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THE RELATIONSHIPS OF MARINE MAMMAL DISTRIBUTIONS, DENSITIES AND ACTIVITIES TO SEA ICE CONDITIONS

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The Relationships of Marine Mammal Distributions, Densities and Activities to Sea Ice Conditions

I. INTRODUCTION

This study began with the knowledge that some relationship exists between the annual cycle of movements and activities of marine mammals that inhabit the seasonal ice zone of the Bering, Beaufort and Chukchi Seas and the characteristics in space and time of the ice cover itself. The observation that these mammals are adapted to the various configurations of the pack ice as it changes through the year further implies some degree of regularity and repeatability in the distribution and features of the ice. It is logical to expect such repeatability because the environmental factors which form the ice and cause it to move and deform are generally cyclic or recurrent. The seasonal temperature cycle is the most obvious of these. Prevailing winds are repetitive by definition, and ocean currents tend to be consistent on the average. Finally, the ice in motion intersects immovable coastlines and islands which have constant shapes. These factors interact to form the features of the ice cover. To the extent that the contributing factors are repetitive and predictable, the same should be true of the marine mammals as well.

That each species of marine mammal residing in the ice-covered zone has a distinctive and predictable annual cycle of movements and activities, timed to coincide with specific characteristics and events of the ice itself, is a very old concept. The Eskimos of western and northern Alaska have been acutely aware of it for thousands of years. Every male resident of every Eskimo community on the coast was schooled in understanding the perpetually changing ice conditions of local areas and the ways in which these were related to the presence and absence of the different species of seals and whales. For it was of vital importance to know the ice, the effects of weather on it, and the influences of both ice and weather on the marine mammals that they hunted for food, clothing, and other raw materials essential to their existence.

The perception by these coastal people of the relationships of marine mammal distributions, densities, and activities to sea ice conditions was (and still is) understandably more local than regional, by reason of the limited mobility of the hunters. But it was more extensive than one might expect, for these people did travel out into the ice by boat within about 30 miles of their villages and ranged widely along the coasts by dog sledge. They climbed the local mountains, promontories, and ice ridges for a better overview, and they learned to interprete the reflections ("ice blink") on the clouds, as well.

Much of the lore and art of judging local ice conditions and relating them to availability of marine mammals still is utilized by modern Eskimos in coastal Alaska, for they continue to be dependent to a considerable degree on that mammalian resource for food and income. Utilizing some of their lore, together with personal experience, data from aerial surveys, and reports from Soviet sealers, Burns (1970) compiled the first broad overview of the associations of Bering-Chukchi pinnipeds with the seasonal pack ice, pointing out the general, regional pattern of their distribution in relation to specific ice zones. Drawing on similar sources, Fay (1974) summarized the "state of art" up to the winter of 1971-72 as regards the dynamics of this seasonal ice sheet and the ways in which the northern seals and whales are adapted to and make use of it. These were pioneering efforts, based more on intuition and logic than on objectively gathered data, for we did not have at that time the marvelous synoptic views from earth-orbiting satellites or the benefit of extensive, repetitive aerial and shipboard surveys, the data from which are now available in profusion.

Data on the extent and characteristics of the seasonal sea ice, relative to marine mammals, were first obtained in the 1950's and 60's during aerial surveys, small boat operations from shore, and multidisciplinary oceanographic cruises. Broad-scale, synoptic views became available from ERTS imagery, starting in 1972, from DAPP in 1973 and from NOAA/VHRR in 1974. Thus our analyses of characteristics of the ice habitats were based on data from several scales of observation: high and very high altitude satellite imagery, low altitude aircraft surveys, observations from ships, and surface observations from small boats and afoot on the ice.

Distributions of marine mammals were determined through a series of aerial surveys conducted intermittently from 1958 to 1979 and from shipboard expeditions in 1968, 1970-1973 and 1975-1979.

Data from aircraft and surface observations of ice were qualitative and included general descriptions of extent, relative thickness and size of floes, amount of snow cover, extent of rafting and deformation, and proximity of open water. These surface and near-surface observations were compared with characteristics apparent in satellite imagery obtained during the same time periods.

The first detailed overall views of the seasonal pack ice of western and northern Alaska from satellite imagery became available in the winter of 1972-73 from the U.S. Air Forces' DAPP system. About the same time, more restricted views but with finer resolution became available from the National Aeronautics and Space Administration's ERTS systems. The imagery from these and from subsequent systems tended to confirm the speculations by Fay (1974) of a general north-south movement of the seasonal pack in the Bering-Chukchi region (Shapiro and Burns, 1975a, 1975b; Muench, 1974) and related that movement to prevailing northerly winds (Muench and Ahlnas, 1976). The imagery from these systems also disclosed patterns of lead and flaw formation, convergence, and divergence that showed promise of helping to explain some of the distributional problems faced by marine mammals and to answer some of the questions concerning the reasons for their concentration in certain parts of the pack.

The work reported here was conceived in 1975 as an extension of our earlier investigations. Its goal was to determine more definitely which marine mammals of the pack ice zone might be affected by proposed exploration and development of petroleum resources of the outer continental shelf of the Bering, Chukchi, and Beaufort seas. Insofar as possible, we would try to determine how and to what extent they might be impacted. Our specific objectives were to determine (a) the characteristics, distribution, and extent of the sea ice habitats utilized by marine mammals, (b) the distribution and relative densities of mammals in those habitats, and (c) the major biological events in the lives of those mammals that are linked to their use of the ice. Recognizing that both the seasonal and the "permanent" packs vary in extent and quality from year to year, we sought to develop predictive ability for identifying the areas of critical importance to these mammals at any time, through interpretation of high altitude satellite imagery.

The opening section of this report is a general overview of the subject. Its purpose is to provide a synoptic view of the basic seasonal variations in ice conditions and marine mammal distributions, before describing specific aspects of them in greater detail. The system of ice and associated mammals is never static. During winter and early spring, when the ice cover is at or near its maximum, the marine mammals are dispersed throughout it in specific habitats from the southern edge in the Bering Sea to the consolidated pack of the Arctic. As the spring retreat of the ice begins, so do the migrations of the mammals. The previous associations of each species with specific winter ice habitats change or break down entirely. During the retreat of the pack, discrete masses of ice referred to as "remnants" occur regularly in the Bering Sea and sporadically in the Beaufort and Chukchi Seas. These provide important habitats at times when the pack per se is absent. In the summer months when the pack ice is at its minimum the populations either become pelagic in the open sea, move inshore, or are concentrated along the edge of the ice. As the ice advances southward in autumn, the populations either precede it or remain associated with its fringes. Finally, they disperse once again into their wintering areas.

The general plan of the report follows the cycle outlined above. After the overview, the distribution of potential habitats in the winter pack ice is analyzed in detail. This is followed by a description of the fast ice, and then the fringe and front zones. The origin and distribution of the remnants is then described to complete the discussion of ice habitats. Throughout these sections, the utilization of each habitat by marine mammals is described. Finally, all of the above are discussed in relation to the locations of recognized sedimentary basins on the continental shelf which constitute potential OCS lease areas. The potential effects of development in those areas on the ice-associated marine mammal populations is included.

Ice terminology used in this report, insofar as possible, follows the WMO Sea-ice Nomenclature: Terminology, Codes and Illustrated Glossary, WMO/OMM/BMO No. 259, 147 pp., published in 1970 by the World Meteorological Organization.

II. GENERAL OVERVIEW

A. Introduction

The ice that covers the polar seas differs substantially from that of most fresh water bodies in that it generally is not smooth and continuous but rough, highly variable in quality, and usually interspersed with cracks and other openings (e.g. see Armstrong and Roberts, 1956). Also it generally is weaker and more flexible than freshwater ice, largely because of the brine trapped within it (Weeks and Assur, 1967). The mammals that inhabit the ice-covered areas also are not uniformly distributed there, for each species has its own distinctive habitat requirements. For the most part, their distribution is determined by the juxtaposition of ice of the "right" type over their feeding grounds and by their ability to make and maintain holes through that ice (Burns, 1970; Fay, 1974). The ice itself is a major barrier between the two parts of their environment: the water in which they obtain their food, and the air that they must breath for oxygen to metabolize that food. Those mammalian species that are incapable of making holes through the barrier, or have limited ability to do so, are obliged to reside in the open sea or in parts of the ice sheet where natural openings are dependably present.

For the mammals that have adapted to this barrier, the ice serves many functions, such as a substrate on which to rest, molt, and bear young. As such, it may offer several advantages over the use of shorelines for these functions, because it is closer to the food supply, more remote from predators, more sanitary, and more spacious (in terms of available "shoreline") (Fay, 1974). It also may provide them with shelter from the weather and, incidentally, transportation to new feeding grounds. It is an integral part of their environment and one which is in large part responsible for their great abundance and diversity.

The relationships of these mammals to ice and their level of dependence on it vary seasonally as the ice itself changes in extent and quality. In the following sections of this report, those relationships and dependencies will be described in some detail. By way of introduction, a brief overview of the annual cycle of events on a regional basis is essential, to set the stage for the more detailed considerations to follow.

B. Winter

The winter pack ice is a highly dynamic ice sheet, which interacts to a significant degree with the adjacent continents and islands. Driven principally by northerly and northeasterly winds, it tends to move southward, pushing against the northern coasts of Alaska and Chukotka, forming extensive masses of jumbled, grounded ice inshore. A portion of the Chukchi pack extrudes southward through Bering Strait, into the northern Bering Sea (Shapiro and Burns, 1975a). There, its further southward progress is impeded by St. Lawrence Island, which lies directly across its path. Part of that ice piles up in a deep, dense, more or less triangular mass against the northern side of that island, while the remainder makes its way along the courses of least resistance, around the eastern and western ends, (Shapiro and Burns, 1975b). Once past this barrier, the way is mainly clear for it to continue southward into the central Bering Sea (Muench and Ahlnas, 1976).

Of course, not all of the ice in the Bering Sea is derived from the Chukchi; most of it originates in the Bering itself, especially in the Gulf of Anadyr, in Norton Sound, south of St. Lawrence Island, and in the Nunivak Island to Bristol Bay region. The generation of new ice in these areas takes place throughout the winter, also a consequence of the prevailing northerly winds. For, while the winds drive the pack against the northern coasts of the continents and islands, the same winds move it away from the southern coasts of those features. Thus, there tends to be persistent southward retreat of the Bering Sea ice from the southern coasts of Chukotka, St. Lawrence Island, the Seward Peninsula, St. Matthew and Nunivak Islands, and the Alaskan mainland from the Kuskokwim estuary to inner Bristol Bay (Figure 1). This creates large open water areas immediately to the south of these land masses, in which new ice continually is generated (Shapiro and Burns, 1975b; Muench and Ahlnas, 1976).

Where the moving pack is driven toward a strait between two land masses, it tends to be compressed. In these areas of convergence, such as Bering Strait, close packing and pressure ridging are dominant processes within the moving ice, while shearing occurs at its edges (Shapiro and Burns, 1975a, 1975b). To the south of such straits are zones of divergence, where leads and polynyas develop in profusion as the pack expands into areas of low or no compression. New ice quickly forms on the openings, adding further mass to the pack as it advances.

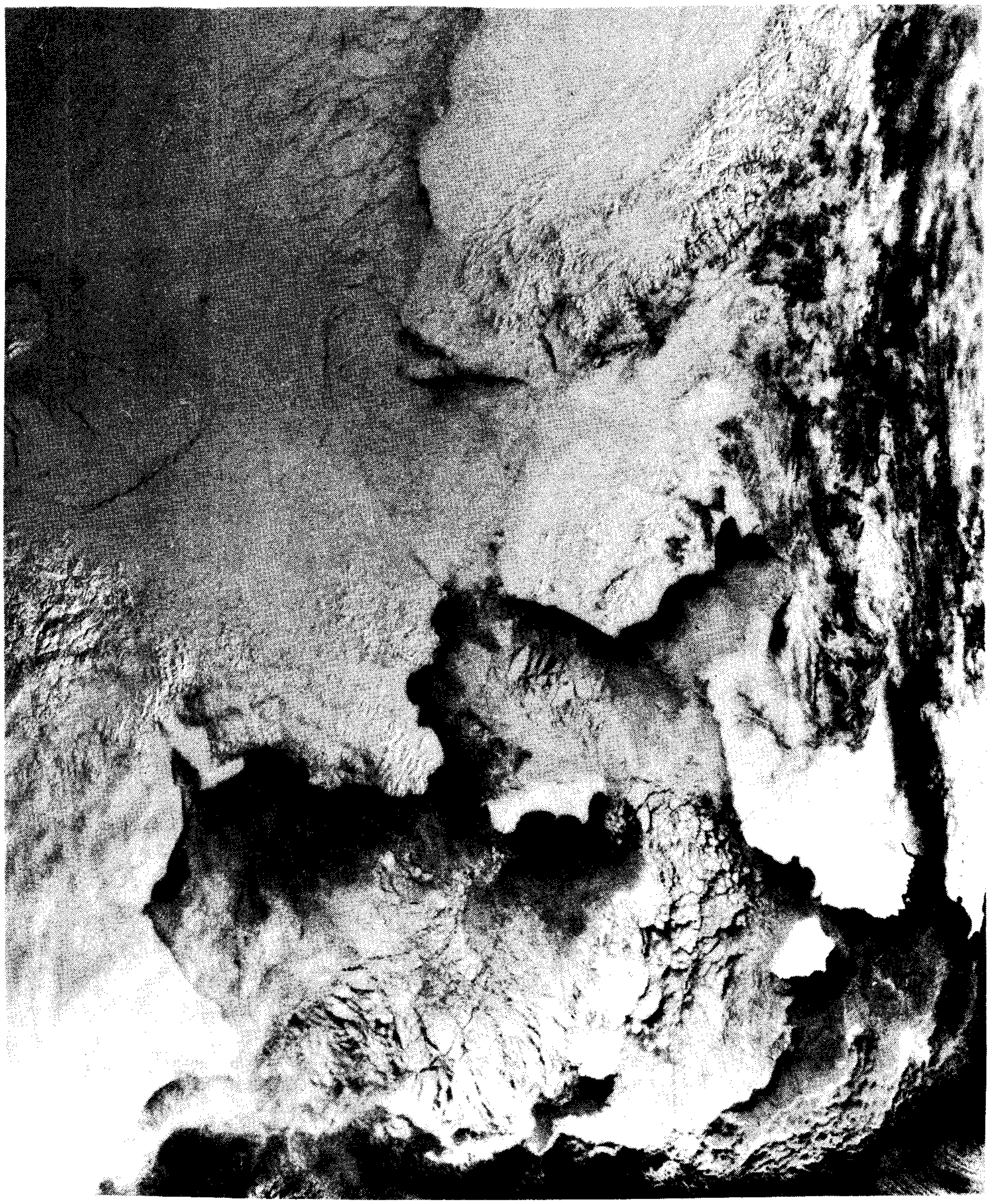

Figure 1. NOAA/VHRR visible band imagery of the eastern Bering and southern Chukchi Sea; acquired on 20 March 1978.

Nearer to shore, particularly in sheltered bays and to a lesser extent on the rest of the coast, locally formed ice freezes fast to the shore and, in shallow waters, to the bottom as well. This sheet of landfast ice extends out over the neritic waters, and at its outer edge interacts with the moving pack which may add to it or subtract from it, depending on the nature of the interaction. Between the stationary fast ice and the moving pack is a strip known as the "flaw", which, as the term implies, usually contains some open water. Depending on the rate and direction of movement of the pack, the flaw may be a lead as narrow as a few millimeters or a zone tens of kilometers wide in which case it may include a large amount of broken white ice and newly formed gray ice.

At its southern periphery, the pack tends to be open and made up of smaller floes than are found farther north. Tongues of broken and melting ice extend out into the open sea for several kilometers, beyond the edge of the consolidated pack. For several kilometers back into the pack from this southern "fringe" is a zone in which the floes are repeatedly subjected to vertical motion by ground swells from the open sea. This motion tends to break up the large ice fields into smaller floes and to create large amounts of brash in the interstices. We refer to this zone as the "front", a term borrowed from the North Atlantic sealers who have recognized for a long time that it is an important habitat for certain marine mammals.

Movement of the ice in the Bering Sea towards the north does occur during periods of cloudy weather, which are generally associated with winds from the south. However, the distance and rate of movement to the north are limited by lack of space, i.e. by the presence of immovable barriers (land masses) in the northern Bering Sea and by the increased mass of the pack through addition of new ice in the leads and polynyas. The result is a net transport of ice toward the south through the winter and early spring months. The average rate of north-south movement in March-April 1974, as determined by Muench and Ahlnas (1976) from satellite imagery, was about 15.5 km/day, which corresponds well to our own observations from icebreakers in March-April 1971 and 1972 in that area. If this is typical (as it seems to be), it means that ice in the vicinity of St. Lawrence Island would tend to reach the southern ice front after about one month of drifting during that period.

In the Bering Sea area, surface winds tend to be strongest and air temperatures lowest during February (Brower at al., 1977), and we presume that the rates of north-south movement, consolidation, and new ice formation are highest at that time in most years. Similar but slightly milder conditions prevail in March, but by late April and May, surface air and water temperatures and wind velocities over the Bering Sea usually ameleorate to the extent that production of new ice ceases.

The effect of all of these processes working on the winter pack in concert, is creation of a wide variety of pack ice habitats which occur with such regularity, year after year, that certain marine mammals have become adapted to them and can reliably be found in them. The principal general categories of these are: (1) fast ice, (2) persistent flaw, (3) polynyas which are centers of new ice formation, (4) divergence zones, and (5) the front. For in nearly every case, these mammals require movement and dispersion of the ice sufficient to create new leads and polynyas. In such situations, access to the air is virtually assured, either through natural openings or temporary holes made by the animals themselves in thin ice. Thus, the bearded seal (*Erignathus barbatus*) resides in habitats (2) through (5); and the spotted and ribbon seals

(*Phoca largha* and *P. fasciata*) reside almost entirely in (5). Only one species, the ringed seal (*Phoca hispida*), is sufficiently adapted to unbroken ice to be able to reside by choice in (1), the shorefast ice, and in other areas of vast, unbroken floes. Being most adaptable, it also resides to some extent in each of the other habitats. The walrus (*Odobenus rosmarus*) winters mainly in Bering Sea, primarily in habitats (3) and (4). Small numbers winter in the Chukchi Sea and occasionally in the Beaufort Sea (Stirling, 1974), as the annual severity of ice conditions allow.

C. Spring

The winter pack generally reaches its southernmost limit for the year in late March or April (Wittman and MacDowell, 1964; Brower at al., 1977). At that time, the processes of deterioration also begin to be evident in the Bering Sea (Muench and Ahlnas, 1976; Burns and Fay, unpublished). The position of the maximum southern border of the pack varies by as much as 6° of latitude (about 665 km) from year to year, in southeastern Bering Sea (Brower et al., 1977), but it tends to be not far from the southern edge of the continental shelf in most years. Its rate of degradation also varies appreciably, generally being most rapid in years of minimal extent and least rapid after maximal advance. Nevertheless, the recognized habitat types enumerated above tend to occur in the same relative locations in the pack, though not necessarily in precisely the same geographical positions.

While the general southerly and southwesterly movement of the Bering Sea pack continues to take place through April, leads and polynyas become larger. This appears to be due to diminution in rate of new ice formation, while the rates of fracture and deformation remain largely unchanged. This appears to be ultimately the result of a 3-fold increase in incident solar radiation (Johnson and Hartman, 1969), which upsets the previous balance between heat gain and heat loss. By late April there is abundant evidence of loosening of the winter pack, especially in the southern and eastern parts of the Bering Sea. This continues at an increasing rate thereafter (e.g. see Muench and Ahlnas, 1976) as melting of the ice takes place with increasing warmth of the surface environment. At the same time, winds become more variable and weaker, leading to cessation of the general north-south trend of ice movement.

By mid- to late-May, even in the northern Bering Sea, rising surface water temperatures result in melting of the floes, as evidenced by extreme undercutting and development of numerous holes (the "Swiss cheese" effect) in the submerged parts. Under those conditions, the thinner ice disintegrates rapidly and only the most massive floes persist into June. By the end of May, the ice sheet that has covered nearly the entire shelf of the Bering Sea is reduced to a few rafted remnants of heavy, broken ice that cover less than one-fourth of that area, and these too disappear in June or early July (Muench and Ahlnas, 1976).

