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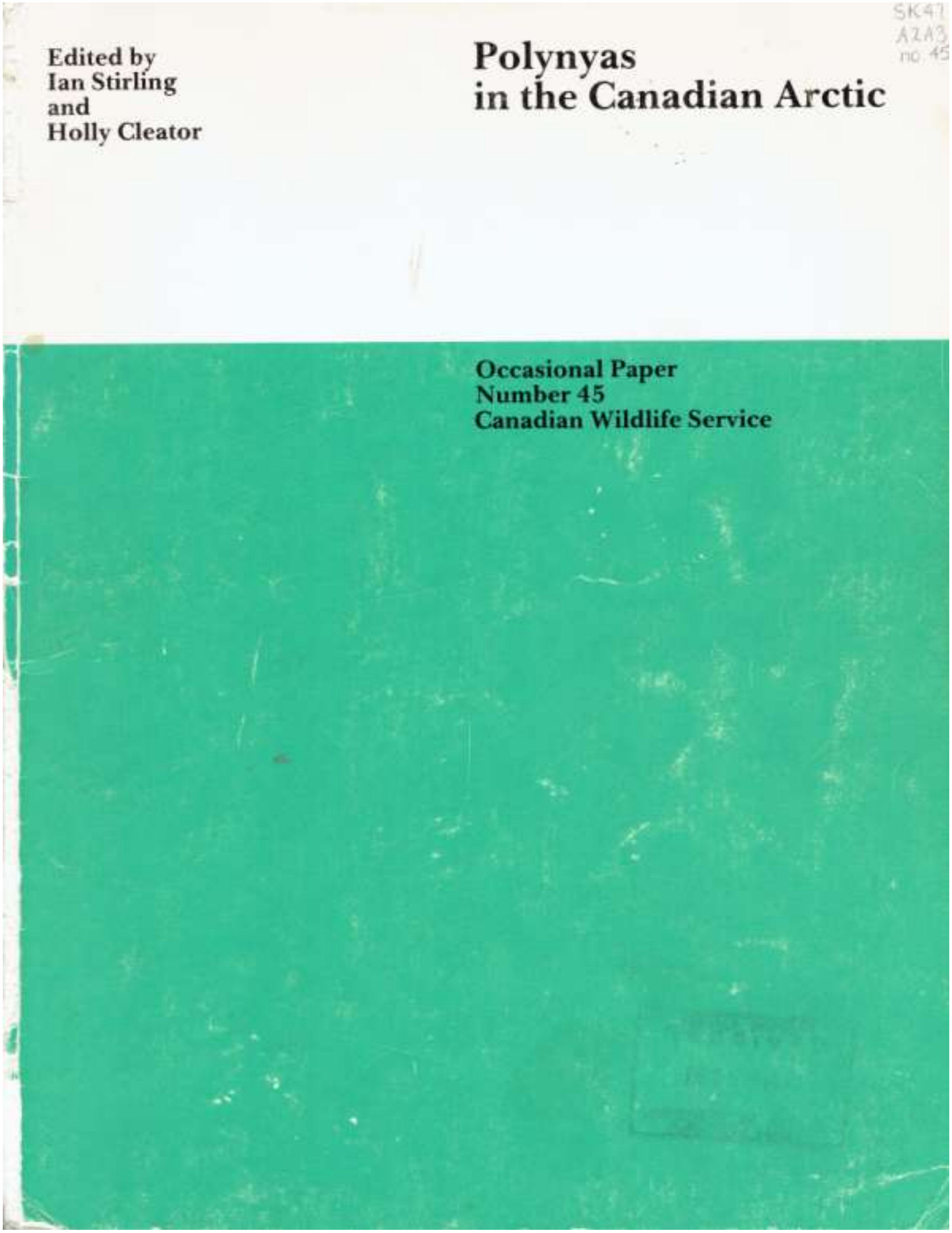

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Polynyas in the Canadian Arctic

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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.

