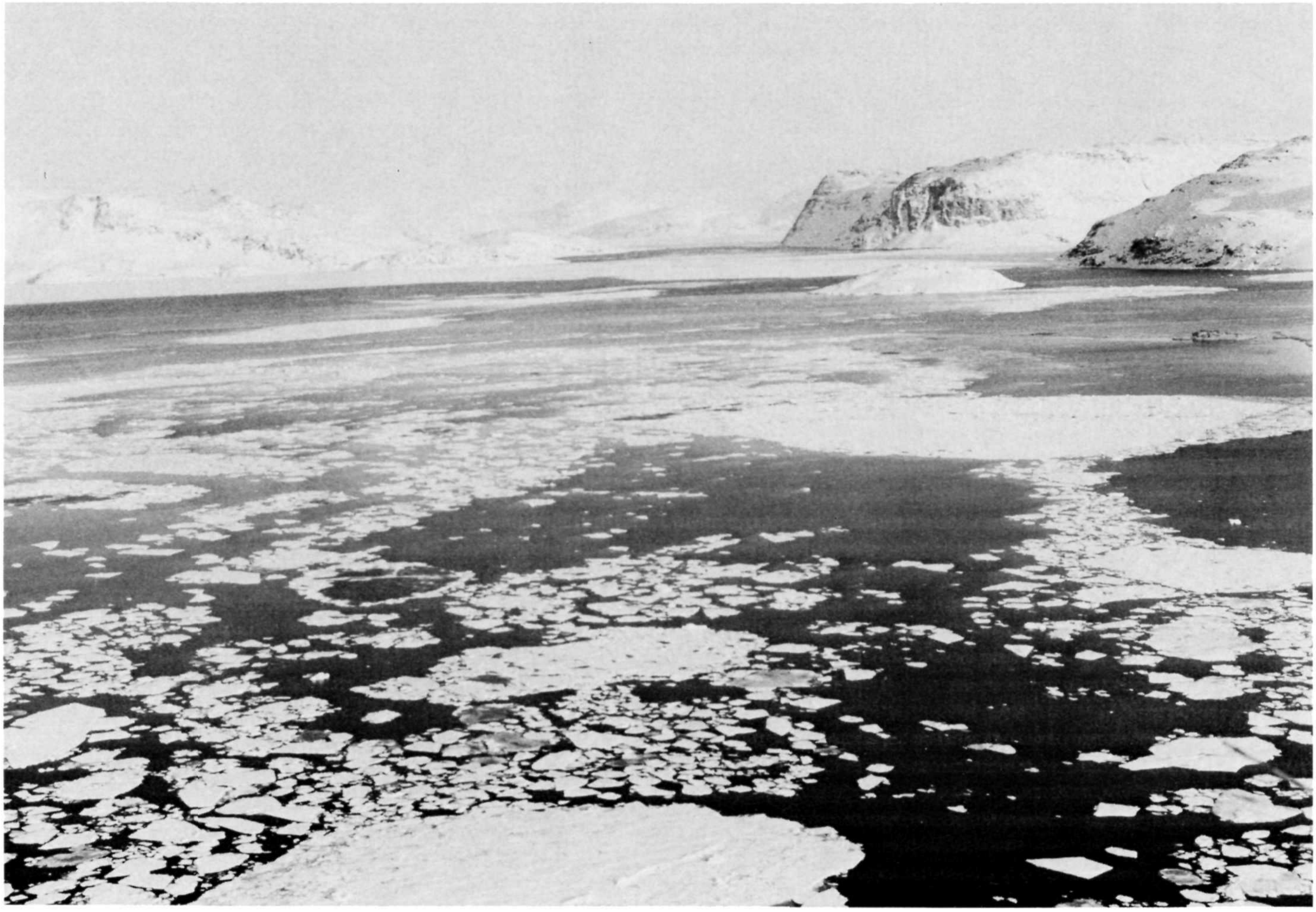
Small recurrent polynya at Misty Island on the southeastern coast of Baffin Island (photo: I. Stirling)