Meanwhile, the Chukchi pack, which has remained largely intact throughout April, begins to show signs of impending breakup (Figure 2). In March and April the flaw along the Alaskan coast becomes more persistent and ice-free, whereupon the bowhead and belukha whales (*Balaena mysticetus* and *Delphinapterus leucas*) begin their annual northward migration along it. Slightly later, an increasingly evident east-west fracture pattern develops in the southern Beaufort Sea (Figure 2), and the whales apparently make use of it to pass eastward, toward Banks Island. By late May or early June, in most years, there is significant loosening of the southern

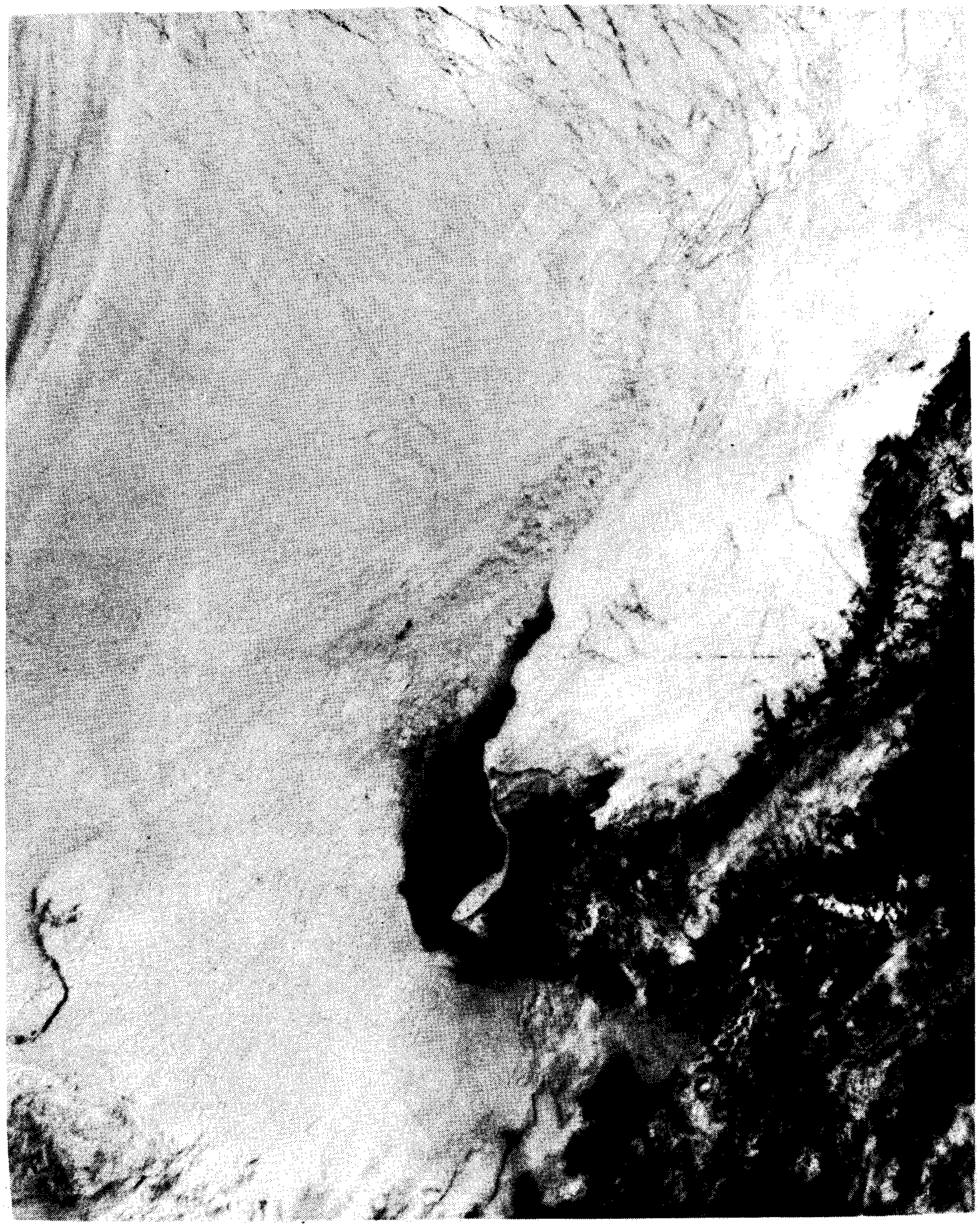

Figure 2. NOAA/VHRR visible band imagery of the northeastern Chukchi and southwestern Beaufort Seas; acquired on 23 May 1978.

part of the Chukchi pack, probably due mainly to influx of warmer water from the now nearly ice-free Bering. By the end of July, the Chukchi pack usually is reduced to one-third or less of its former extent, and by August, the western Beaufort shows extensive opening.

Not far behind the bowheads and belukhas (which begin their northward migration in late-March) are the walruses, whose vanguard advances through Bering Strait in April. By late May, most of their numbers have passed that point, as have the bearded and ringed seals that wintered in the Bering Sea. The spotted and ribbon seals do not migrate extensively until the last remnants of the Bering Sea pack have melted, at which time the spotted seals mainly move up along the coast, while the ribbon seals apparently become pelagic in the open sea.

D. Summer

When the ice sheet is at its annual minimum in late summer, most of the ice-associated marine mammals of the Bering-Chukchi-Beaufort region inhabit either the open sea to the south of the ice or the fringe of the "permanent" polar pack. Those associated at least partially with the fringe are the polar bear (Ursus maritimus), walrus, bearded seal, ringed seal, belukha, and bowhead. This polar ice cap exists mainly over the abyssal part of the Arctic Ocean, but extends southward also over the continental shelves of the northernmost continents and islands. It is relatively thick and old, being made up mostly of multi-year accumulations of sea ice and bits of glacial ice principally from the Greenland and Ellesmere ice caps. Its movement relative to the continents is generally clockwise around the polar basin, which translates into east-to-west movement in the western Beaufort and northeastern Chukchi seas, off northern Alaska. The average rate of movement of ice in the offshore polar gyre in summer is about 2 to 2.5 km/day (Webster, 1954). Nearshore, in the Beaufort Sea, it is more like 10 km/day (Marko, 1975). The mammals residing in the perimeter of this ice utilize it as a resting and feeding area. Some, such as the ringed and bearded seals and the polar bear, penetrate well into it in some circumstances.

E. Autumn

The formation of new ice in the Beaufort Sea begins inshore in September or early October, starting earlier in the western than in the eastern part of that area (Markham, 1975; Marko, 1975). New ice begins to form extensively in the Chukchi Sea by mid-October in most years but usually is delayed until late November or December in the northern Bering Sea. Apparently, the bowhead and belukha whales leave the Beaufort for the Chukchi in August and September (Fraker et al, 1978), and they and most of the other marine mammals leave the Chukchi for the Bering during October and November. Left behind are the polar bears, many ringed seals, and a few bearded seals, which inhabit the northern ice throughout the winter. Most of the migrating pinnipeds tend to stay in the water at this time; however, the walruses come out on shore in traditional hauling grounds (e.g. see Gol'tsev, 1968).

Up to a month before the formation of new ice in the Bering Sea, a few large chunks of multi-year ice from the polar pack drift southward through Bering Strait, frequently stranding on the northern coast of St. Lawrence Island (Fay, unpublished). This is a stormy season, with frequent, strong, northerly winds and high seas. Surface waters may become supercooled, leading to formation of a substantial amount of anchor ice (on the bottom) along the exposed coasts, while at sea broad strips of "grease" and slush ice form up parallel to the wind. During periods of calm, vast areas at sea become covered with new, gray ice, which becomes "finger-rafted" when set in motion. As might be expected, the protected embayments, such as Kotzebue Sound, Port Clarence, and Norton Bay, are the first to be iced over entirely.

III. ANALYSIS OF PREDICTABLE FEATURES OF THE WINTER PACK ICE OF THE BERING, CHUKCHI AND BEAUFORT SEAS

A. Method of Approach

1. Selection of Data

One problem addressed in this study was identification and description of the major, repetitive features of the moving pack ice in winter (excluding the ice fringe and front zones) and evaluation of their importance as habitats for mammals. Because the ice cover is almost continuous from the ice fringe in southern Bering Sea northward, it is logical to inquire as to the extent with which it moves and deforms as a unit. While data from any area within this region are of interest, synoptic coverage of the entire area is required if the regional relationships are to be recognized and understood. Also, it is desirable to know if ice conditions change in a systematic manner throughout the study area, or within definable sub-units. Is there some identifiable pattern to the distribution of ice conditions? This is relevant to the study because it describes the distribution of various possible ice habitats and the relationships in time between them. Information acquired over large areas within a specified time range obviously is required to answer this question.

The first step in the approach to this study was selection of scales, both temporal and spatial, on which data were required. The temporal scale is dictated by the rates at which major changes in the configuration of the ice cover can occur. Since these are closely tied to changes in weather patterns, the scale will be up to a few days (but generally less than a week). Major changes in the character of the ice cover in any area can occur faster than the mammals in that area can respond by moving to a more favorable location. Therefore, the presence of mammals in an area implies recurrence of favorable conditions. To define such persistence or recurrence, data must be acquired on a time scale which is shorter than that required for major changes to occur; that is, on a daily basis.

In a preliminary study prior to the start of this project, (Shapiro and Burns, 1975b) as well as in the early stages of the project, LANDSAT imagery was used extensively to identify and describe the features which tend to recur repeatedly. LANDSAT imagery of the study area is only obtained for 3 or 4 consecutive days (depending upon latitude) of each 18 day cycle of the satellite so that the spacing in time between LANDSAT images is greater than the time scale required for this project. In addition, LANDSAT data generally are not supplied for scenes with greater than 50% cloud cover, which further decreases the number of available images, and can lead to misleading results.

The temporal requirement in scale dictated that the bulk of the study be done using satellite imagery from the NOAA/VHRR weather satellites. These provide daily coverage of most of the Bering, Beaufort and Chukchi Seas, (satisfying the requirements of spatial scale) with IR imagery during the winter and with visible and IR during the rest of the year. With this imagery it is possible to examine ice conditions on a small scale, over the entire area of interest every day.

2. Organization and Data Extraction

Several attempts were made to develop a quantitative description of sea ice conditions which defines the state of the ice as habitat for marine mammals. In order for such a description to be useful, it must be based upon quantifiable measurements from satellite images, in order to take advantage of the repetitive and synoptic aspects of these data.

Two basic elements are required for the development of such a description. First is the determination of the parameters of the ice habitats of each species, and the second is to learn how to identify and measure those from the satellite data. Data for the first requirement would need to be developed through aerial surveys and surface ecological studies, preferably coinciding with satellite passes. The second requires experimentation with procedures for extracting information from the satellite data. The methods by which the discrimination of ice conditions was attempted are described here.

The major problem to be solved in developing a quantitative description of ice conditions is that some method for determining ice thickness from the satellite is required. No method for rigorously accomplishing this is known, and our attempts to do so for this project have been unsuccessful, despite the fact that the only requirement is that the thickness greater or less than about 20 cm can be discriminated. The problem was approached using LANDSAT imagery for consecutive days in which a lead or polynya was observed to be in the initial stages of formation on the first image and continued to expand on subsequent days. New ice forming in a lead or polynya will grade in thickness from zero at the edge of open water to some greater thickness at the boundary with older ice. This thickness will depend upon the ambient weather (see, for example Stehle, 1965). Since there is a gradation of tone changes from black for open water to light gray for thick pack ice, a series of measurements of film density on a photographic product of the data (or of reflectance from the digital data) forming a profile across such an area might provide a means of associating reflectance with ice thickness up to the limit of light penetration into the ice.

This possibility was investigated by examining the distribution of reflectance levels of newly formed ice in leads as shown on a printout from digital tapes of LANDSAT image 1228-22273-7 (Figure 3) acquired on March 8, 1973. The results were negative because the reflectance from the surface of the newly formed ice in the lead became almost constant a short distance from the open water. Estimates based upon the assumption of a constant rate of lead opening (for the 24 hours since the previous image was acquired) and on knowledge of the temperature at the nearest weather stations, indicated that the thickness of the ice probably was less than 10 cm when the reflectance became constant. It is not possible to determine whether this was due to a lack of light penetration into the ice, the growth of ice flowers, or the addition of blowing snow to the surface. Whatever the cause the result is the same and negates the method.

In the absence of a method for estimating ice thickness from the imagery, a classification was adopted for the purpose of determining floe size and spacing between floes from LANDSAT imagery. The ice was divided into two categories: 'thick' ice, which has high reflectivity and appears in tones of light gray on band 7 of the LANDSAT imagery, and open water or 'thin' ice, which ranges from black through the darker gray tones. Using these, it was possible, statistically, to define the parameters of floe size and open water.

In order to make the measurements, a scanning microdensitometer was used to establish the film density along a number of lines on a

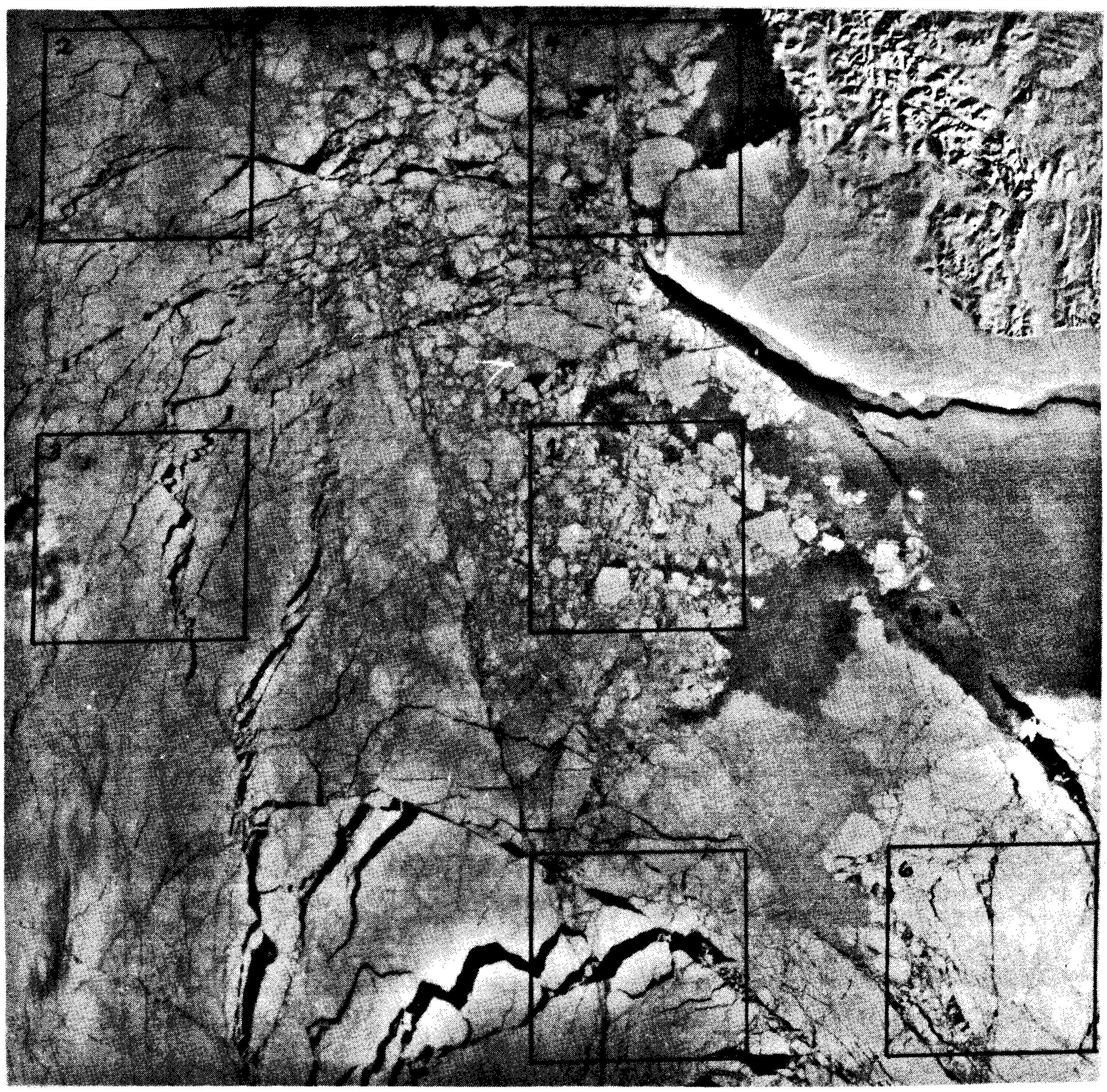

Figure 3. LANDSAT image #1228-22273-7 of the southeastern Chukchi Sea, acquired on 8 March 1973.

70 mm positive transparency of band 7 of LANDSAT Image 1228-22273-7, shown in Figure 3. The scene covers the southeastern Chukchi Sea, with Point Hope in the upper right quadrant. Note that this scene is part of the sequence studied by Shapiro and Burns (1975a) so that the ice motion at the time the image was acquired is known. Outlined on the picture are six areas with dimensions of 35 x 35 km which were used in the study. Each area was scanned twelve times by the microdensitometer; six scans each in north-south and east-west directions. The density variation was recorded as a continuous curve on a strip chart recorder where the scanning and recording speeds were known so that distances along the curve could be scaled as distances on the image. From these charts, sharp changes in film density between thick ice floes and thin ice or open water were readily identified. The exact value of film density at which the changes occurred was determined by comparison of observed densities of thick and thin ice on the image with the density scale on the transparency. Having established a "decision level", the path distances over thick ice, and over thin ice or open water, were measured along the curve. The results (Table 1) define numerically the differences in ice conditions in the six areas.

The range of values in Table 1 does serve to indicate that differences in ice characteristics can be detected and expressed quantitatively.

TABLE 1

SUMMARY OF STATISTICAL DATA FROM MICRODENSITOMETER TRACES

	THICK ICE PATH LENGTHS					THIN ICE - OPEN WATER PATH LENGTHS				
Area	% Path	Mean(1)	Standard Deviation	Median	Mode	% Path	Mean	Standard Deviation	Mediun	Mode
1	75.1	1.18	2.26	0.46	0.23-0.46	24.9	0.33	0.54	0.17	0.23-0.46
2	90.2	3.15	4.07	2.05	1.82-3.65	9.8	0.40	0.88	0.26	0.23-0.46
3	90.1	3.47	5.18	1.37	1.82-3.65	9.9	0.43	0.48	0.23	0.11-0.23
4	70.1	1.33	2.75	0.23	0.23-0.46	27.9	0.53	1.12	0.11	0.23-0.46
5	83.1	2.76	3.54	1.48	0.46-0.91	16.9	0.63	1.00	0.40	0.11-0.23
6	91.3	3.10	5.81	1.03	1.82-3.65	8.7	0.33	0.32	0.23	0.23-0.46

(1) All path lengths in kilometers

As an example, most of areas 1 and 4 include ice which is typical of that deformed in the flaw zone along the coast. These areas have lower values of percent of ice cover, mean, standard deviation, and mode of thick ice path length and median open water - thin ice path length, than do the remaining areas. Thus, the ice cover in these areas consists of relatively small flows separated by narrow leads, which implies that the ice is in the process of being broken into small floes, and that there has not been sufficient time for the leads to freeze over.

Areas 2, 3 and 6 are all dominated by thick ice. However, at the time the image was acquired, long, narrow tension fractures were developing in areas 2 and 3 and the pack ice was therefore probably diverging. At the same time, the ice in area 6 was drifting at a relatively uniform rate to the south-southeast, at a velocity of about 9 - 10 km/day. The data for these areas are generally similar except that the parameters for the thin ice - open water path lengths suggests that these are of more uniform size in area 6 than in areas 2 and 3. The differences would probably be enhanced if the data were taken from the LANDSAT image of the area acquired on the following day when the tension cracks in areas 2 and 3 had opened to widths of several kilometers.

Finally, ice within area 5 is in the process of being deformed by the development of tension fractures as well as by shear along the line trending NW-SE across the area. The statistical parameters for this area are correspondingly different from those of the remaining areas.

This method demonstrated that it is possible to derive statistical descriptions of the ice cover which can reveal distinctions not readily apparent by visual inspection. However, the time required to accomplish the work described here was simply too great to permit routine coverage for the entire area of interest. An attempt was made to duplicate these results using digital tapes of LANDSAT images. This too proved feasible, but the expense of acquiring the tapes was more than the project could bear for the entire area. As a result no further study of this type was done. In the future, when distribution and habitats of the various marine mammals are better defined, such work could be done for the relevant areas.

An attempt was made also to obtain data required for classification of ice types using the Fourier transforming properties of spherical lenses. In theory, the technique is straightforward. A point source of monochromatic light from a laser is passed through a spherical lens to form a plane wave. The beam then passes through a small area of a photographic image which is placed at the back focal plane of a second spherical lens. The light collected by the second lens forms a diffraction pattern in the front focal plane. This diffraction pattern, which is the Fourier transform of the illuminated photographic image, provides information about the spatial frequency distribution of the photograph. The geometry and intensity of the light distribution in the diffraction pattern relates directly to the size distribution and spacing of objects in the photograph. Thus, in theory it would be quickly and conveniently possible to obtain detailed information about sea ice states by applying the technique to photographic products of either the LANDSAT or NOAA satellite data.