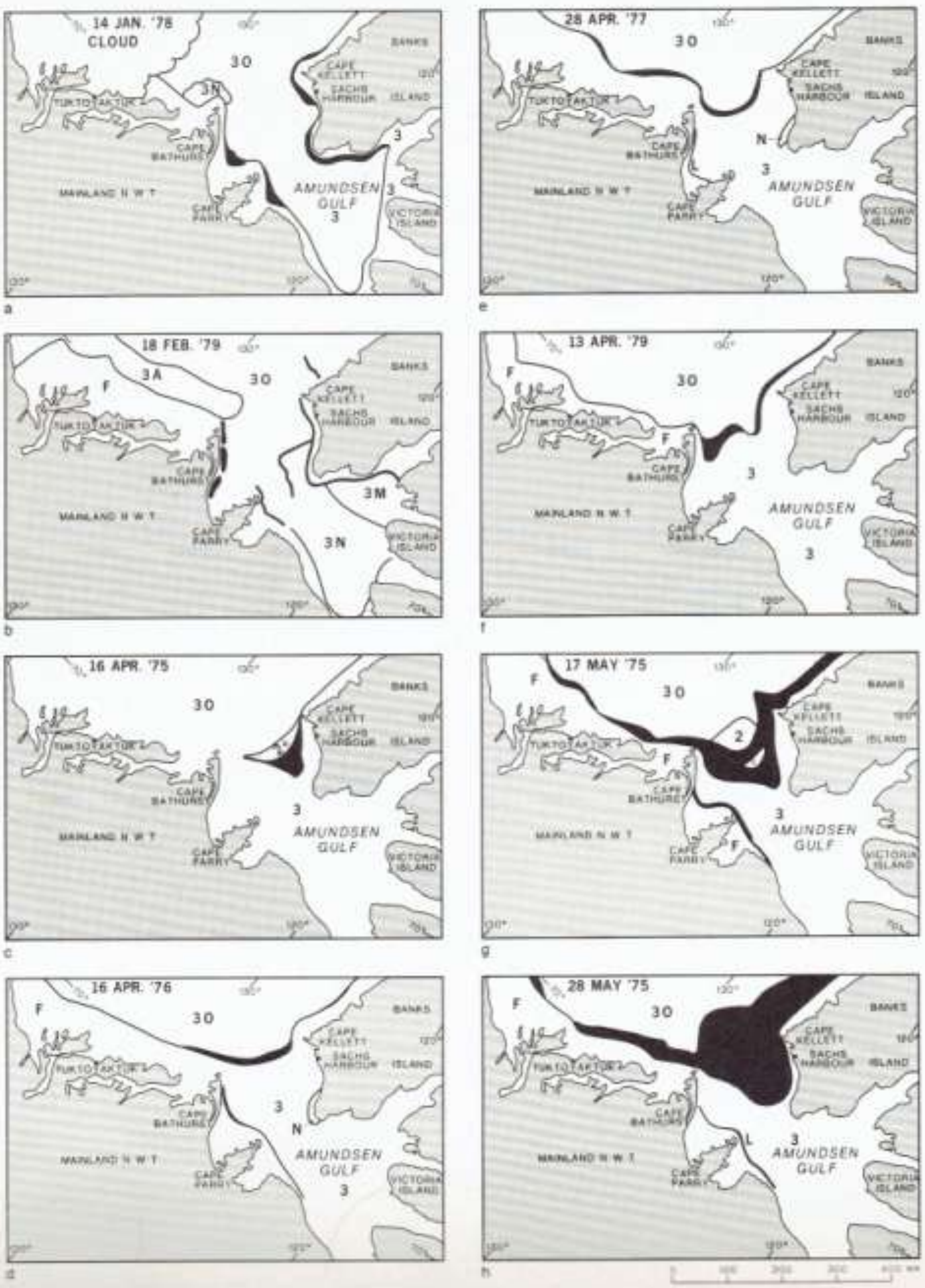
There has been no previous comprehensive study of polynyas in Canadian Arctic waters, although Stirling (1980) has recently drawn attention to their biological importance. Nevertheless, there have been a number of studies related to individual polynyas, for example Dunbar (1958, 1969), Aber and Vowinckel (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.