Polynyas and seaducks

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1. Abstract

With the exception of the recurring lead systems in Hudson Bay and Hudson Strait, polynyas are not used extensively by overwintering seaducks in the Canadian Arctic. Some recurring polynyas, especially those in the western and central Arctic, are important as staging areas prior to the breeding season. The Cape Bathurst polynya and associated leads are a particularly critical staging area for birds moving eastwards into the central Arctic and southeastwards through Dolphin and Union Strait into Queen Maud Gulf. Oil pollution in recurring polynyas, particularly in the Beaufort Sea during spring staging, could greatly reduce arctic seaduck populations.

2. Résumé

À l'exception des réseaux récurrents de chenaux de la baie d'Hudson et du détroit d'Hudson, les polynies de l'Arctique canadien ne sont pas beaucoup fréquentées par les canards de mer pour y hiverner. Certaines polynies récurrentes, en particulier celles de l'ouest et du centre de l'Arctique, sont importantes comme points d'arrêt avant la saison de reproduction. La polynie du cap Bathurst et les chenaux qui lui sont associés constituent un point d'arrêt particulièrement critique pour les oiseaux se déplaçant vers l'est pour atteindre la partie centrale de l'Arctique et vers le sud-est par les détroits de Dolphin et Union pour atteindre le golfe Reine-Maude. La pollution des polynies récurrentes par le pétrole, en particulier dans la mer de Beaufort durant l'escale printanier, pourrait grandement réduire les populations arctiques de canards de mer.

3. Introduction

Three species of seaducks predominate in the Canadian Arctic: King Eider *(Somateria spectabilis)*, Common Eider *(S. mollissima)* and Oldsquaw *(Clangula hyemalis)*. Recent estimates indicate breeding populations in the Arctic of 1–1.5, 1.5–2, and 3–4 million birds respectively (Bellrose 1976). The King Eider is the most truly arctic species and the Common Eider is the least. Common Eiders are the most colonial and are more closely associated with marine habitats during breeding than are the other two species. King Eiders and Oldsquaws may nest up to 100 km from the sea and are rarely colonial.

The food habits of these three arctic seaducks have not been adequately documented in Canada. However, in Greenland and Alaska they have been recorded feeding on molluscs, gastropods, and crustaceans (Cramp 1980). Common Eiders feed along relatively shallow inshore waters usually not exceeding a depth of 10 m, whereas both King Eiders and Oldsquaws are capable of feeding at depths up to a maximum of 60 m.

In late summer, large numbers of King Eiders make highly synchronized moult migrations east and west, to Greenland and the Bering Sea respectively (Salomonsen 1968; Palmer 1975). Oldsquaws also undertake moult migrations but winter farther south on the Great Lakes, Gulf of Alaska, coastal British Columbia, and the Atlantic coast from Newfoundland to Chesapeake Bay. They are generally nocturnal migrants and make lengthy overland flights. The Common Eider is more abundant in the southeastern Canadian Arctic than it is in the west. Those breeding in the western Arctic follow the same migration routes as the more numerous King Eiders, passing through the Bering Strait in spring and autumn. Most Common Eiders breeding in the eastern Arctic winter in the Gulf of St. Lawrence and the Atlantic provinces.

4. Polynyas and breeding distributions

Table 1 summarizes published records of breeding concentrations of the Common Eider in the Canadian Arctic. The locations of polynyas as reported in Alliston *et al.* (1976), Schledermann (1980), and Stirling (1980), and breeding colonies of Common Eiders are presented in Figure 1. Clearly, many of the eider colonies in Hudson Bay, Foxe Basin, and Hudson Strait are located near recurring polynyas. However, the significance of this correlation to the survival and reproductive success of Common Eiders has not yet been studied.

At higher latitudes, where King Eiders and Oldsquaws predominate, there are insufficient data to evaluate breeding distribution and reproductive success in relation to recurring polynyas. However, because these latter species are not colonial breeders, we suspect that a positive correlation may not exist.