In practice, however, the accuracy and utility of the method is limited by the "noise" in the system. For this project, the necessary apparatus was set up using available equipment which was known to be too crude for detailed work, but was adequate for judging if the method was sufficiently promising to justify further effort. Light from a laser source was passed through a small part of a 70 mm transparency of a LANDSAT image and of a NOAA satellite image, generating diffraction patterns which changed as the images were moved through the beam. In both cases the changing pattern reflected changes in the image which the beam was sampling. However, the noise level of the resulting pattern was too great for usable data to be obtained. It was determined that the bulk of the noise was due to the film grain on the images. Noise from this source could not be overcome and would render any results unsatisfactory so that this approach was not pursued further.

Thus, the total effort devoted to finding automated methods of rapid classification of ice relative to the habitats of marine mammals did not prove feasible within the constraints of the project. Hence, the decision was made to use visual inspection of the daily coverage available from NOAA/VHRR satellites to obtain the necessary data.

3. Description of Data from NOAA Satellite Imagery

Ideally, imagery from at least one satellite pass per day should have been available for the time period over which the study was conducted.

However, occasional difficulties in transmission or absence of data from a suitable pass (see below) reduced the number of available images. The totals by month for the period from March, 1974, when data was first received, to June 1977, when data acquisition for the project ended, are shown in Table 2. This constitutes the basic data set used in the study.

The imagery used included both visible and infrared bands for the months when sufficient light was available for the visible band to be useful. In winter, only the infrared band was available. Comparative data from the IR and visible imagery in spring and summer shows little difference.

Of the large number of images available each day, the one centered on Bering Strait was chosen for study when available, since it provided the best possible view of the area.

The scale of the NOAA imagery is about 1 mm = 9 km, and the resolution is about 0.6 km. The ice classification adopted was intended to describe features and conditions visible at that scale and resolution. As discussed below (Section III.A.5.), the descriptive terms used appear to be applicable to scales at least as large as that of the LANDSAT imagery (1 mm = 1 km) in some cases.

The NOAA satellite imagery used was all in the form of positive transparencies; these were studied on a light table. In this form, on the visible band, the ice ranged in color from almost black for thin, new ice, to light gray or white for snow-covered, thicker ice. The imagery from the infrared band of the NOAA satellite provides, in effect,

TABLE 2

NUMBER OF NOAA/VHRR IMAGES AVAILABLE

Month	1974	1975 (Year)	1976	1977	Total
December	-	29	17	31	77
January	-	23	10	31	64
February	-	28	29	28	85
March	24	31	31	31	117
April	17	29	30	30	106
May	28	31	31	31	121
June	27	30	26	30	113

a map of surface temperatures. On positive transparencies, the density scale ranges from light gray to black with increasing temperatures, so that open water appears dark and the colder ice surface appears in a lighter tone. The identification of open water presents no problem, but there is some loss of detail in ice-covered areas because the surface of both thick and thin ice tends to be at a uniform temperature. In the visible band, ice bordering a new polyna can be identified by its dark gray tone when not snow covered, but when its surface temperature reaches that of the adjacent older ice, it cannot be discriminated in the infrared imagery. Some difficulty was encountered also in discriminating between clouds and ice in the IR band, but texural differences usually were sufficient to resolve that problem. In general, visible band imagery was used when available.

4. Definition of Sub-Areas

In a preliminary study, Shapiro and Burns (1975b) utilized imagery acquired during March and April of 1973 and 1974 from the DAPP and the NOAA/VHRR systems to identify the major features of the ice cover in the Bering and Chukchi Seas. The results were verified with available LANDSAT data. The procedures used in the present project were based upon the experience gained in that study.

Daily ice conditions throughout the study area were described by classifying the ice in each of 23 sub-areas (Table 3, Fig. 4) selected on the basis of experience gained in the preliminary study. The ice conditions within each sub-area had been recognized as sufficiently uniform for any particular satellite image to permit description by a single term.

TABLE 3

BERING, CHUKCHI AND BEAUFORT SEA SUB-AREAS

Sub-area #	Area
1	East of Prudhoe Bay
2	West of Prudhoe Bay
3	West Coast of Alaska, Barrow to Point Hope
4	Coastline East of Pt. Hope
5	Kotzebue Sound
6	Open Sea North of Bering Strait
7	Wrangell Island
8	North Coast of Chukchi Peninsula
9	Bering Strait - Diomede Island
10	South Side of Seward Peninsula
11	Norton Sound
12	Siberian Coast South of Bering Strait
13	Open Sea South of Bering Strait
14	North Side of St. Lawrence Island
15	South Side of St. Lawrence Island
16	Strait Between St. Lawrence Island and Siberia
17	Sea Between St. Lawrence Is. and Mouth of Yukon River
18	Gulf of Anadyr
19	Bering Sea Between St. Lawrence and St. Matthew Islands
20	Nunivak Island
21	St. Matthew Island
22	Pribilof Islands
23	Bristol Bay

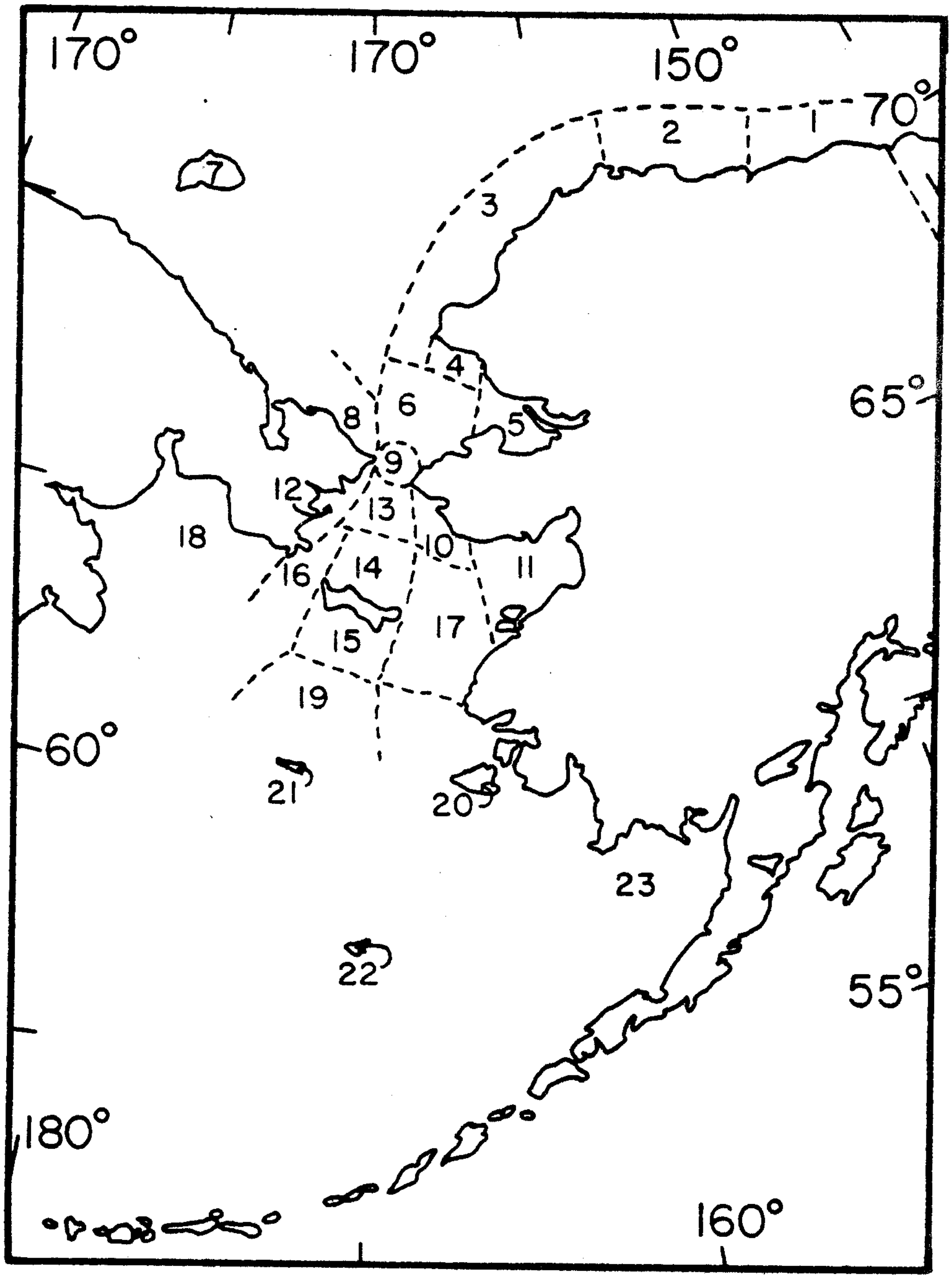

Figure 4. Locations of sub-areas.

5. Classification of Ice Conditions

The standard method of describing sea ice distribution is based on oktas (or eighths) of ice cover. This was not applicable in the present study, since areas with the same okta rating may contain a few large floes or many small floes, and be very different from the aspect of marine mammals. Most of the Bering Sea is classified as 7 or 8 oktas throughout the winter months, but much of that ice is thin and presents no barrier to most of the mammals; for them thin ice is of equal value to open water. Classification by oktas was therefore simply too coarse for the purpose of this project.

Details of the manner in which the various species of marine mammals utilize the pack ice are discussed elsewhere in this report. In general, the critical factor in areas north of the front zone appear to be persistence of open water or thin ice, either as polynyas or recurring leads, through which the animals can pass to and from the water. The amount of "shoreline," in the sense of linear interface between open water (thin ice) and heavy ice also appears to be important for some species. In addition, the persistence of leads along migration routes is clearly important at certain times of year. The occurrence of these features is a function of the dynamics of the ice, as well as of air and sea temperatures, which determine the rate of freezing. The dynamics are clearly more important because ice in motion at differential velocities (such as movement around a point or through a constriction) is continuously breaking and forming new leads.

The ice classification adopted was based upon features visible on NOAA imagery to which the terminology of the WMO classification generally could not be applied. Although the resolution of the NOAA satellite imagery is only 0.6 km, leads smaller than that can be detected, since the energy reflected or radiated is averaged. An area which includes a mixture of ice and open water will have a gray tone intermediate between areas of continuous ice and continuous open water or thin ice. The tone will indicate the relative proportions of each. It is not possible to assign percentages of cover to areas of intermediate gray tones by visual inspection of an image, but the presence of open leads within an area generally can be inferred, if the area is relatively large compared to the size of a resolution element.

The categories of ice conditions identified were:

1. Continuous Heavy Ice Cover: This category was applied where the ice cover appeared as a relatively continuous field of white to light gray tones with no recognizable leads. Gradients in tone sometimes implied separate floes, but distinct leads were absent.

2. Flaw Zone: This category was applicable only in coastal areas. Two sub-categories were recognized: (a) narrow flaw lead separating the landfast ice and pack ice, indicating the early stage of offshore ice motion, and (b) flaw zone, in which the ice is broken by numerous leads or occurs as discrete floes in a relatively narrow zone. The flaw zone which frequently develops along the Alaskan coast between Point Hope and Point Barrow sometimes reaches widths of more than 50 km. Examples of flaw lead and flaw zone are given in Figures 16 and 20 of Section III.B.3.

3. Pack Ice with Leads: This is pack ice crossed by leads which generally are sub-parallel and may intersect. This category represents the first stage of breaking of continuous ice cover. An example in the southern Beaufort Sea is shown in the NOAA/VHRR image in Figure 5. A LANDSAT image of the same area acquired on the same day is shown in Figure 6. The increase in scale shows the presence of more leads and

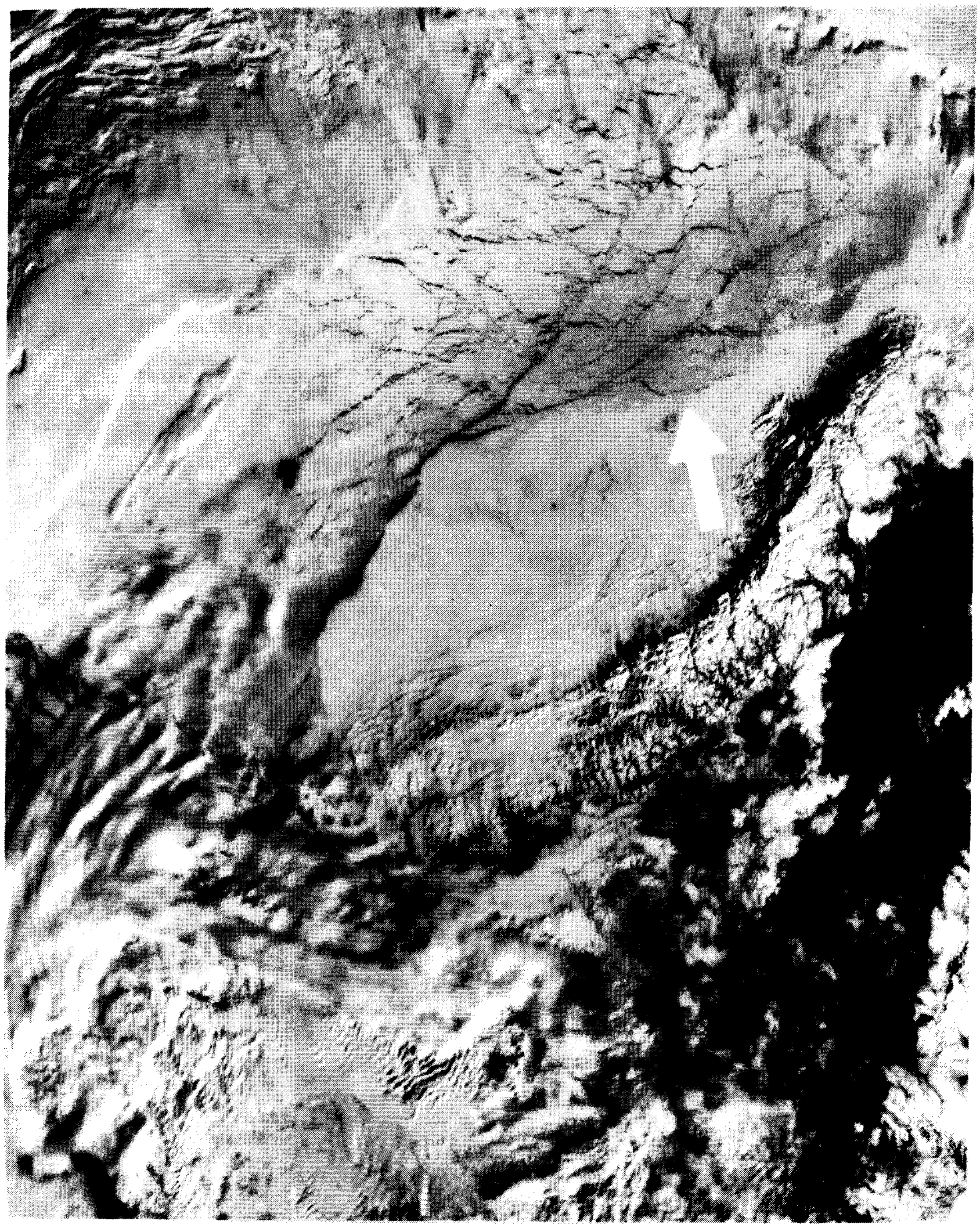

Figure 5. NOAA/VHRR visible band imagery acquired on 19 April 1975.

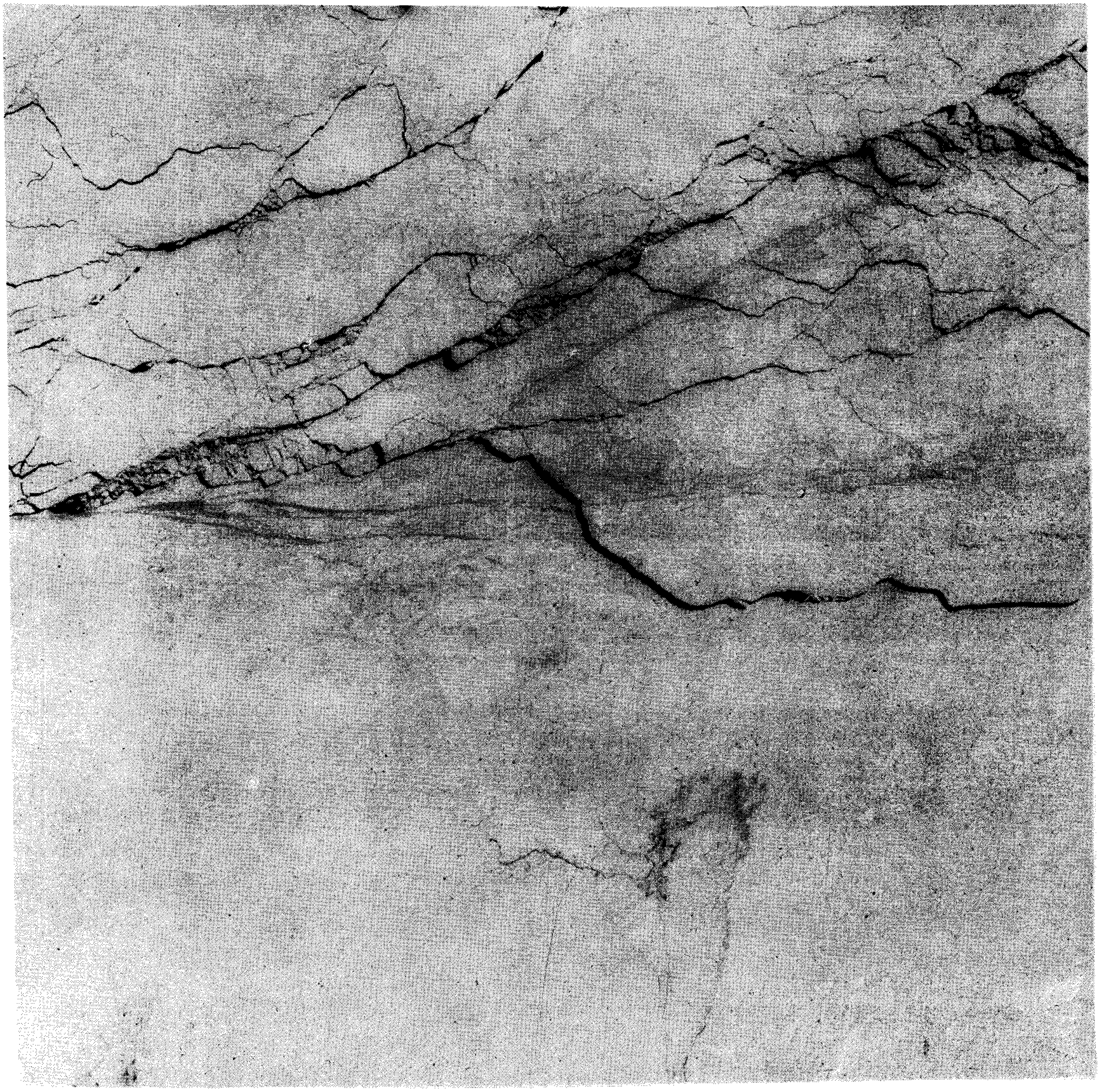

Figure 6. LANDSAT image #2087-21112-7 acquired on 19 April 1975.

illustrates the comparative resolution of the NOAA/VHRR and LANDSAT imagery.

4. Broken Pack Ice: Broken pack ice was identified by the presence of two or more intersecting sets of leads forming floes of variable sizes but generally with an angular form. This configuration represents an additional step beyond category 3 in breaking of the ice cover. In areas classified as broken pack, heavy ice occupies more than 85% of the surface. The NOAA/VHRR image for March 30, 1977 (Figure 7) shows an example of this ice category over most of the Bering Sea south of St. Lawrence Island. A more detailed view acquired on the same day by LANDSAT is shown in Figure 8. As in Figures 5 and 6, the greater detail of the LANDSAT image is obvious, but the classification is the same.

5. Rounded Pack Ice: This refers to areas of at least 50% heavy ice cover in which the floes are predominantly rounded, rather than angular. An example is shown in the area between St. Lawrence and Nunivak Islands in Figure 9. A LANDSAT image of the area just west of Nunivak Island on the same day (Figure 10) indicates that the classification is applicable on that scale as well. This category was applied even when heavy ice was almost continuous, provided that discrete, rounded floes separated by thin ice or open water were identified.