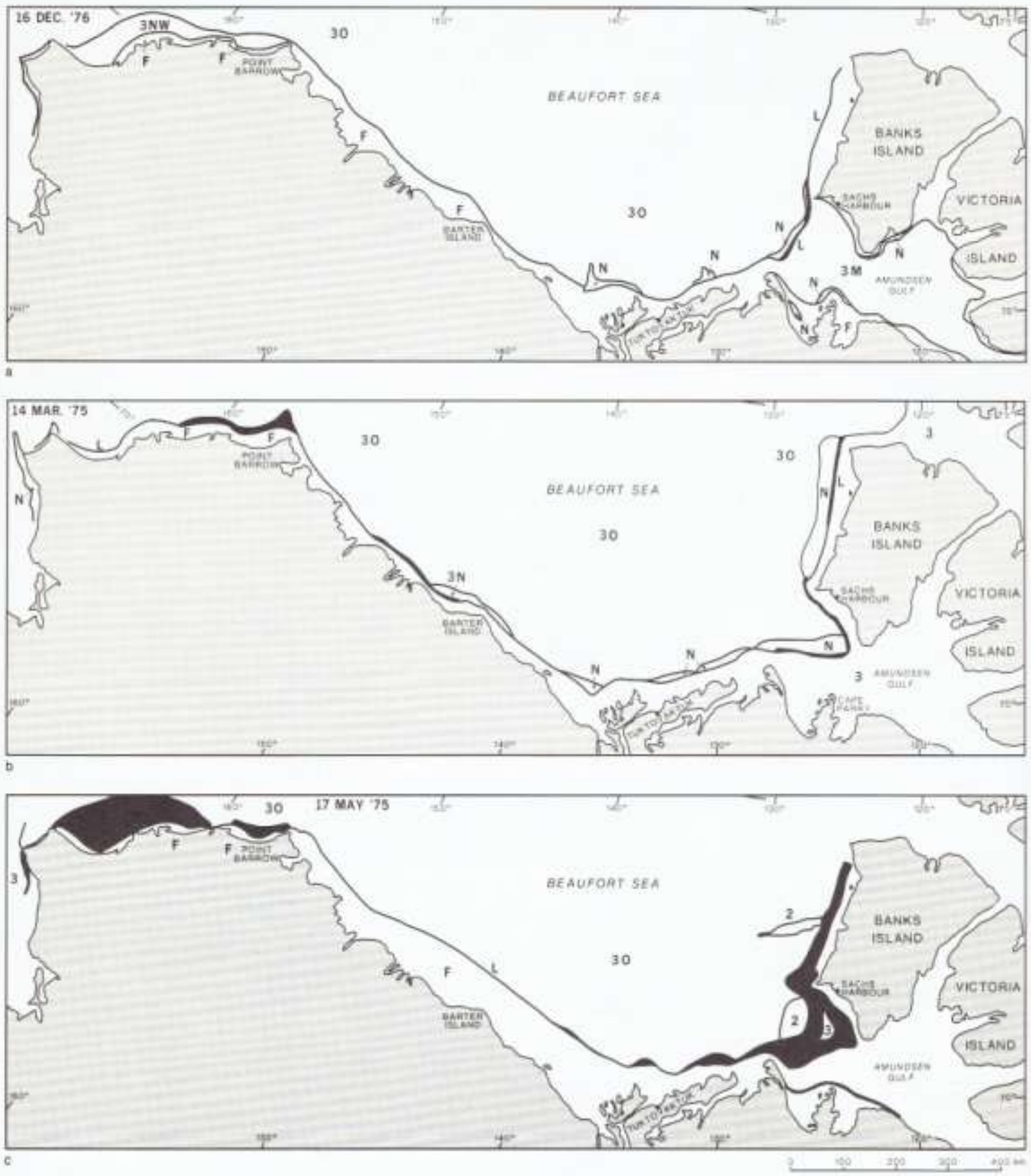
4. Materials and methods

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.

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 5, page 10, for key to symbols



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.

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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, shoreleads, 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

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 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.

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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 chaîne 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