5. Winter use

Although most seaducks winter south of the ice-covered arctic waters (Table 2, Fig. 1), there are more Common Eiders in the Canadian Arctic during winter than the other two species combined. With the exception of the North Water (Smith and Rigby, this publication, Fig. 3), recurring polynyas are too small to support significant numbers. Furthermore, polynyas north of 65°N may be too dark during the winter to permit sufficient feeding. The exception is the Hudson Bay eider *(S. m. sedentaria)*, which winters in polynyas around the Belcher Islands (Freeman 1970; Snyder 1957),

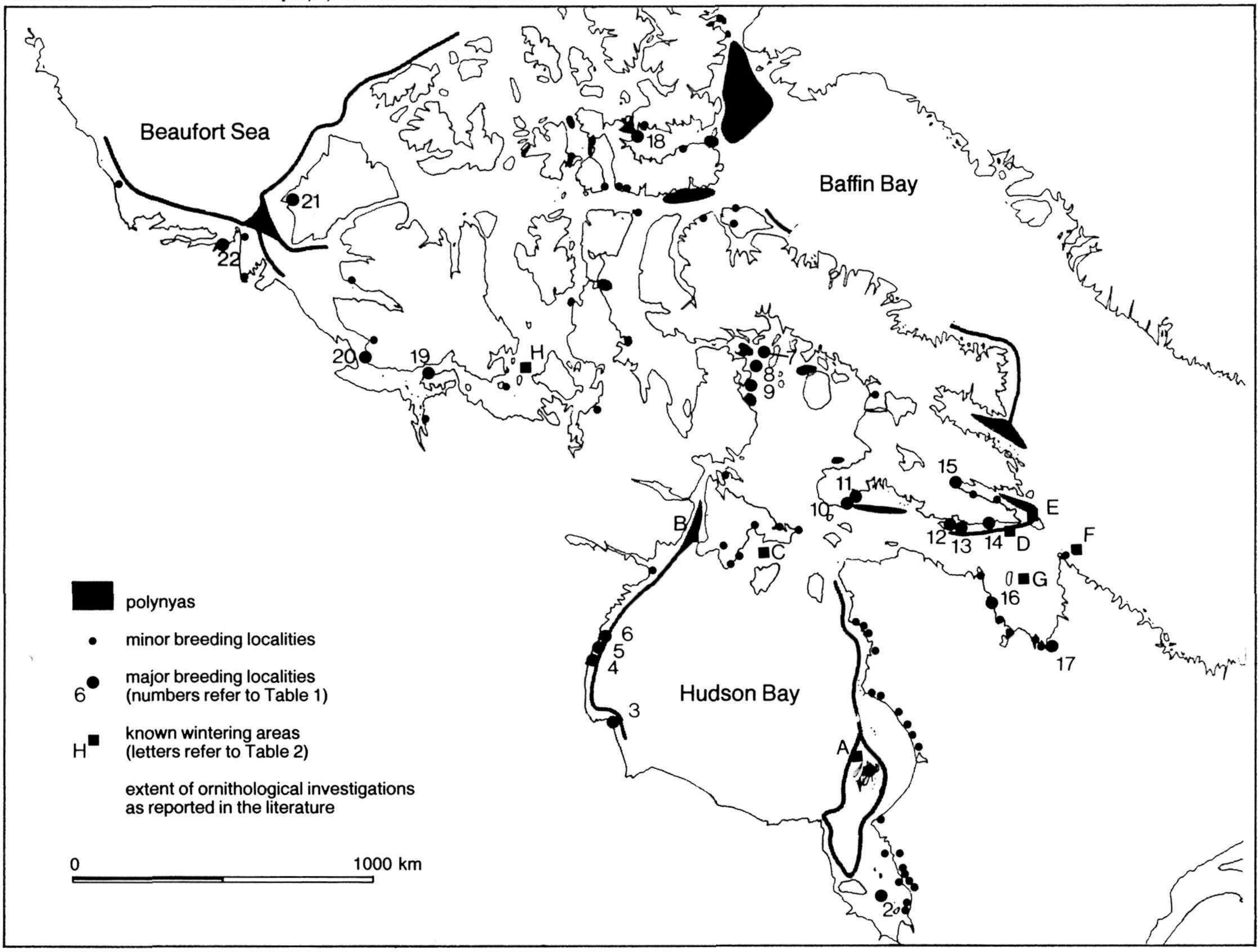
Table 1
Major known breeding concentrations of the Common Eider in the Canadian Arctic