6. Loose Pack Ice: This category was used for areas with less than 50% heavy ice cover consisting of scattered floes. The space between the floes was either open water or thin, new ice. Comparative NOAA/VHRR and LANDSAT views of the area east of St. Lawrence Island are shown in Figures 11 and 12.

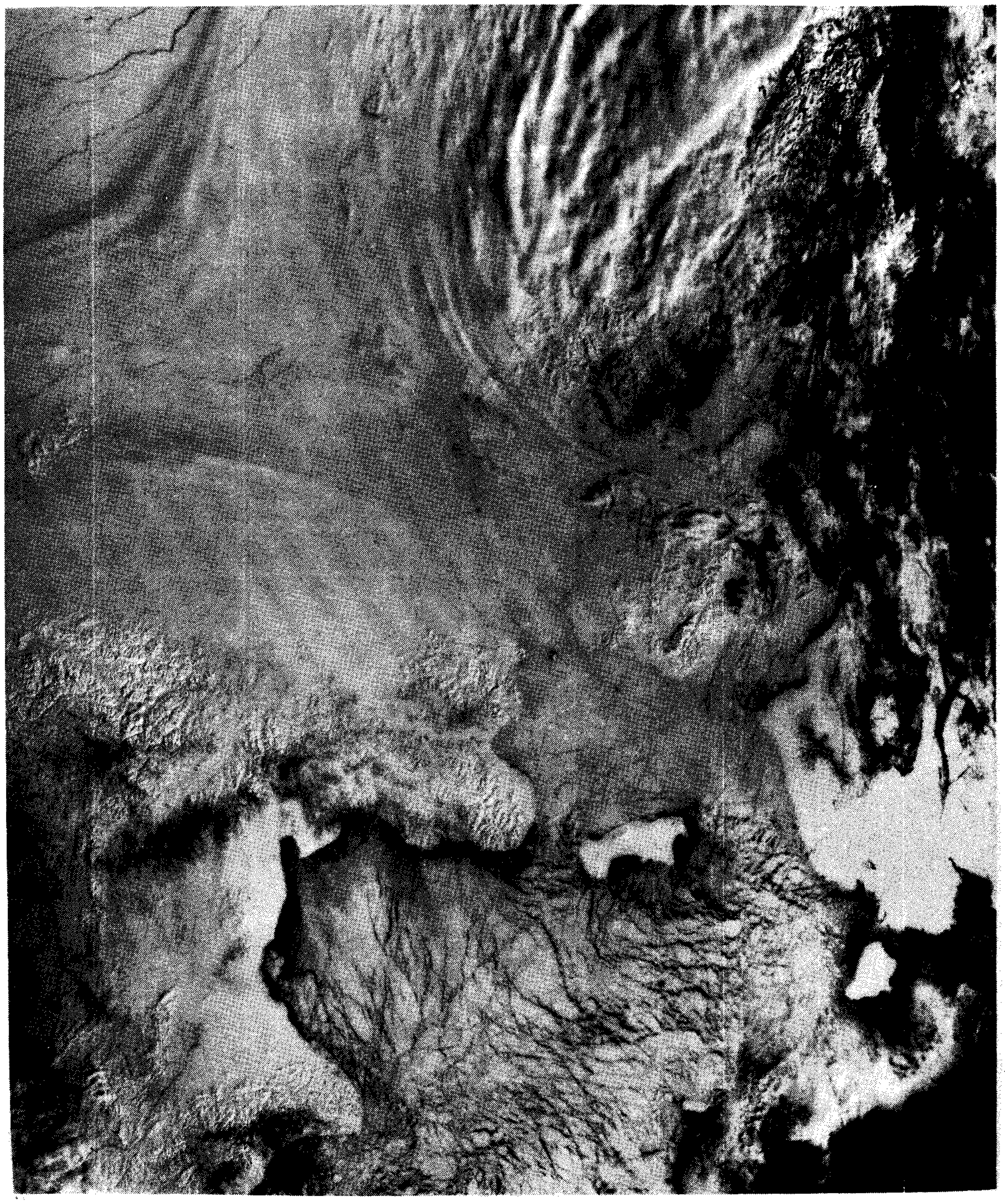

Figure 7. NOAA/VHRR visible band image acquired on 30 March 1977.

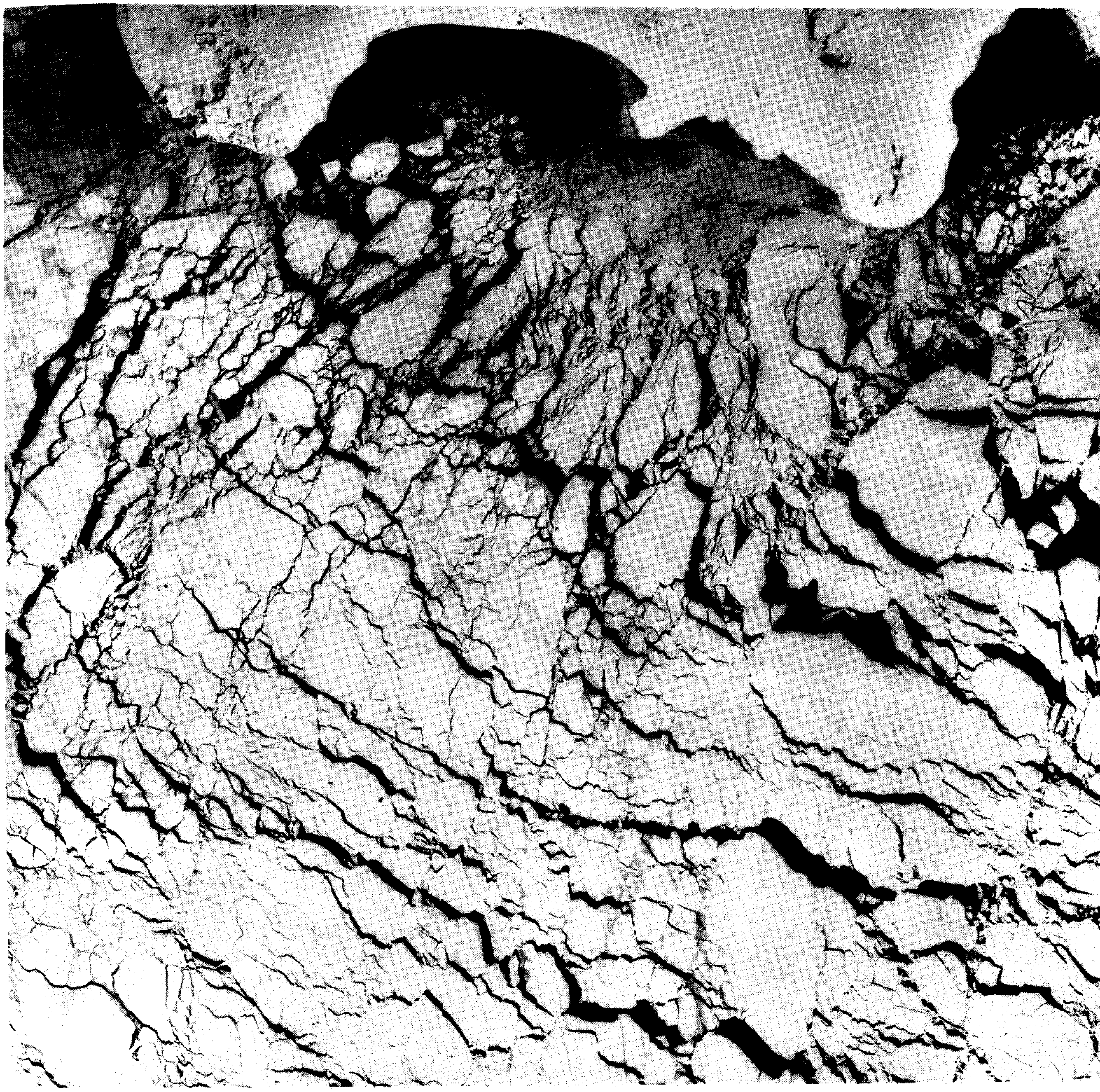

Figure 8. LANDSAT image #2798-21484-5 acquired on 30 March 1977.

Figure 9. NOAA/VHRR visible band image acquired on 19 April 1976.

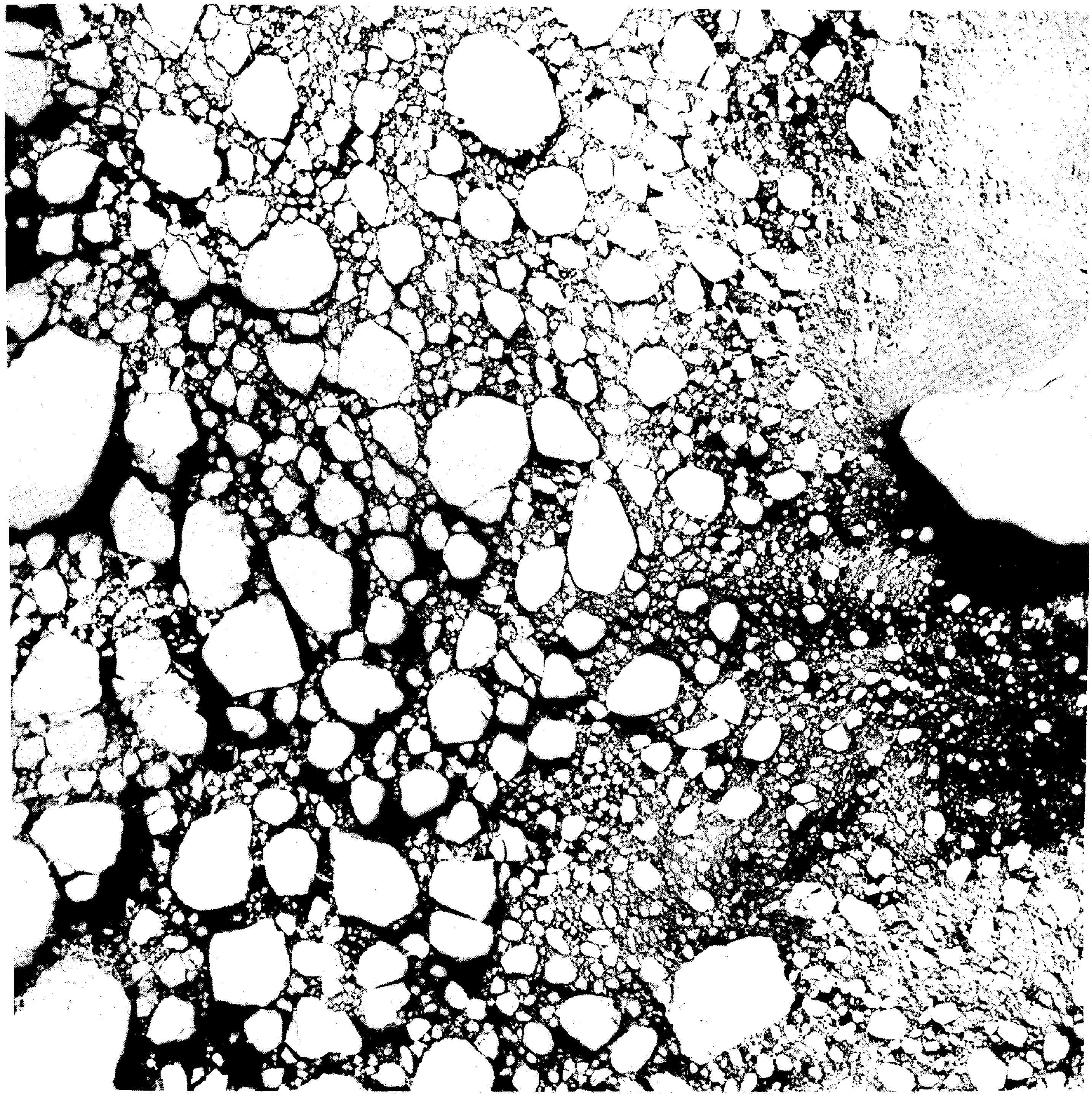

Figure 10. LANDSAT image #2453-21440-7 acquired on 19 April 1976.

Figure 11. NOAA/VHRR visible band image acquired on 21 May 1977.

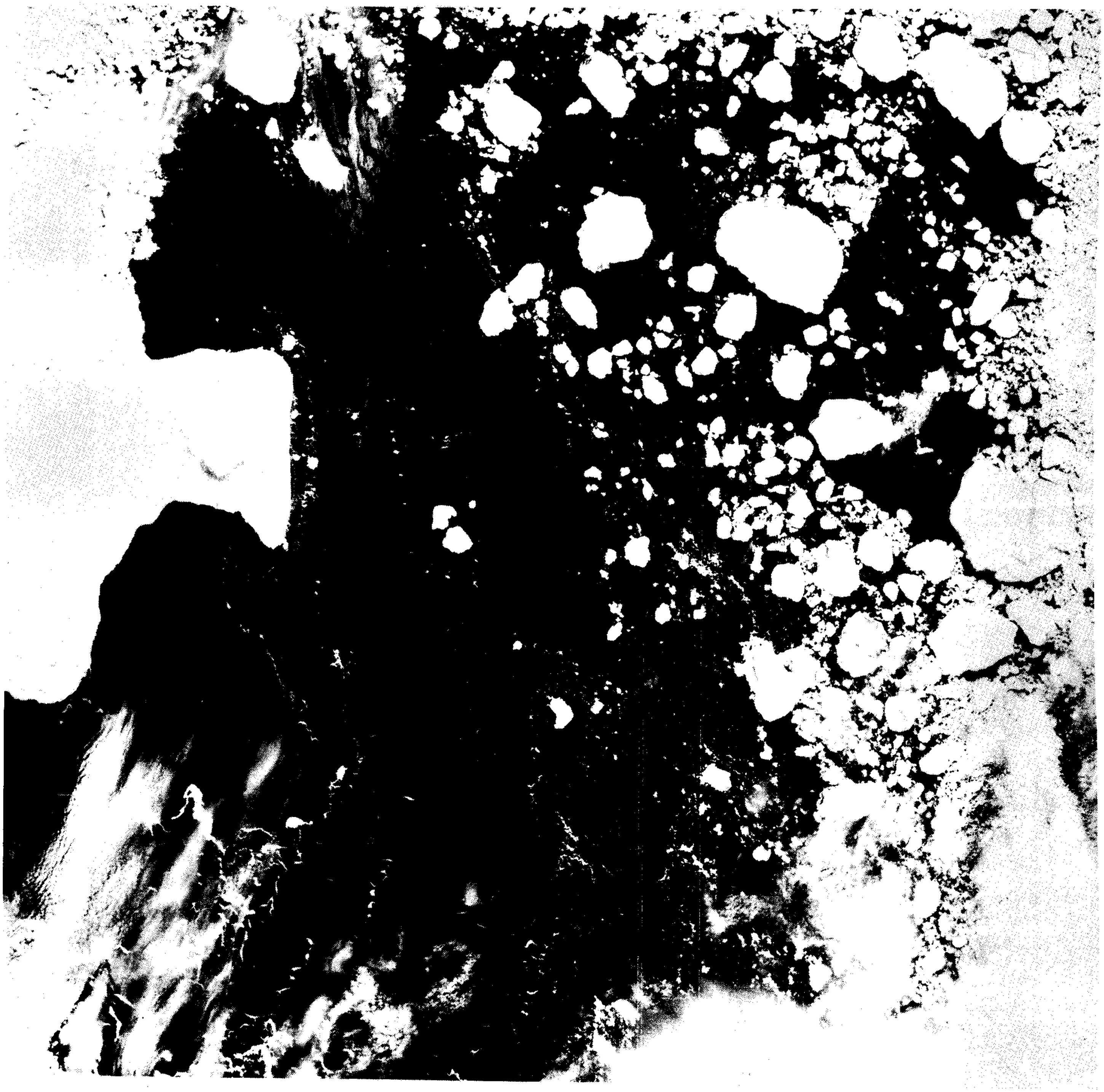

Figure 12. LANDSAT image #2050-21343-5 acquired on 21 May 1977.

7, 8, 9, 10, 11. Open: Areas in which no heavy ice was present (although new, thin ice may be) were classified as 'open'. Category 7 was open sea. Categories 8, 9, 10 and 11 were applied in coastal areas or near islands to indicate that portion of the coast along which a polynya had formed:

8 - polynya or open to the north

9 - polynya or open to the south

10 - polynya or open to the east

11 - polynya or open to the west.

This classification represents a gradation from continuous, heavy pack ice to open water or thin ice, but it is not meant to imply that conditions in any one area must pass through all the intervening stages in changing from a low to a high numbered category. Ice along a coastline can change from category 1 to category 2, and then to category 7 (or 8 - 11), without passing through the intervening stages, if the pack moves offshore as a unit. This is a common sequence along the coast east of Point Hope (Sub-area 2), where the ice tends to drift rapidly away from shore with little or no internal fracturing.

6. Method of Data Acquisition

All of the data for ice classification were obtained by visual inspection of NOAA satellite imagery. The available imagery for each day was examined, and the ice in each of the sub-areas listed in Table 3 was categorized. The extent of ice cover in each sub-area also was estimated, and the image was compared with those from the previous one or two days to determine whether the ice had moved perceptibly in that time and the direction of movement. Presence of clouds obscuring a sub-area also was recorded. Finally, the quality of the data for each sub-area was noted as an indicator of the level of confidence with which the ice was classified.

C. RESULTS

1. Introduction

Data on ice conditions could only be obtained from satellite imagery when cloud cover was very thin or absent, hence the data are obviously biased toward clear weather days. In general, those were associated with periods when the winds were from the north, driving the ice toward the south. Cloudy periods, in the Bering and southern Chukchi Seas, usually occurred when winds were from the south, tending to move the ice toward the north. The ice conditions resulting from southerly winds therefore were less often observed than those resulting from northerly winds. Observation of the pattern resulting from southerly winds generally was possible only when the weather was changing from cloudy to clear and the ice was beginning to respond to the new weather system. On the first day of clear weather following a cloudy period, the ice in any sub-area was usually in the state that could be associated with southerly winds. Subsequently, it changed to a condition (or series of conditions) typical of clear weather periods in that sub-area. The length of time required for the transition depended upon meteorological variables, but it was obvious that the initial and transition states of the ice were not typical of clear weather conditions. A similar lag must also occur following the transition to cloudy weather, but usually cannot be observed. Ice conditions in any sub-area sometimes could be observed even during cloudy periods, when the overcast was thin or there were gaps between clouds. The 'typical' cloudy weather ice conditions for any sub-area, can therefore be determined, given sufficient observations during and just after cloudy periods, but there is little possibility of obtaining data during the transition from clear to cloudy weather. As a result, we were unable to assemble the data set required for a complete statistical treatment of ice conditions.

The data available provided 3-year coverage for the months of December, January, February and June, and 4 years for March, April and May. For any particular sub-area and month, the number of clear weather days varied, so that the data set available was not necessarily typical of long-term trends. One unusual month could strongly bias statistics on the frequency of occurrence of conditions. For example, the number of clear days for some sub-areas during February 1976 was almost 4 times as great as the number in 1975 and 1977, so that statistics for February are dominated by conditions in 1976. There will be no method for judging the representativeness of the February data set until observations from more years are available. While it is representative of the clear weather ice distribution, it probably is not representative of the overall conditions in that month.

Our analysis of the data has been directed toward defining 'typical' patterns associated with clear and cloudy weather. These are the most common conditions and can be used to define the consistency of the ice conditions as habitat for marine mammals. Clearly, if major changes can occur in the ice cover with each change of weather and if these severely affect the ice as habitat for a species, then the species cannot reside there.

No attempt has been made to correlate the occurrence of cloudy weather with particular storm tracks. We recognized that all storm systems do not follow the same path, so that the local winds which affect the ice in any area may not be the same for each occurrence of cloud cover. However, the general association of clear weather with northerly winds and cloudy weather with southerly winds does seem valid as recently demonstrated for the Beaufort Sea by K. Jayaweera (in preparation). Therefore, we assume that anomalous ice conditions or lack of consistency in the association of observed ice and weather conditions reflects some unusual deviation from the normal relationships.

2. Descriptions of Ice Conditions by Sub-Area

Sub-Areas 1 and 2-Beaufort Sea Coast East and West of Prudhoe Bay

These two sub-areas were treated separately in order to determine whether there were recognizeable differences in ice conditions between them. The results did not indicate this, hence they were combined for this description.

From December to May, the ice in both sub-areas was consistently classified as continuous ice cover, pack ice with leads, or flaw lead (categories 1, 2, or 3). The frequency of occurrence of each category in any month was virtually identical for the two areas. Continuous ice cover occurred with a frequency of 57% to 74% on clear weather days from January to May, and 40% to 50% in December and June. In most instances, periods of cloud cover longer than 4 days were associated with a shift of conditions to more open ice, that is, from category 1 to 2, or category 2 to 3. Shorter cloudy intervals led to reversals in conditions, such that if the ice was classified in category 2 or 3 prior to the area becoming cloud covered, then it was in category 1 on the next clear day.

Ice of category 1 changed to category 2 or 3 under similar conditions. The month with the highest percentage of continuous ice and the most stable conditions was April, in which category 3 never occurred. Broken pack ice (category 4) was recognized in June, but only on 5% of the days for which data were available.

Conditions throughout December to June in these sub-areas were generally stable with no areas of persistent small floes, open water, or thin ice. Leads tended to form at the pack ice - landfast ice boundary or, if farther offshore, parallel or sub-parallel to that boundary. Secondary sets of leads perpendicular to the shore seldom formed.

These sub-areas are utilized during winter mainly by ringed seals and by the polar bears which prey on them. Apparently bowhead whales and belukhas use the offshore leads during the spring migration.

Sub-Area 3-Point Hope to Point Barrow

Ice conditions in this sub-area were less variable than were those of any sub-area other than Kotzebue Sound (where the landfast ice is stable all winter). For the period from December to June, the ice was classified as category 2 (flaw zone or flaw lead) for 86% of the observations. On the first day following cloudy periods, the ice was usually in this category, so that the frequency of occurrence probably was higher than that for clear days alone.

The occurrence of a narrow flaw lead tended to be associated with closing of the polynya southeast of Point Hope (sub-area 4) when the wind was predominantly from the south or southeast. At such times, a nearly continuous flaw lead tended to open along the coast from Point Hope to Point Barrow, as a result of movement of the ice to the north or northeast. When the wind was from the northeast or north, the pack ice moved along the coast in a southwesterly direction. At such times, small polynyas formed along the coast, leads radiated from promontaries, and other leads formed across the width of the flaw zone. These sometimes extended up to 50 km offshore, and were often concave to the south, indicating movement in that direction. Repeated occurrences of such southwesterly movement were responsible for formation of the wide flaw zone (Figure 13).

The flaw lead and flaw zone generally were more common in March, April and May than earlier in the winter. From December through February, their frequency of occurrence during clear weather was in the range of 65% to 72% with continuous ice present about 27% of the time in January and February. In March, however, the frequency of occurrence of continuous ice droped to near zero, and the flaw lead or flaw zone was present from 92% to 99% of visible days until break-up.

The pattern described above virtually assures the continued formation of a relatively dense network of new leads in this sub-area through most of the winter. Because of this, the sub-area normally provides winter and spring habitat for bearded seals as well as ringed seals and polar bears. The former apparently require the presence of open water in areas of relatively shallow water where they can feed. As a result, their winter distribution north of Point Hope is mainly restricted to the width of the flaw zone.

The flaw zone also provides the migration path for belukhas and bowhead whales in spring, and in this context, it may be of interest that the frequency of occurrence of continuous ice cover in the area

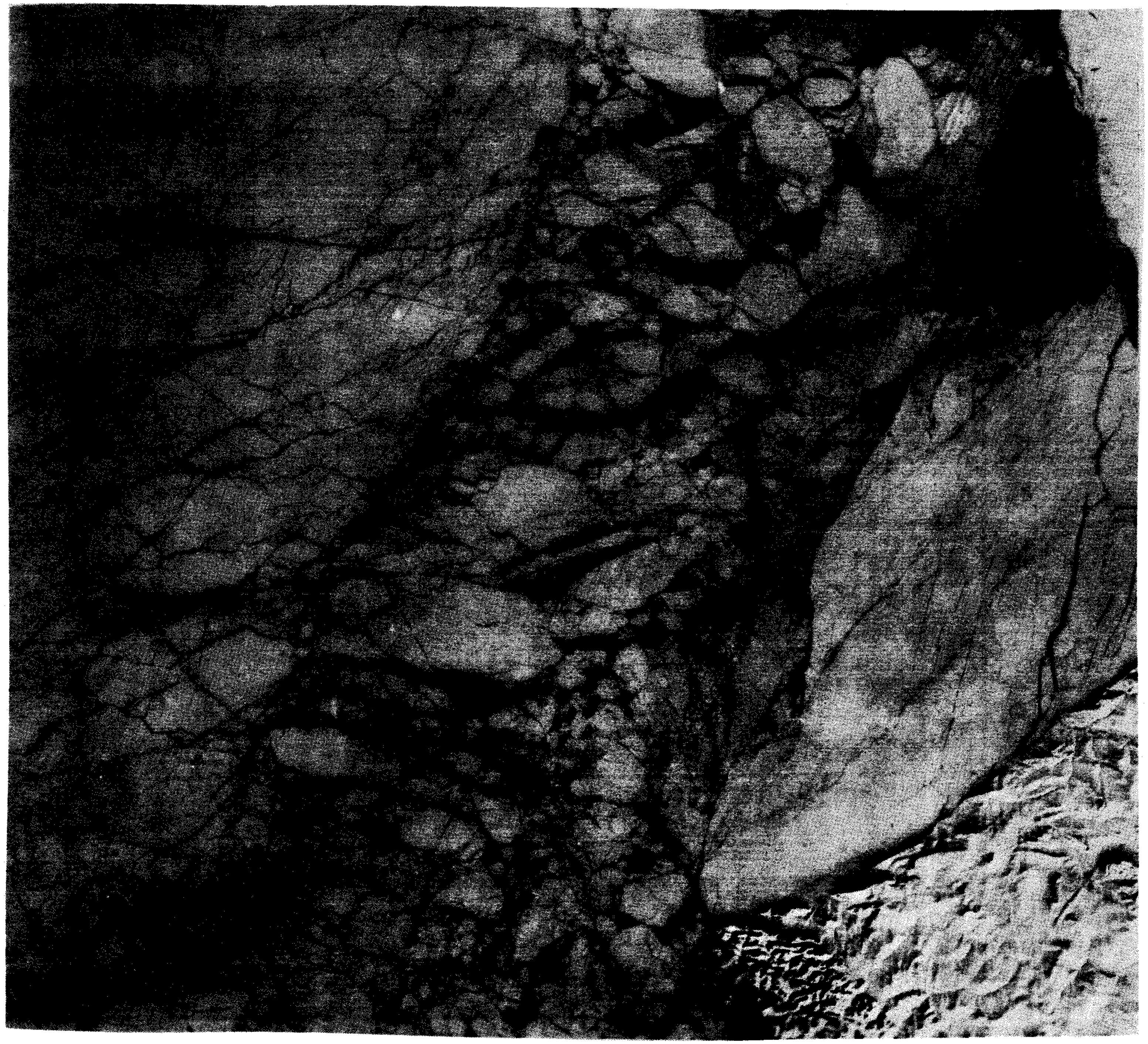

Figure 13. LANDSAT image #1228-22270-7 acquired on 8 March 1973.

drops to nearly zero in March when the migration normally starts. In addition, some birds appear to follow the flaw zone during spring migrations, and walruses also pass through it on their annual transit northward. Thus, the flaw zone is a habitat of outstanding importance in the life cycle of many species. It also is likely to be the path followed in any attempt to extend the shipping season to the North Slope. Any OCS development along the Chukchi Sea coast of Alaska must also occur within this zone, so that the potential for environmental damage in this sub-area could be high.

Sub-Area 4-Coast Southeast of Point Hope

This sub-area extends from Point Hope to the edge of the landfast ice in Kotzebue Sound. The coast is oriented in a northwest-southeast direction, almost perpendicular to the prevailing northeasterly winds. Those winds, which are associated mainly with clear weather, tend to push the ice offshore producing a polynya along the coast. Previous work in this area, based on LANDSAT imagery, has suggested that this polynya is persistent. However, the data presented here, based on NOAA imagery, indicate that the ice cover is continuous along that coast more often than the polynya is present. LANDSAT images generally are supplied only for days of minimal cloud cover, hence the data available from them are strongly biased to clear weather when the polynya is present. Daily images from the NOAA satellites show that the polynya closes during cloudy periods. When data were available for the first day following a cloudy period, or when the sub-area was visible through the clouds, the ice cover was observed to be continuous with the shore. If the days when the area was classified as continuous ice cover (category 1) are combined with the number of days of cloud cover (when ice conditions probably also were in this category) the polynya was open in less than 40% of days in January, March and April, 52% in February and 45% in May. Movement of ice in this sub-area tended to be onshore and offshore, with little evidence of motion along the coast. Movement along shore would be expected to cause formation of leads and breaking of the ice, but categories 3, 4 and 5, which would indicate this, occurred only 12 times during all of the period of observation.

This sub-area is utilized in winter by ringed seals, bearded seals and polar bears. Bowhead and belukha whales migrate through the western part of it, around Pt. Hope and northward into the flaw zone in April-June. Persistent leads radiating northward from the east side of Bering Strait (see below) probably provide the route of access to this sub-area from the south.

The fair weather ice conditions affecting marine mammal distribution are illustrated by Figure 14. The pattern is dominated by the polynya, which is bounded on the west by a stream of small floes. The latter probably were formed by fracture of the ice as the pack drifted southward around Point Hope. This pattern is similar to that commonly present to the west and southwest of St. Lawrence Island, an area that is heavily utilized by walruses. The question arises as to why the Point Hope area is not also used by this species, and the answer seems to be that the pattern simply is not persistent enough to accommodate them. Frequent reversal destroys the potential habitat by closing the ice against the shore, whereas, in the St. Lawrence Island area, reversals of wind, while compressing the pack ice, seldom produce continuous ice cover. In addition, the lower air temperatures at the latitude of Point Hope probably

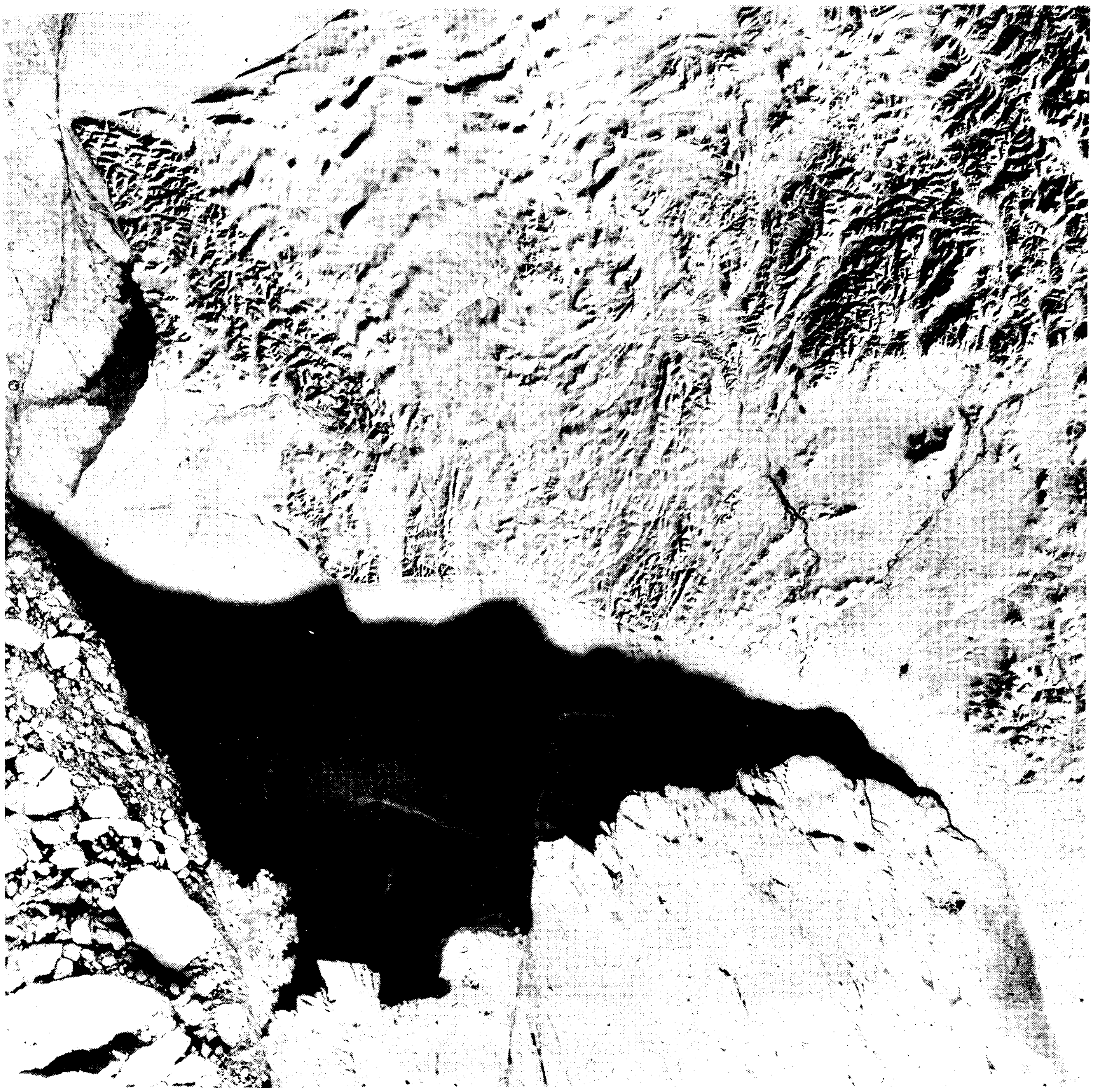

Figure 14. LANDSAT image #2420-21595 acquired on 17 March 1976.

result in more rapid refreezing of new leads and more rapid attainment of ice thickness too great for walruses to break through.

Sub-Area 5-Kotzebue Sound

The ice in Kotzebue Sound is essentially stable from freeze-up to break up, with little or no evidence of movement on the scale of the NOAA imagery from December to June. Ringed seals are the only mammals which regularly inhabit the area during the winter. Belukhas and spotted and bearded seals enter it after breakup.

Sub-Area 6-Sea North of Bering Strait

The ice in this sub-area is mainly a southern extension of the flaw zone north of Point Hope which is often present as a recognizable 'stream' of broken floes (Figure 3). The eastern boundary of the sub-area is defined by a series of leads that extends northward from the massive ridge of grounded ice which annually forms on Prince of Wales shoal.

The ice within the sub-area tends to be continually in motion. As noted earlier, the ice along the coast southeast of Point Hope is very sensitive to local winds, which open and close the polynya there with each change in weather. When the polynya opens, the pack ice south of it is forced toward Bering Strait where it converges to continuous ice cover until southward breakout occurs through the Strait. When the polynya closes, the ice converges to the north against the coast. New ice formed in the sub-area must therefore be absorbed in ridging or rafting. Because there is no exit for the ice to the north, the net ice transport is to the south.

Ice conditions in this sub-area ranged from continuous to broken pack through most of the winter. Continuous motion of the ice, combined with the differential motion between the ice east and west of the stream (as described under Sub-Area 8, the north coast of the Chukchi Peninsula), results in frequent formation of new leads. As a result, bearded seals as well as ringed seals are widely dispersed in this sub-area. In spring it is used intensively by migrating bowheads, belukhas, and walruses.

Sub-Area 7-Wrangell Island

The Wrangell Island area was included in this study because preliminary work showed that a polynya usually is present somewhere along its coast. This suggested that some information regarding large scale circulation of the Chukchi Sea pack ice might be obtained from a correlation between the location of the Wrangell Island polynya and ice conditions along the Alaskan coast. Unfortunately, the data were not adequate to test this possibility. Because this is the westernmost sub-area it was observable only on imagery from the satellite pass over Bering Strait (see above). Images obtained from passes farther east generally were too distorted along the western margins to provide useful information on the Wrangell Island area. This limitation, combined with the normal cloud cover, greatly restricted the number of days in which the sub-area could be observed.

The most common clear weather pattern showed the polynya on the east side of the island during December, January and February. In March, it occurred on the east side 32% of the time, the same frequency with which continuous ice surrounded the island. In April, continuous ice occurred 86% of the time, and the only polynas were on the west side of the island. During May, continuous ice occurred 62% of the time and the polynyas were on the north and west sides of the island with almost equal frequency. There was no apparent consistency to the ice configuration following cloudy periods. Polynyas on all sides of the island, as well as continuous ice cover, were observed on the first clear weather days.

Sub-Area 8-North Coast of the Chukchi Peninsula

The coastline in this sub-area is oriented approximately northwest-southeast, perpendicular to the prevailing northerly winds. North and northeast winds associated with clear weather kept the ice tightly packed against the coast. The lowest frequency of occurrence of continuous ice (category 1) was 75% in December; the highest was 98% in February. We anticipated that the ice would be moved off the coast during cloudy periods (i.e. with southerly winds) but this was not consistent. On the first clear day after a cloudy period, a lead or small polynya usually was present, but these leads and polynyas closed rapidly, returning the ice to category 1 within one or two days. When Point Hope was cloudy, or when ice was closed against the coast in that area, there usually was continuous ice cover in Sub-Area 8. This implies a degree of differential motion of the ice across Sub-Area 6 (sea north of Bering Strait) which may explain the persistence of leads in that area. The fact that the pack ice can be held tightly against both the coast southeast of Point Hope and that on the north side of the Chukchi Peninsula at the same time suggests that the internal inertia of the pack ice of the western Chukchi Sea is sufficient to overcome the force of local southerly winds.

Sub-Area 9-Bering Strait - Diomede Islands

During most clear weather periods, the ice in Bering Strait was in categories 3, 4, and 5 with leads actively forming. This indicated motion and general instability. However, in March, April and May, the frequency of occurrence of continuous ice was up to 35%, about 5 times greater than during January and February, indicating a tendency toward greater stability in those months. During cloudy periods, the ice tended to converge into the Strait from the south. When the clouds cleared, the ice condition on the first day always was continuous cover with few or no large leads.

A prominant shoal (Prince of Wales Shoal) projects northward from the east side of Bering Strait. A large grounded ice mass forms annually on this shoal (Kovacs, 1971) and anchors the landfast ice along the northwestern coast of the Seward Peninsula. As a stationary feature in a moving ice field, it also acts as the stress concentrator that initiates north-trending leads on the east side of Sub-Area 6. In spring, those leads provide the routes for migrating bowhead and belukha whales as well as walruses. In addition, there is evidence that some birds also follow this lead system during spring migration, rather than the more circuitous route around Kotzebue Sound.

A small concentration of walruses usually is present just south of the Diomede Islands in winter. During periods of southerly ice motion a small polynya forms there in the lee of the islands and the landfast ice which joins them. When the direction of movement reverses, it seems likely that leads are still present between the small floes where the pack ice breaks around the islands, thus maintaining access between air and water.

Sub-Area 10-Seward Peninsula between Bering Strait and Nome.

The orientation of the coast in this sub-area is similar to that of the coast southeast of Point Hope and ice conditions usually were sensitive to local winds. During clear weather periods, a polynya formed all along the coast. However, its southeastern boundary often was distorted by the presence of one or two important shear zones which extended to the southeast. These zones separated the ice in Norton Sound from that in Bering Sea to the west (see below) and tended to form rapidly when the ice moved in a southerly direction. During cloudy periods, pack ice moved against the coast, so that the ice on the first day after even a short cloudy interval always was classified as continuous ice cover. Usually within one day the ice moved offshore and the polynya was reestablished.

The ice in this sub-area moves rapidly and continually and can generally be characterized as 'active'. Because of the continual ice movement, formation of new ice between floes does not appear to be enough to exclude walruses from the area in winter but they occur in small numbers only in the vicinity of Sledge Island in that season. Bearded seals are present throughout this sub-area in winter.

Sub-Area 11-Norton Sound

As noted above, the ice in Kotzebue Sound was stable over most of the winter. In contrast, the ice in Norton Sound tended to be in motion most of the time. The dominant clear weather pattern in this sub-area included a polynya along the northern shore of the Sound with a second polynya in Norton Bay at the head of the Sound. Occasionally, the pattern reversed and the ice closed against the northern shore, leaving a polynya along the southern shore. This occurred even when the polynyas to the southeast of Point Hope and in Sub-Area 10 were well developed under north to northeasterly winds. This suggests that the ice in Norton Sound can move independently of these, which is consistent with the appearance of the shear zones noted in the discussion of Sub-Area 10. There is no barrier to southwesterly movement of ice out of the Sound.

The position of the polynyas tended to reverse following cloudy periods. That is, when the polynya was on the south side of the Sound at the start of a cloudy period, then it usually was on the north side when the clouds moved off.