Location	Population	Reference
1. Belcher Islands	55 000 pairs	Davis *et al.* 1973
2. Gasket Shoals	200 pairs	Todd 1963
3. La Pérouse Bay	Two colonies: 200, 250 pairs	Cooke *et al.* 1975
4. McConnell River	250 pairs	Davis *et al.* 1973
5. Maguse River	100 pairs	Davis *et al.* 1973
6. Austin Island	100 pairs	Davis *et al.* 1973
7. Sioraq Island	"a great many eider eggs"	Parry 1824; Bray 1943
8. North Ooglit Island	"numerous"	Bray 1943
9. South Ooglit Island	"numerous"	Bray 1943
10. Cape Dorset	"large numbers"	Macpherson and McLaren 1959
11. West Foxe Islands	1259 pairs	Cooch 1965
12. Islands west of Big Island	"large nesting colonies"	Soper 1946
13. Big Island	"hundreds of nests"	Short and Peters 1942
14. Middle Savage Island	"large nesting colonies"	Soper 1946
15. Frobisher Bay	"large nesting colonies"	Soper 1946
16. Payne Bay	2000 pairs	Currie 1963
17. Whale River	100+ pairs	Todd 1963
18. St. Helena Island	140 pairs	Prach, in prep.
19. Findlayson Islands	Large numbers	Parmalee *et al.* 1967
20. Dolphin and Union Strait	"one of the largest colonies in western Canadian Arctic"	Nettleship and Smith 1975
21. Banks Island – Moose I. to Sachs Harbour	500 pairs	Manning *et al.* 1956
22. Liverpool Bay	"immense numbers"	MacFarlane 1891

Table 2
Known wintering areas of the Common Eider in the Canadian Arctic

Location	Comments	References
A. Belcher Islands	"large numbers of eider (common) breed and pass the winter"	Freeman 1970
B. Cape Fullerton	"some remained in the open water all winter (1903–04)"	Eifrig 1905
C. Southampton Island	cited as wintering	Sutton 1932
D. South Coast Meta Incognita Peninsula	"a few individuals remain throughout the winter."	Soper 1946
E. Resolution and Edgell islands	1600+, Mar. 1968 (extrapolated from Fig. 5–5)	MacLaren Marex Inc. 1979
F. Button Islands	10 000 to 20 000 450+, Mar. 1968 (extrapolated from Figs. 5–5, 5–6)	Anon 1972 MacLaren Marex Inc. 1979
G. Akpatok Island	350+, Mar. 1968 (extrapolated from Fig. 5–5)	MacLaren Marex Inc. 1979
H. Taylor Island	subadult female collected on 9 Jan. 1918	Parmalee *et al.* 1967

Figure 1
Locations of breeding concentrations and wintering areas of the Common Eider in relation to the locations of polynyas in the Canadian Arctic



Roes Welcome Sound, and perhaps Evans, Fisher, and Hudson straits. This appears to be facilitated by the great tidal range (8–13 m) and strong currents of Hudson Strait and southeastern Baffin Island, which create shoreleads in waters shallow enough to permit feeding throughout the winter. Longer day length in these more southerly latitudes may also contribute to feeding success. Common Eiders, as well as some King Eiders and Oldsquaws, also winter near Resolution and Edgell islands, and Cape Chidley at the northern tip of Labrador. The total number of seaducks that overwinter in Hudson Bay and Hudson Strait probably does not exceed 25 000 birds.