Ringed and bearded seals are abundant in Norton Sound during winter. Highest densities of the former occur in the shore fast ice and the adjacent flaw zone. Bearded seals are present throughout the drifting ice. Walruses are absent in Norton Sound in winter except at Sledge Island. During the spring migration, walruses occur in large numbers throughout the western part of the Sound and in small numbers in the eastern part.

Sub-Area 12-Coast of Chukchi Peninsula from Bering Strait to Cape Chaplin

This area was separated from Sub-Area 13 (the sea south of Bering Strait) for the purpose of obtaining a record of the frequency with which pack ice is in contact with the coast. Based upon previous work, we knew that heavy ice often is absent in winter from Anadyr Strait, between Cape Chaplin and western St. Lawrence Island. Therefore, the question arose as to whether this was due to a drift trend around the eastern side of the island, or to convergence of ice north of Anadyr Strait which impeded ice movement through it. If the former was the case, the ice should have tended to remain away from the Siberian coast north of the strait. The clear weather imagery did not indicate any such tendency; instead, the ice was packed against the coast at least 70% of the time and was classified in categories 1, 3, 4 and 5. This also occurred after cloudy periods, indicating that both north and south winds tended to converge the ice against the coast. These observations suggest that the generally lighter ice between Cape Chaplin and western St. Lawrence Island is mainly the result of restricted flow between the Island and the Siberian mainland, rather than to drift away from the latter. The blockage appears to develop between the Siberian coast and the wedge of heavy ice north of the Island (see below). The southern, more open water part of this sub-area is occupied by large numbers of walrus and bearded and ringed seals throughout the winter. Anadyr Strait is a major migration route for whales, walruses and seals in spring and fall.

Sub-Area 13-Sea South of Bering Strait

The extent of ice cover in this sub-area during clear weather increased through December and January, reaching a maximum in February when the area was covered by continuous pack ice 72% of the time. March and April were similar to January (40%-45% continuous ice); in May, the onset of melting and movement of ice out of the area was apparent. Following cloudy periods, the ice was invariably in category 1, apparently as the result of southerly winds forcing the ice northward toward Bering Strait and the adjacent coastlines, where further movement was impeded.

Open water periods in clear weather increased from 1% during May to 80% in June, illustrating that break-up and disappearance of the ice in this sub-area occurs rapidly.

There was little correlation between the extent of ice in this sub-area and that south of Point Hope. Sub-Area 13 is effectively a channel for ice moving northward or southward. Changes in wind direction affect the direction of ice movement, but do not appreciably affect the extent of ice cover. In effect the ice surges back and forth with changes in the wind, probably with a net southerly transport during the period of ice growth (December to April).

During winter, this area is occupied mainly by ringed seals; the peripheral parts are utilized by bearded seals and walruses. Walruses, bowheads, belukhas, and seals migrate through the area during March to June.

Sub-Areas 14 and 15-North and south sides of St. Lawrence Island

These two sub-areas are described together because the ice conditions in them tended to be complimentary. Generally, there was continuous ice on the north side of the island when the polynya south of the island was well-developed. During clear weather, this configuration was present more than 80% of the time. The first day after cloudy periods however, invariably showed the pattern reversed, with the pack ice north of the island more open and the polynya to the south closed. A polynya seldom developed in the northern area; instead, the ice was more often in category 4 or 5. At such times, the ice on the south side seldom compacted to category 1; rather, it usually was in category 4 or 5.

During periods of sustained northerly winds, the ice was driven tightly against the northern side of St. Lawrence Island. At such times, it tended to form a compact wedge-shaped mass of heavy, pressure ridged ice extending northward for more than 100 km (Figure 15). This

Figure 15. Mosaic of LANDSAT images #1226-22165, 22171, and 22174 acquired on 6 March 1973.

was described and analyzed previously by Shapiro and Burns (1975a,b) and by Sohdi (1977).

Under the influence of winds with a strong component parallel to the long axis of the island, the ice on both the north and the south sides tended to disperse as broken or rounded pack ice.

The discussion of the distribution of marine mammals around St. Lawrence Island is deferred to the next section.

Sub-Areas 16 and 17-St. Lawrence Island to the Yukon River Delta and St. Lawrence Island to Gulf of Anadyr

During the period December to April, the ice was most commonly in categories 3 and 4 east of St. Lawrence Island; west of the island, it tended to be in categories 4, 5 and 6. Continuous ice cover occurred significantly more often east of St. Lawrence Island than to the west. Close to the eastern end of the island, the ice tended to break into small fragments in a narrow zone close to shore. To the west of the island, conversely, the ice was looser, and the broken ice along the coast dispersed over a wider area. Heavy ice was absent from the western sub-area following periods of prolonged winds from the north, resulting in a significant number of days in which open water or thin ice predominated. This occurred in all months of ice cover other than January and February for the area west of the island. It never occurred in the eastern sub-area from December to April.

In both sub-areas, periods of cloudy weather were associated with a general convergence of the ice.

The ice conditions in the four sub-areas surrounding St. Lawrence Island can be summarized as follows: with the exception of the wedge of heavy ice which forms on the north side, the ice around the island generally is heaviest to the east, lightest to the west, and classifiable as broken to rounded pack throughout the winter and spring. This implies that the ice to the east, south, and west usually is active, with new leads forming almost constantly. Ice movement around the eastern and western ends of the island produces areas of small highly deformed floes, in which the length of edge between heavy ice and open water is large. Along the eastern side of the island, the small floes are restricted to a narrow zone near shore, while the corresponding zone to the west usually is much wider.

Some of the heaviest concentrations of walruses in the Bering Sea occur to the west and south of St. Lawrence Island in winter. Bearded and ringed seals are abundant in the same areas and some bowheads and belukhas apparently winter there.

Sub-Area 18-Gulf of Anadyr

During clear weather the Gulf of Anadyr was dominated by continuous heavy ice in its southwestern sector and a large polynya just south of the Chukchi Peninsula. The polynya was present on 39% of the clear weather images for December. This increased to 81% in January, then dropped to 50% in February, and was 79% and 73% for March and April, respectively. For most of the remaining clear weather days, the ice was classified as continuous cover (category 1). Following prolonged periods of cloudy weather, the pack ice on the first clear day usually was continuous with the shore, indicating closure of the polynya. During a visit to the area in March, 1979, the ice along the northern part of the polynya was observed to be only about 10-25 cm thick; farther south, the thickness increased to about 1m. Over the distance in which this occurred there was little or no evidence of ridging or rafting (B. P. Kelly, oral comm, 1979). If this is typical, it implies that the opening and closing of the polynya are rather 'gentle' processes, essentially closing the open water areas without appreciable internal deformation of the ice cover. The gradual thickening of the ice to the south also implies a general drift in that direction, the ice in the south being older than that in the north.

Sub-Area 19-Bering Sea Between St. Lawrence and St. Matthew Islands.

The ice in this sub-area during clear weather was consistently classified as broken pack (category 4) from January through March. For December and April, the frequency of occurrence of this condition dropped to 63% and 76% respectively, with the ice on the remaining days classified as rounded pack (category 5). Category 5 also was the most common classification in May, occurring 44% of the time. The ice usually was gone from this sub-area in late May, and was present only on 7 occasions in June.

This is part of the principal wintering concentration areas of walruses and bearded seals. It also is used as a wintering area by some bowheads and belukhas.

Sub-Area 20-Nunivak Island

Imagery for a total of 18 days of clear weather were available in December for the Nunivak Island area. All of the images showed pack ice around the island; a polynya was present to the south on 12 of the 18 days. Only 2 clear days occurred during January. The polynya was present in one of these; for the other, the island was surrounded by continuous pack ice. In the remaining months of ice cover the limited data indicated the polynya to the south to be the most common feature of the ice cover, with occasional periods of continuous ice or polynyas to the north. The latter apparently is the usual condition during cloudy periods, as it was generally present on the first day after even short periods of cloud cover.

Walruses and bearded seals are common west and south of Nunivak Island in winter.

Sub-Area 21-St. Matthew Island.

There are few observations available for the St. Matthew Island sub-area because of frequent cloud cover. The data for clear weather in December, January and February indicated loose pack ice surrounding the island, with a polynya usually off the southern coast. The latter was the most common ice condition also during clear weather in March, April and May. The first image acquired after the end of a cloudy period invariably showed a polynya off the northern side of the island, and this probably is the prevailing condition during periods of southerly winds.

Aircraft observations of the area in March 1979, when the polynya to the south was present, showed the ice packed tightly against the north side of the island and extensively ridged. A ribbon seal and a sea lion were trapped by the tightly packed ice, suggesting that movement of the ice against the northern shore had been rapid. Bowhead whales were observed off the western end of the island in an area of heavy broken ice (B. P. Kelly, oral comm., 1979).

Sub-Area 22-Pribilof Islands.

The Pribilof Islands, which are close to the southern limit of the pack, usually were obscured by clouds. Only two observations were obtained for December and January, both of which showed no ice in the area. Images in February showed open water on four occasions and continuous ice on 3. In March and April (32 and 35 observations, respectively) there was continuous ice cover on only 6 days. During four days in April, the ice edge was south of the islands, with a polynya close to them. All observations in May were of open water. When clouds covered this sub-area, the ice apparently withdrew to the north, leaving open water around the islands.

This is an area utilized mainly by spotted and ribbon seals and some walruses and steller sea lions in the fringe and front zones.

Sub-Area 23-Bristol Bay

Clouds obscured the Bristol Bay sub-area most of the time during this study. Of the few observations available for the months of December, January and February, most showed either continuous ice, open water, or thin ice. The totals for March were 11 days of continuous ice, 8 days of open water or thin ice, and 7 days in which the ice was classified as category 3 and 5. April totals were 5 days of continuous ice, 17 days of open water or thin ice, and 17 days of ice in category 5. Of the 32 days in May for which observations were possible, 31 showed open water.

Harbor seals are present in the coastal zone of this sub-area throughout the year. Spotted and ribbon seals are associated with the ice fringe and front zones whenever these habitats are present. Walruses and bearded seals are most abundant in the sub-area during January to April.

3. Illustration of the Ice "Cycle".

A series of NOAA/VHRR images in the visible band acquired during 9 to 30 April 1975 illustrate the sequence of events in an ice 'cycle', beginning with the pattern prevailing under northerly winds to that resulting from southerly winds, then back to northerly. This particular series of images was chosen because it provides the maximal number of sequential views over a single complete 'cycle' of southward-northward-southward movement.

In the first image of the sequence (Figure 16), the lead extending northeast from Point Barrow along which a set of northward-trending leads terminates, separating the more stable ice of the Beaufort Sea from the diverging pack to the north and west. The single dark spot approximately due west of Point Barrow and the two smaller spots northwest of Cape Lisburne are open water or thin ice surrounding grounded ice masses (Stringer and Barrett, 1975; Kovacs et al., 1975); the small polynyas are on the leeward sides of these grounded floes. These ice masses act as stress concentrators because of their resistence to the movement of the pack ice. Their role as loci of lead formation will be apparent in the succeeding images of the sequence.

The flaw zone along the coast between Point Hope and Point Barrow is unusually wide. The bight just northeast of Cape Lisburne contains a large landfast ice mass. This is a persistent feature on that coast during winter and spring. For example, it is present also in Figure 13, a Landsat image acquired in March, 1973. The lead within this ice mass in both images is a common feature.

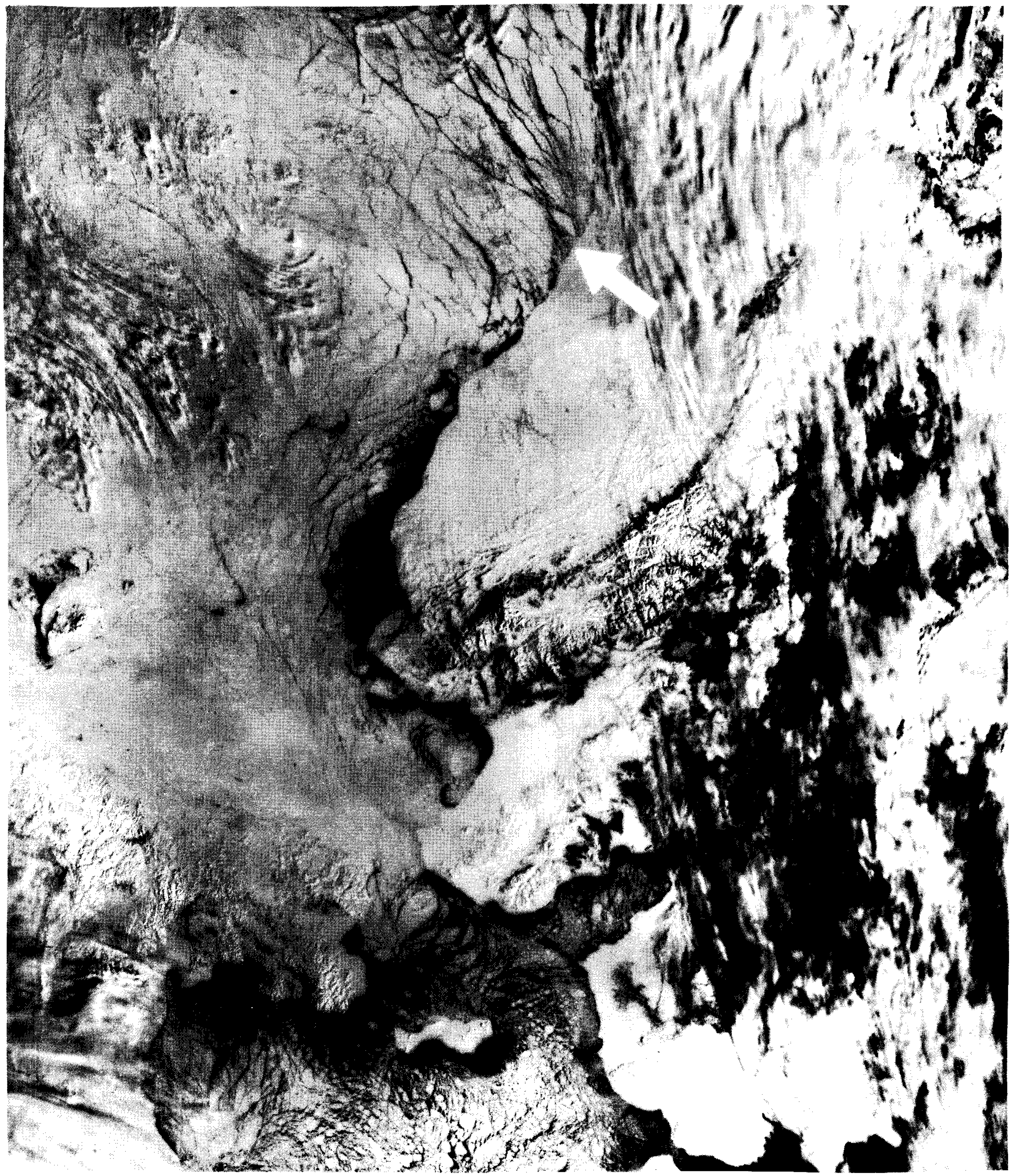

Figure 16. NOAA/VHRR visible band image acquired on 9 April 1975.

A polynya extends southeastward along the coast from Point Hope, then curves around the edge of the landfast ice in Kotzebue Sound. This is unusual; the more normal extent of this polynya is indicated in Figure 14.

The ice cover immediately north of Bering Strait appears to be continuous, although a few long north-south leads traverse the area, indicating some movement. South of Bering Strait, the pack is more open, and there are several indicators of recent southward movement. These include (a) the narrow lead along the Siberian coast, just south of Bering Strait, (b) the concave NE-SW leads between the Chukchi and Seward Peninsulas, (c) a small polynya south of the Diomede Islands, (d) a polynya along the western coast of the Seward Peninsula, (e) a shear zone extending north-south across the mouth of Norton Sound, and (f) the polynyas south of St. Lawrence Island and the Chukchi Peninsula. Note that the only extensive area of open water in Norton Sound is in Norton Bay, at its head. The change in extent of ice cover in the Sound will be apparent in the later images of the sequence.

The tendency for ice moving south from Bering Strait to pass east of St. Lawrence Island is evident. Clearly, the ice east of St. Lawrence Island is significantly heavier than that to the west, and our aerial and shipboard observations have shown that the eastern ice is extremely ridged and deformed. The ice on the north side of the island is very compact and ridged and is virtually continuous, while the polynya to the south of the island is large and slightly east of its usual position.

In the northern Gulf of Anadyr, the ice is close to shore in the west, and farther offshore and open toward the east. South of the open polynya, the ice is broken into angular floes which contrast with the more rounded floes in the area south of St. Lawrence Island.

To the southeast in Kuskokwim and Bristol Bays, a polynya along the south-facing shore is apparent, and ice is rather tightly packed against part of the northern shore of Nunivak Island.

Several changes are apparent in the clear areas of the image acquired two days later on April 11 (Figure 17). The small polynya south of the Diomede Islands has disappeared and a larger polynya has opened to the north. Closure of the polynya southeast of Point Hope also is evident, as is the formation or widening of leads north of Bering Strait. There is a new lead trending northeastward from Prince of Wales Shoal indicative of northerly movement. The ice in the eastern Gulf of Anadyr has closed against the shore, and there may be more ice in the area between St. Lawrence Island and the Siberian coast than in the previous image. The presence of cloud cover makes interpretation of the image difficult for that area. Finally, more open water is present along the south side of the Seward Peninsula and the linear aspect of the shear zone has been destroyed.

By April 15 (Figure 18), the pattern of the ice has changed markedly. The polynya south of St. Lawrence Island is nearly closed, heavy ice almost fills Anadyr Strait, and the ice appears to be farther offshore in the northwestern part of the Gulf of Anadyr. A polynya is visible along the southern shore of Norton Sound as a dark area in the clouds. The changes north of Bering Strait are more striking. The flaw has closed along the coast from Point Hope to Point Barrow, and short new leads are scattered through the area. The component of movement perpendicular

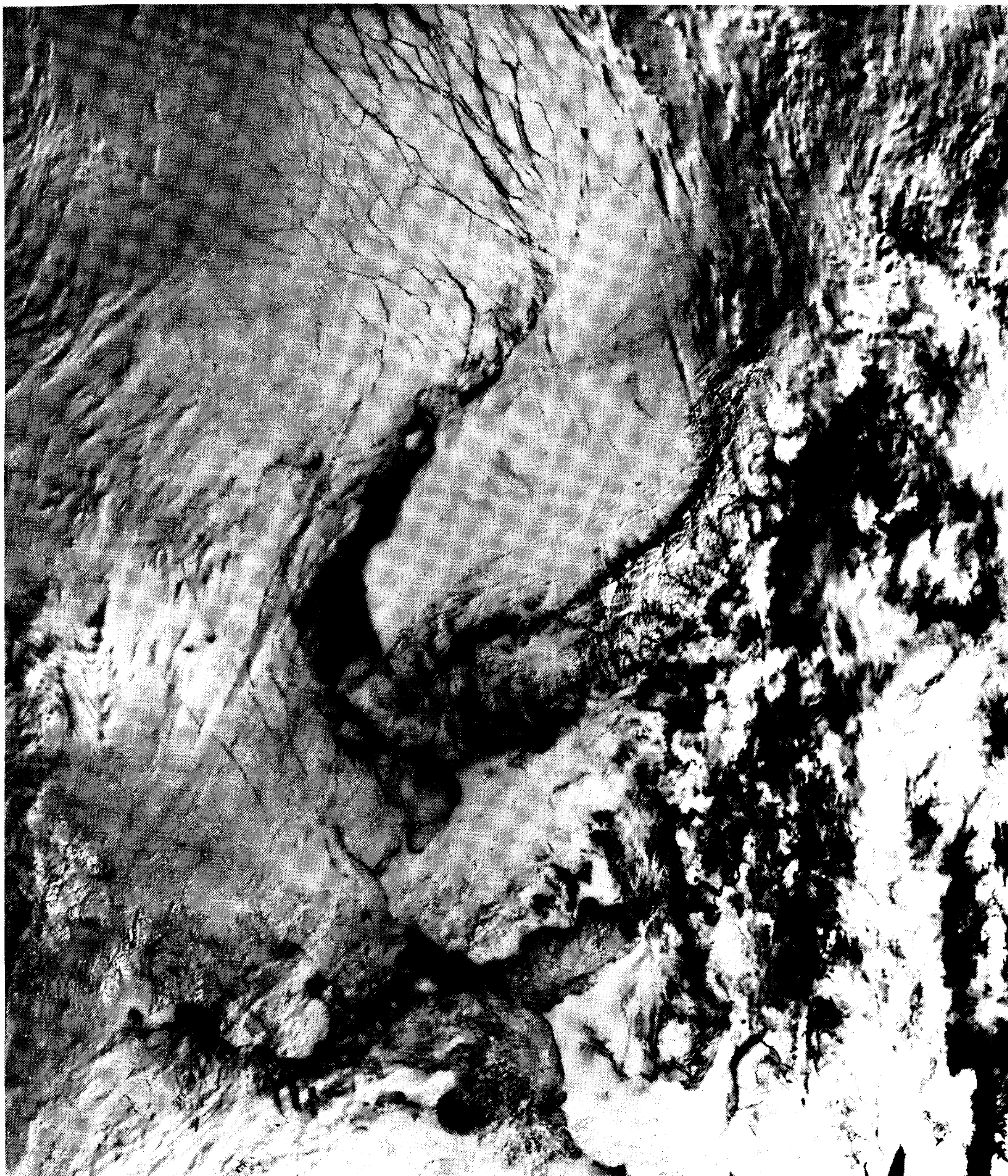

Figure 17. NOAA/VHRR visible band image acquired on 11 April 1975.

Figure 18. NOAA/VHRR visible band image acquired on 15 April 1975.

to the coast was estimated at about 15 km from "marker floes" visible in a few locations on the NOAA/VHRR infra-red images. The lead in the fast ice in the bight north of Cape Lisbourne is closed. A narrow lead is visible along the northern coast of the Chukchi Peninsula. The long, concave southward set of leads across the Arctic Ocean, shown in the earlier figures, is closing, and a new lead is visible along the edge of the landfast ice east of Barrow.

On April 17 (Figure 19), there is a new set of leads in the Arctic Ocean, and these are concave to the north, indicating movement of the ice in that direction. A few new leads are present along the Beaufort Sea Coast and in the area of Point Hope and Cape Lisburne. The polynya east of Point Hope is now almost closed, with heavy ice close to shore. The lead along the north side of the Chukchi Peninsula has extended northwestward. In the Bering Sea, the ice has closed northward toward Bering Strait, and leads are present in the heavy ice north of St. Lawrence Island. The polynya along the southern shore of Norton Sound is clearly visible, as is one along the northern shore of Nunivak Island. Etolin Strait appears to be free of ice. The ice in the Gulf of Anadyr, however, shows little or no evidence of northward motion between Figures 18 and 19 though it is less open in the east and more open in the west than in earlier images.

The Bering Sea was cloud covered when the image of April 19 was acquired (Figure 20). However, the flaw along the Chukchi Sea coast of Alaska can be seen to have opened as a result of northerly movement of the pack ice. The flaw along the edge of the landfast ice in the western Beaufort Sea also has opened wider, and the large mass in the bight

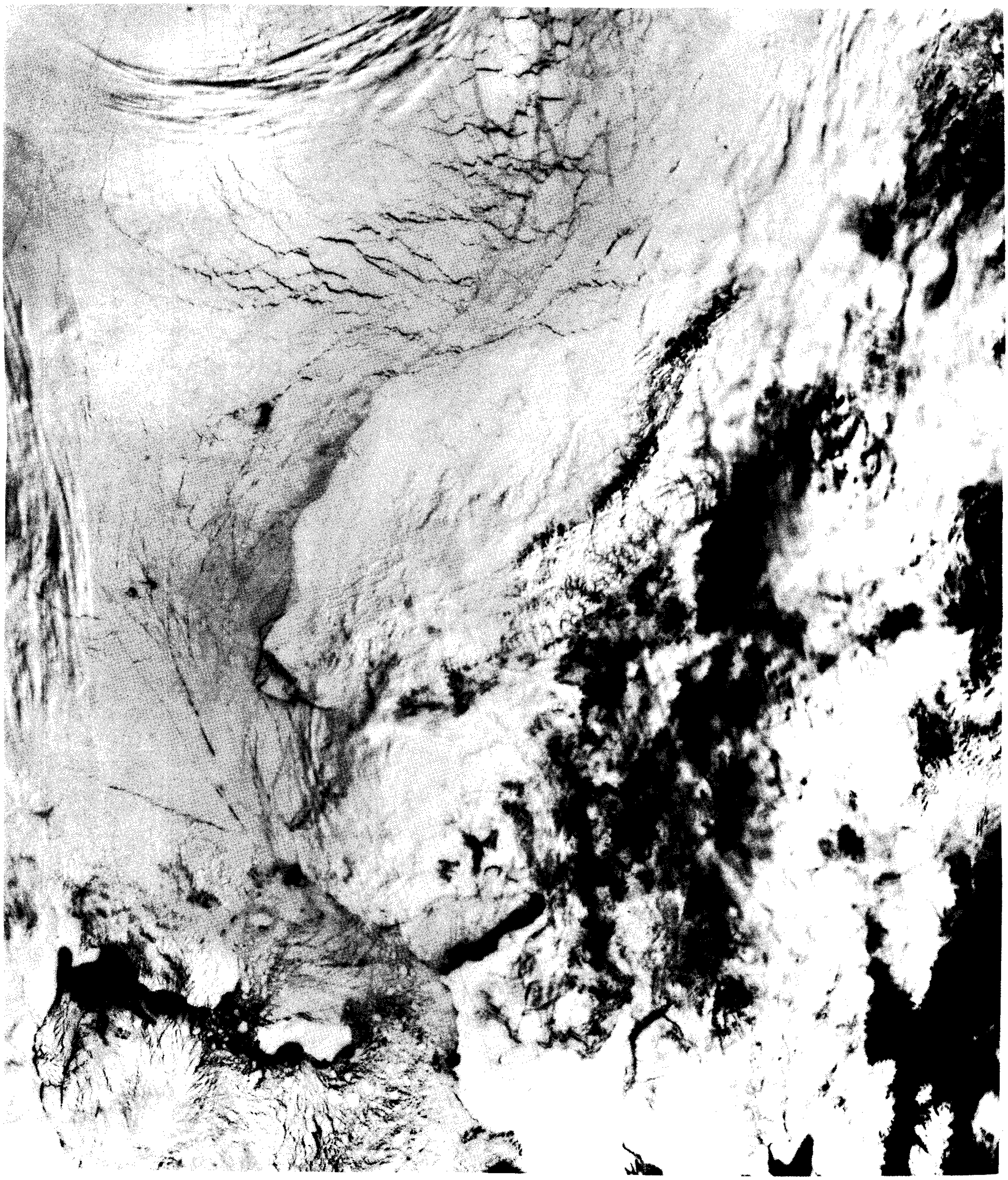

Figure 19. NOAA/VHRR visible band image acquired on 17 April 1975.

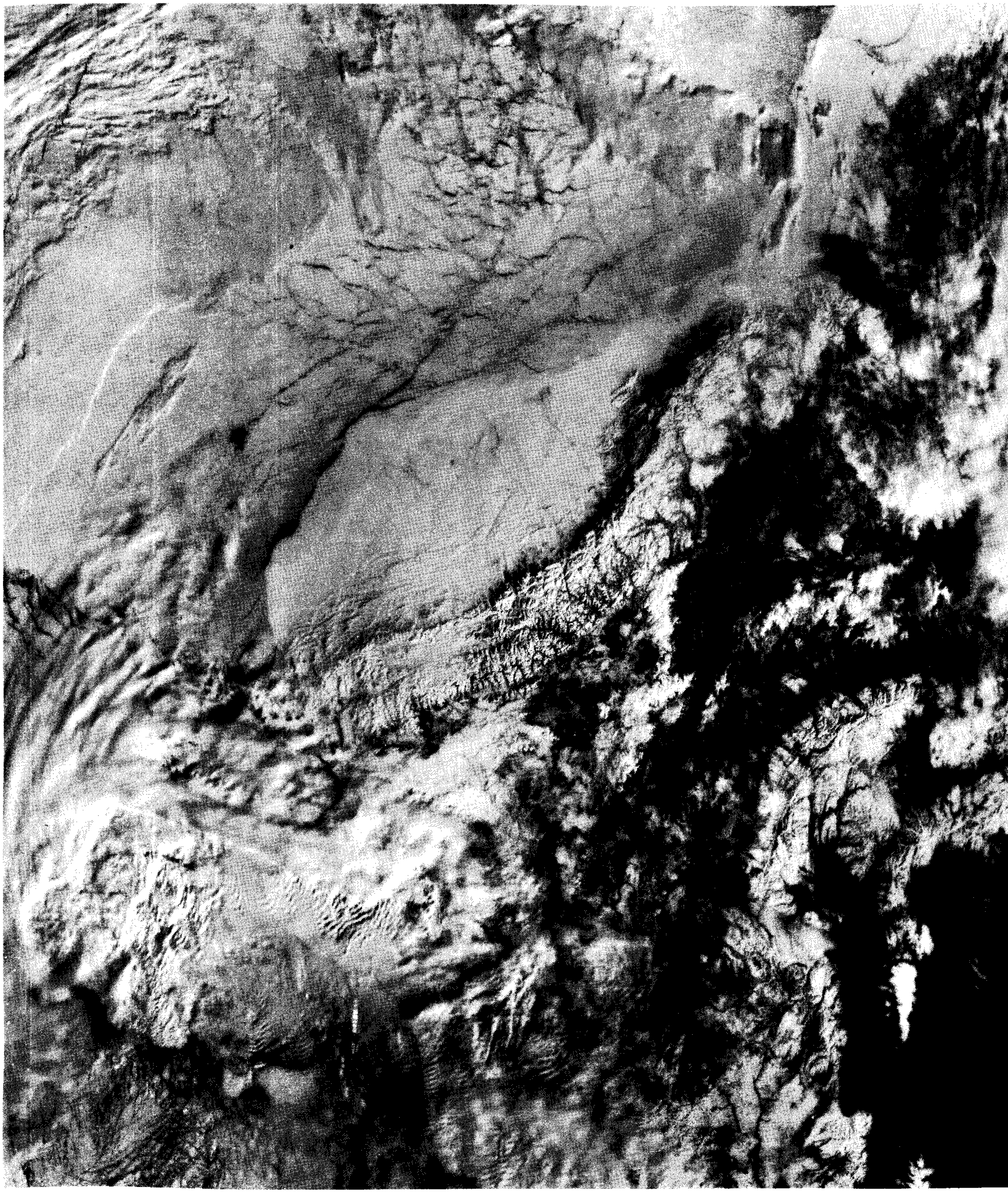

Figure 20. NOAA/VHRR visible band image acquired on 19 April 1975.

north of Cape Lisburne is again defined by a lead on its shoreward side, as it was in Figures 13 and 16. The coast between Point Hope and Cape Lisburne is open, while the ice is tight against the coast southeast of Point Hope.

The image from April 22 (Figure 21) shows continuation of the northerly movement in most areas. The ice has closed completely against the coast southeast of Point Hope, and an unusual pattern of broken ice has developed in the mouth of Kotzebue Sound. However, along the northern side of the Chukchi Peninsula, just west of Bering Strait, the ice again has closed against the coast, and a set of leads trends northwestward from the western side of the Strait. The ice off the northern side of the Seward Peninsula, the polynya on the northern side of the Diomede Islands, the curving leads, concave to the north in Bering Strait, and the ice against the coast in northern Gulf of Anadyr and Norton Sound all indicate that the ice is moving northward everywhere in the region, except along the northern coast of the Chukchi Peninsula.

The remaining images in the series for April 23, 26 and 30 (Figures 22, 23 and 24) show the transition back to the pattern dominated by southward movement under northerly winds. The first indications of this are the formation of a narrow lead along the coast southeast of Point Hope and movement of the ice off the southwestern coast of the Seward Peninsula, the southern sides of St. Lawrence and Nunivak Islands, and the south-facing coast of Kuskokwim Bay (Figure 22). On the image for April 26 (Figure 23), the ice in each of those areas has moved farther south; in Norton Sound, it has been driven against the southern shore. Southerly motion of the ice in the Gulf of Anadyr also is evident, and

Figure 21. NOAA/VHRR visible band image acquired on 22 April 1975.

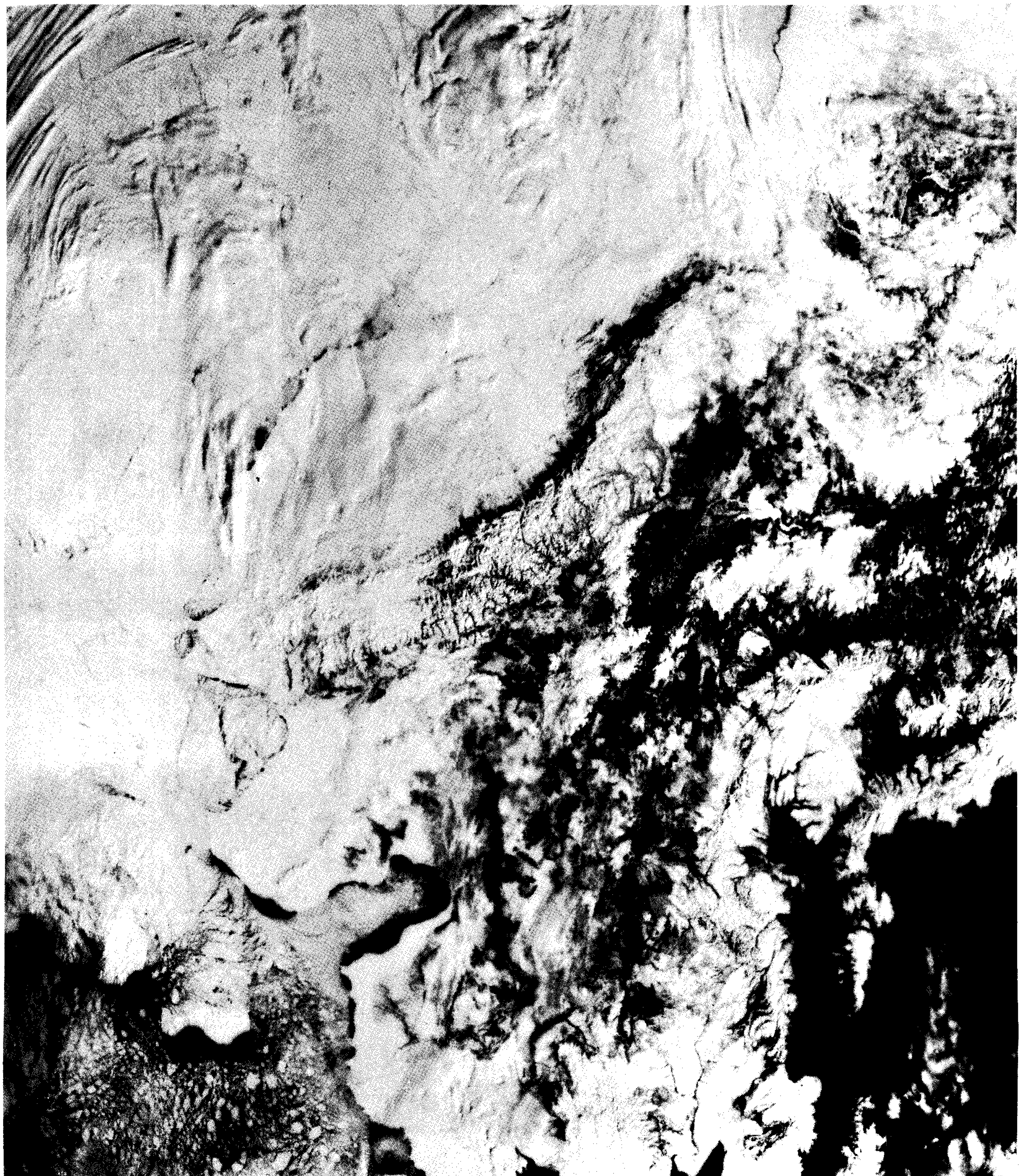

Figure 22. NOAA/VHRR visible band image acquired on 23 April 1975.

Figure 23. NOAA/VHRR visible band image acquired on 26 April 1975.

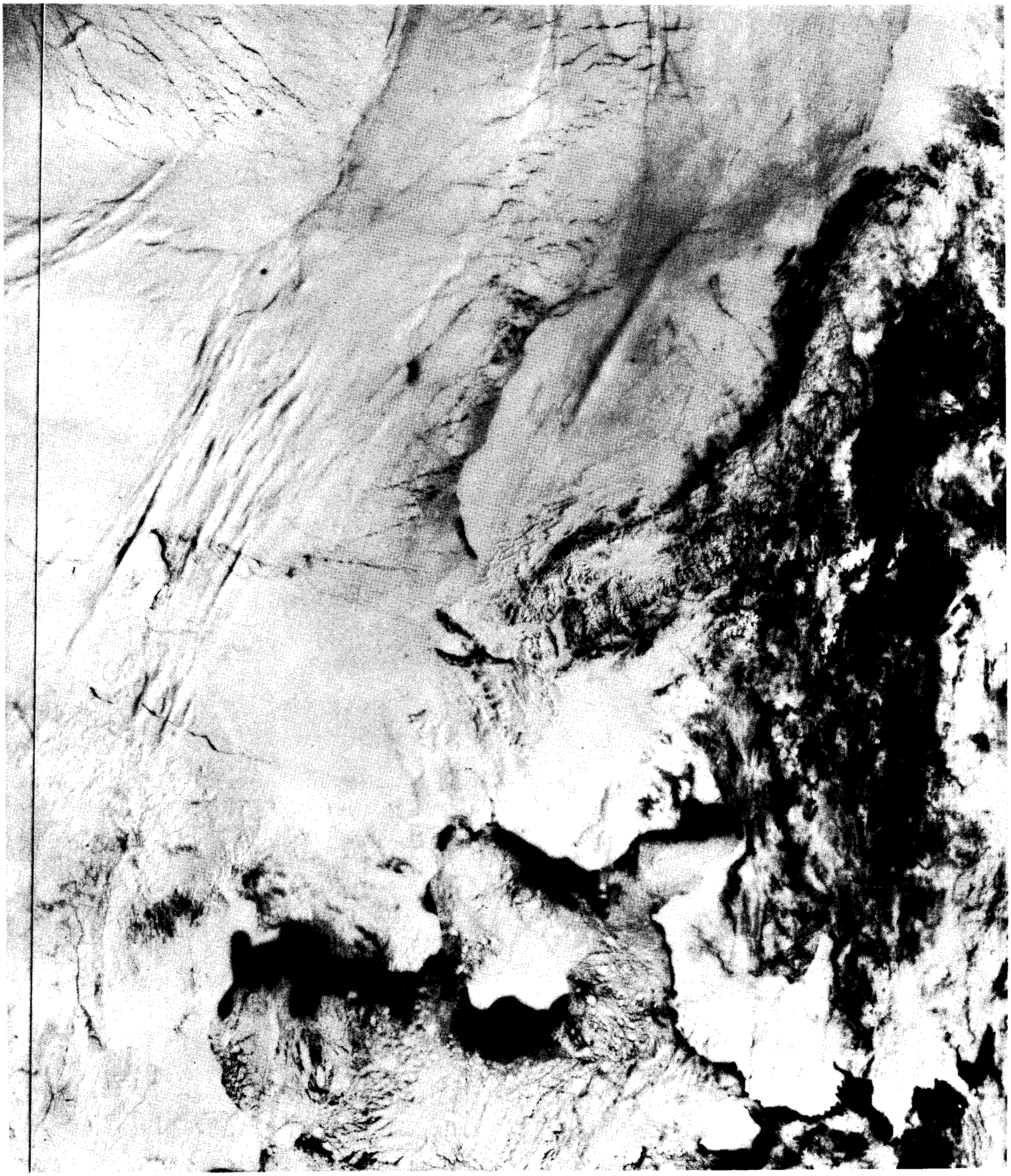

Figure 24. NOAA/VHRR visible band image acquired on 30 April 1975.

the ice again has converged against the northern side of St. Lawrence Island and diverged in the area west of the island. The polynya southeast of Point Hope is noticeably wider than in the last image. The inshore lead in the large ice mass in the bight northeast of Cape Lisburne is again closed and the polynya north of it has been reestablished. The ice along the remainder of the coast to Point Barrow is broken and clearly drifting southward, establishing a broad flaw zone.

Finally, in Figure 24, continued southerly movement is especially apparent in the enlargement of the polynyas south of the islands and peninsulas. The pattern of curving leads just north of Bering Strait also indicates initiation of a breakout of ice southward through the strait.

4. Discussion

The foregoing descriptions of each of the sub-areas indicate that there is consistent recurrence of specific ice conditions in relation to general weather conditions. The data also indicate monthly variations in the ice cover which seem consistent with monthly changes in weather. However, our monthly data sets are not yet large enough to permit saying with certainty the extent of similarity or consistency of ice patterns in different years, though a high degree is implied.