6. Spring migration

In May and June, polynyas are more important to seaducks in the virtually tideless waters of the western and central Arctic than they are in the east. In the west, a large proportion of all three species migrates along 1500 km of coastline from Cape Lisburne, Alaska, to the Cape Bathurst polynya (Smith and Rigby, this publication, Figs. 14 and 15). The coastal leads between Pt. Barrow, Alaska, and the Mackenzie Delta serve as pathways for migrants to the Cape Bathurst polynya and associated shoreleads where they stage prior to breeding. The open water of the Cape Bathurst polynya and shoreleads occurs over depths shallow enough to permit feeding, until nesting areas further north and east are free of snow and ice (Barry 1976). Flocks exceeding 50 000 birds have been recorded in the polynya in May (Searing *et al.* 1975; Barry 1976).

The critical importance of these open water feeding areas to migrating seaducks is emphasized by recording what happens when they are absent. In 1964, open water did not occur in the Cape Bathurst polynya and shoreleads until July. Consequently, migrating seaducks were unable to feed when they arrived in the Beaufort Sea in May and over 100 000 starved (Barry 1968).

In the eastern Arctic, most inbound migrants have less than 500 km to traverse from open water to nesting sites and thus do not face the same problems as seaducks in the western Arctic. Consequently, mortality of the magnitude reported by Barry (1968) probably does not occur. Strong current, tides, and prevailing winds provide considerable open water in Hudson Strait, making movement to alternate feeding areas feasible. In mid May, seaducks tend to move north and west to stage in polynyas such as Fury and Hecla Strait and Hell Gate.

Alliston *et al.* (1976) compared the distribution of a number of bird species in the central Arctic Islands and the Boothia Peninsula in 1974 and 1975. They documented markedly different spring weather conditions between the 2 years which resulted in great variability in the amount of snow and ice cover. In 1974, the spring thaw in the study area occurred much later than in 1975. In 1974, most of the study area was snow covered, preventing birds from dispersing to their nesting areas. In addition, ice persisted in Peel Sound and Prince Regent Inlet throughout June, forcing the seaducks to congregate in the few available areas of open marine water. In contrast, in 1975 the ice in Prince Regent Inlet began to break up in early June and the land was free of snow by mid June. Some 6200 eiders were observed in polynyas in the Bellot Strait (Smith and Rigby, this publication, Fig. 7) in June 1974 and 9200 were there in June 1975. However, although most of the eiders remained in the polynya throughout June 1974, all but about 800 had left Bellot Strait before mid June in 1975.

Observations made at other polynyas demonstrated the same phenomenon. On 23 June 1974, two small polynyas in Crozier Strait near Karluk Island contained 300 eiders. In 1975, 570 eiders were recorded there on 11 June, but by 23 June only 83 remained. Over 1000 King Eiders were observed on a small recurring polynya off Cape Ste. Catherine (along the east coast of Boothia Peninsula) in June 1974 but none were there in 1975. Similarly the small polynyas among the Tasmania Islands (Stirling, this publication, Fig. 1) harboured dense concentrations (278 birds/km^2) of King Eiders and Oldsquaws in June 1974 but not in 1975.

7. Threats from oil pollution

Oil exploration, production, and transportation have greatly increased the possibility that a large scale blowout or spill will occur in the arctic marine environment (Anon. 1979). The possibility of oil pollution, resulting from cleaning up oil tanks or waste disposal, also grows with the increasing volume of ship traffic in the north.

Oil released to the arctic marine environment works its way to the surface and concentrates in ice free areas (Pimlott *et al.* 1976). Seaducks exposed to oil suffer a reduction in the insulating properties of their feathers and subsequent increase in their energy metabolism (Hartung 1967; McEwan and Koelink 1973). Exposure to oil in cold arctic waters will inevitably result in death of the birds (Barry 1970). Oil surfacing in polynyas during the spring will pose a substantial threat to incoming migrant seaduck populations, particularly in the Cape Bathurst polynya and associated leads.

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