While the extent of ice cover is apparent from the NOAA imagery, many of the details of changes in the quality of ice with the seasons or between years may be indeterminate on the scale used in this study. For example, "continuous ice cover" may be a relatively smooth, continuous ice sheet or may represent floes driven together by the wind to form a compact ice mass within which leads or openings are abundant but too narrow to be detected by the imagery. With additional experience, it may be possible to identify these differences on the basis of gray tones and textures of the images, but we did not succeed in solving that problem in the present study. Hence, the patterns described probably include both.

The clear weather ice conditions for any sub-area can be identified without difficulty. Those for cloudy conditions have been determined with reasonable confidence, principally from the data obtained during transitions from cloudy to clear weather. Ice states during transitions from clear to cloudy weather usually were obscured and, in most cases, did not permit determination of the duration of the transitional state. This created some problems in interpretation of the ice cover in terms of its suitability as habitat for marine mammals. The known presence or absence of the mammals themselves, however, provided some guidance. That is, where the ice conditions in clear weather seemed suitable, but the animals were known to be absent, we assumed that some unsuitable conditions prevailed during the unobserved cloudy weather and/or clear-cloudy transitions. A larger number of observations of the transitional states would be needed to permit more objective evaluations.

In the 'typical' pattern for clear weather (in Figure 25), prominent lead systems are indicated and ice conditions are designated according to the classification system described earlier. Boundaries between areas of different ice conditions have been omitted, except where usually represented by leads.

The pattern indicates a shear lead extending northeastward into the Arctic Ocean from the vicinity of Point Barrow, with the ice tight along the Beaufort Sea coast and few leads in the nearshore zone. The flaw

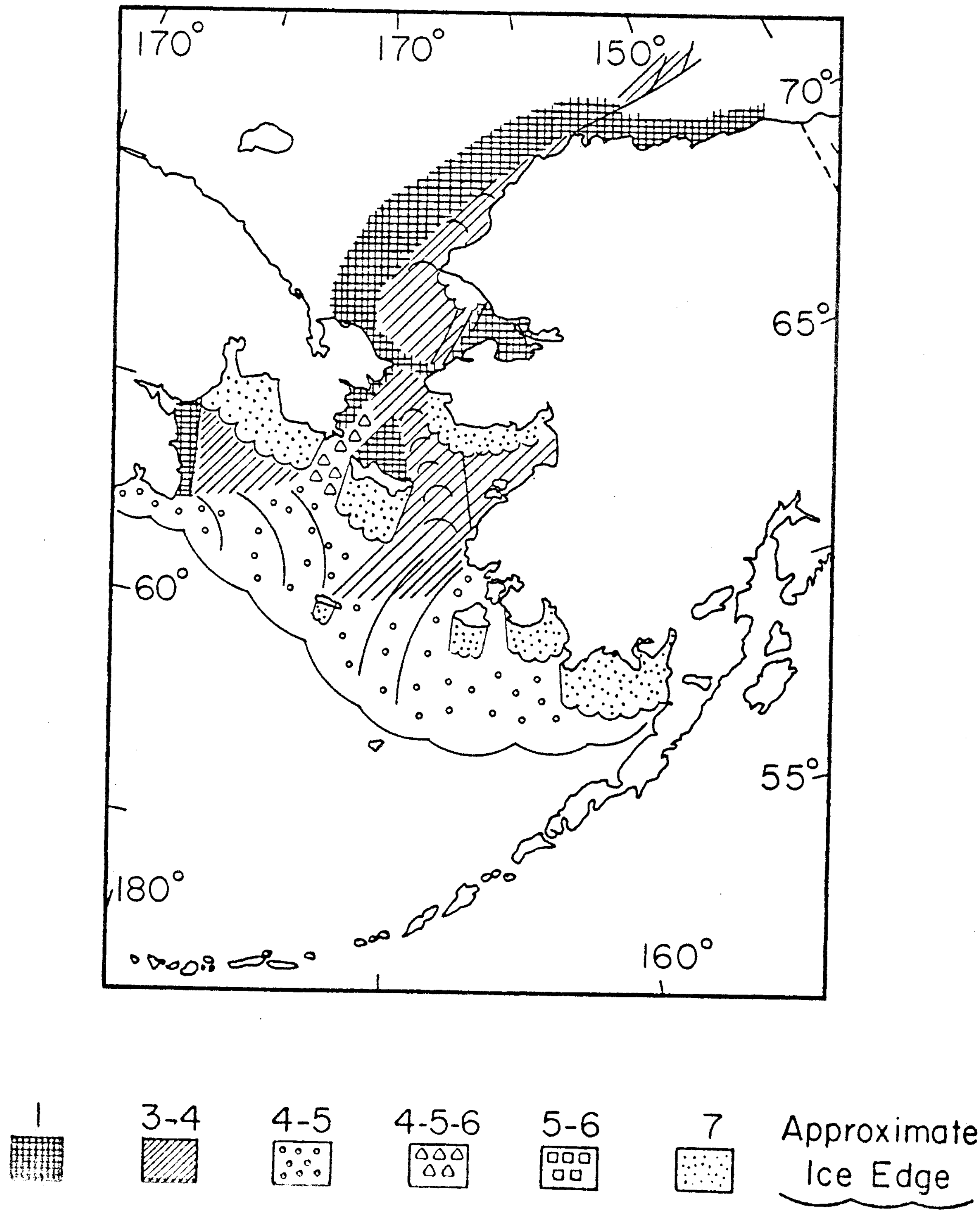

Figure 25. Ice conditions for a 'typical' clear weather pattern.

zone along the Chukchi Sea coast between Point Hope and Point Barrow is well-developed, as is the polynya along the coast southeast of Point Hope. Within the flaw zone the ice is classified as pack with leads or broken pack ice, and this condition extends almost to Bering Strait, where the ice converges to continuous ice cover. During a breakout of ice through the Strait, this would change to a higher numbered category as the ice moves out of the area. South of Bering Strait, the ice is again indicated as category 3 or 4 but could also be in a higher numbered category under sustained northerly winds. Polynyas are indicated along the south facing coasts throughout the Bering Sea, and the wedge of heavy ice north of St. Lawrence Island also is shown. Note the gradient in extent of the ice cover shown between St. Lawrence Island and Siberia.

The 'typical' pattern for cloudy weather (Figure 26) shows a flaw lead along both the Beaufort and Chukchi Sea coasts and generally heavy ice over most of the area north of Bering Strait. The ice cover has converged into the northern Bering Sea, and is generally continuous in the areas just south of Bering Strait. The wedge of ice north of St. Lawrence Island is shown as broken by generally east-west leads with the ice cover reduced, while east and west of the island there is little change in conditions. The polynya to the south of the island is closed, but the ice cover remains relatively dispersed. The only anomaly in this pattern occurred in the Gulf of Anadyr, where convergence of the ice against the coast may or may not be complete.

Comparison of Figures 25 and 26 shows areas of consistency in ice conditions. The ice generally remains dispersed or relatively open in the areas west and south of St. Lawrence Island, and probably elsewhere

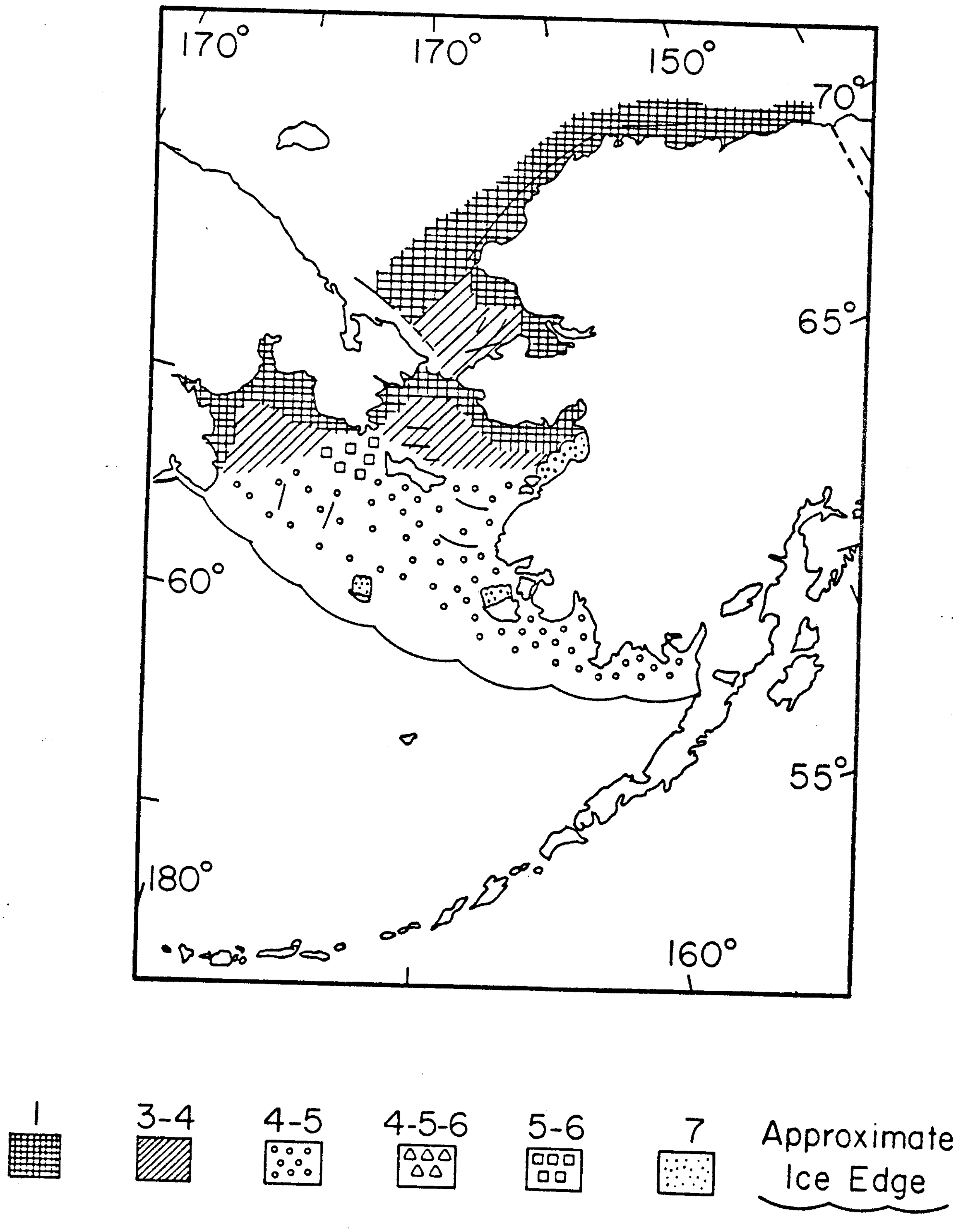

Figure 26. Ice conditions for a 'typical' cloudy weather pattern.

in the southern Bering Sea as well. Presumably, this is the reason why these areas are persistently occupied by walruses in winter, while other areas farther north are not, though they seem suitable in clear weather. To the north, the shifting of the ice maintains some lead systems which are used by bearded seals, but the ice cover is more extensive overall than in the Bering Sea. For that reason, these northern areas are mainly ringed seal and polar bear habitats.

IV. Fast Ice

A. Description and Distribution

Fast ice is sea ice which remains attached to the shore. In Alaska, the local vernacular for it is "shore ice". It begins to develop in autumn, increases in extent throughout the winter, and persists for some time into the spring-summer melting season.

Fast ice develops around all of the larger islands of central and northern Bering Sea, as well as along the mainland coast from Bristol Bay to the Beaufort Sea. In the warmer southern areas, it can be short-lived, occurring only during periods of extreme cold. In the Beaufort Sea it is a normal, persistent feature of the autumn to mid-summer ice cover. It varies in width from a few meters to tens of kilometers, depending on both latitude (temperature) and configuration of the coastline (Stringer 1978).

The most extensive fast ice occurs where the developing ice cover is protected by some physiographic feature from strong winds, currents, and the moving pack. These same forces drive thick ice into shallow water, where it becomes grounded and serves to protect and stabilize the thinner, floating fast ice inshore. Protected embayments such as Norton Bay, Port Clarence, Grantly Harbor and Kotzebue Sound are examples of areas in which a continuous, flat cover of fast ice develops and persists throughout the winter. Much of the northern coastline, facing the Beaufort Sea, has extensive fast ice, often bounded by and interspersed with grounded ridges or floes (Figure 27).

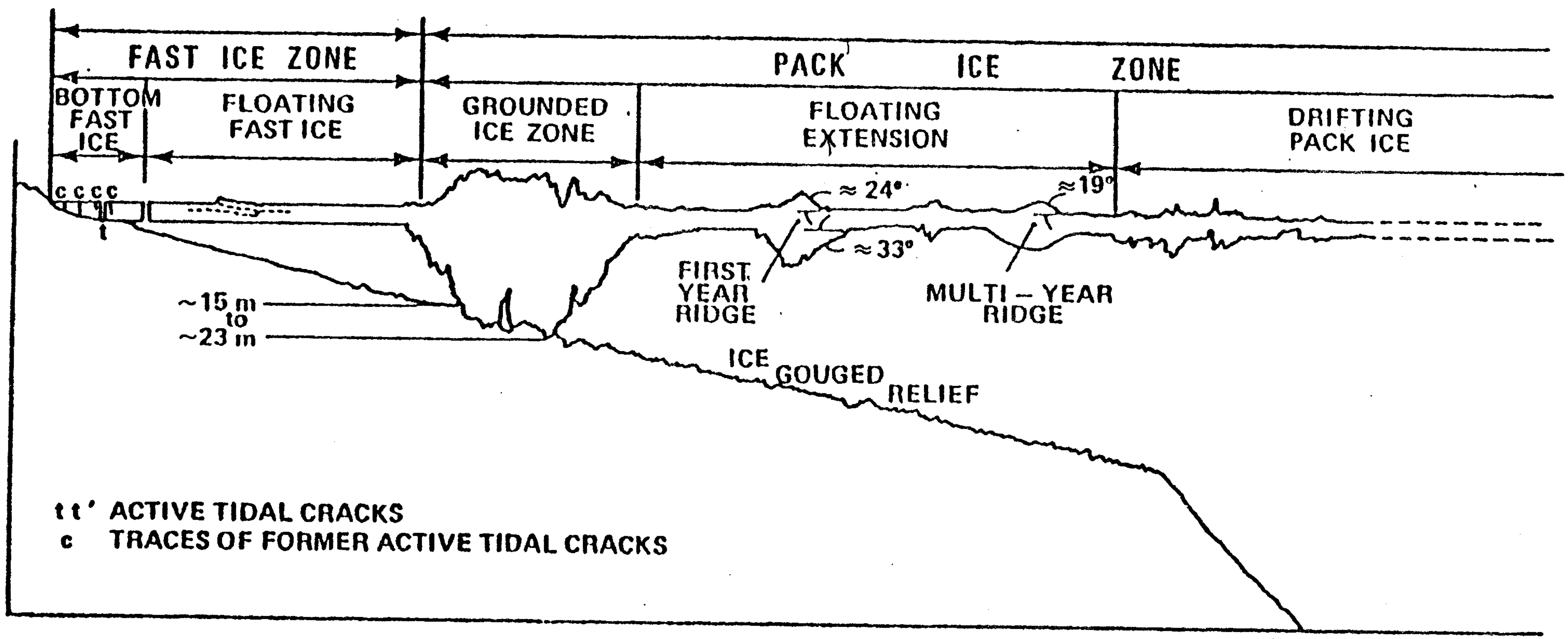

Figure 27. Schematic illustration of fast ice features (modified from Kovacs, unpublished)

Although the extent and structure of fast ice varies annually, this variability is within rather narrow limits for each region. The configuration of embayments is fixed, the direction of seasonally prevailing winds is, by definition, repetitive, and heavy ice floes tend to become grounded in specific locations and water depths. Thus, the extent of fast ice, as well as the configuration of its seaward boundary, tend to be similar from year to year (Figures 28 and 29). The appearance of the seaward margin of fast ice in the Chukchi Sea in June is shown in Figure 30.

B. Use of Fast Ice by Mammals

Since fast ice is a feature of the nearshore zone, it is utilized mainly by those marine mammals which usually occur near shore. These include harbor seals in Bristol Bay, spotted seals in the Bering and Chukchi Seas, and ringed seals in all areas where they occur. The use of fast ice by harbor seals is opportunistic; that is, they are not dependent on its presence but utilize it when it occurs in their area. Fast ice develops irregularly in Bristol Bay and around the Pribilof Islands where these seals haul out. They utilize it when they are prevented by its presence from hauling out on land. Since they do not ordinarily make holes in ice, they inhabit its margin or the irregular openings in its thinner parts. Since, it is inconsistently present within the range of these seals in winter, and since basking is minimal in that season, fast ice is not heavily utilized by harbor seals as a haul-out habitat.

Spotted seals in the Bering and Chukchi Seas utilize fast ice when it first forms in autumn and during late spring-early summer, when it is deteriorating. In winter and early spring they inhabit the moving pack,

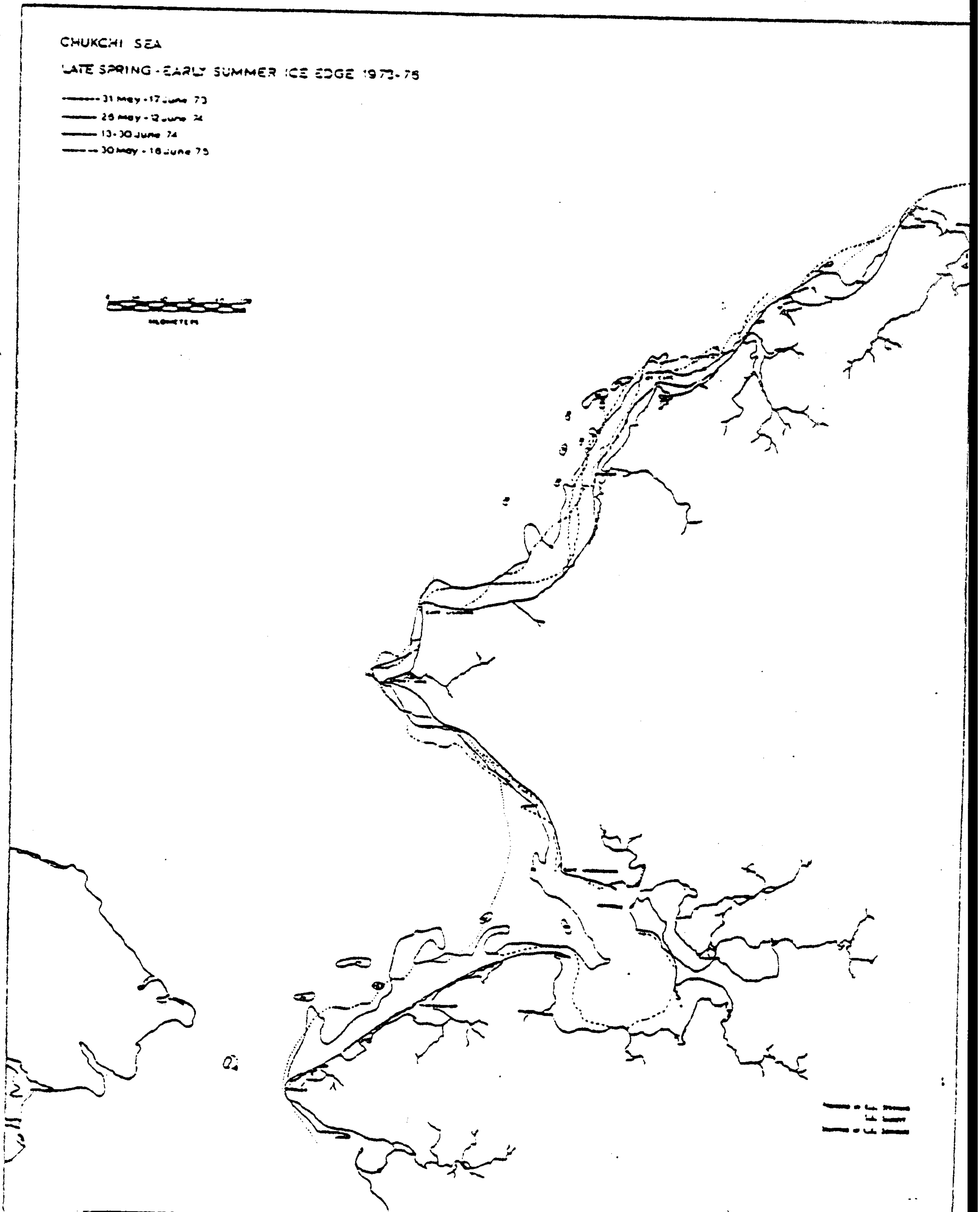

Figure 28. Seaward extent of fast ice along the Chukchi Sea coast (from Stringer, 1978).

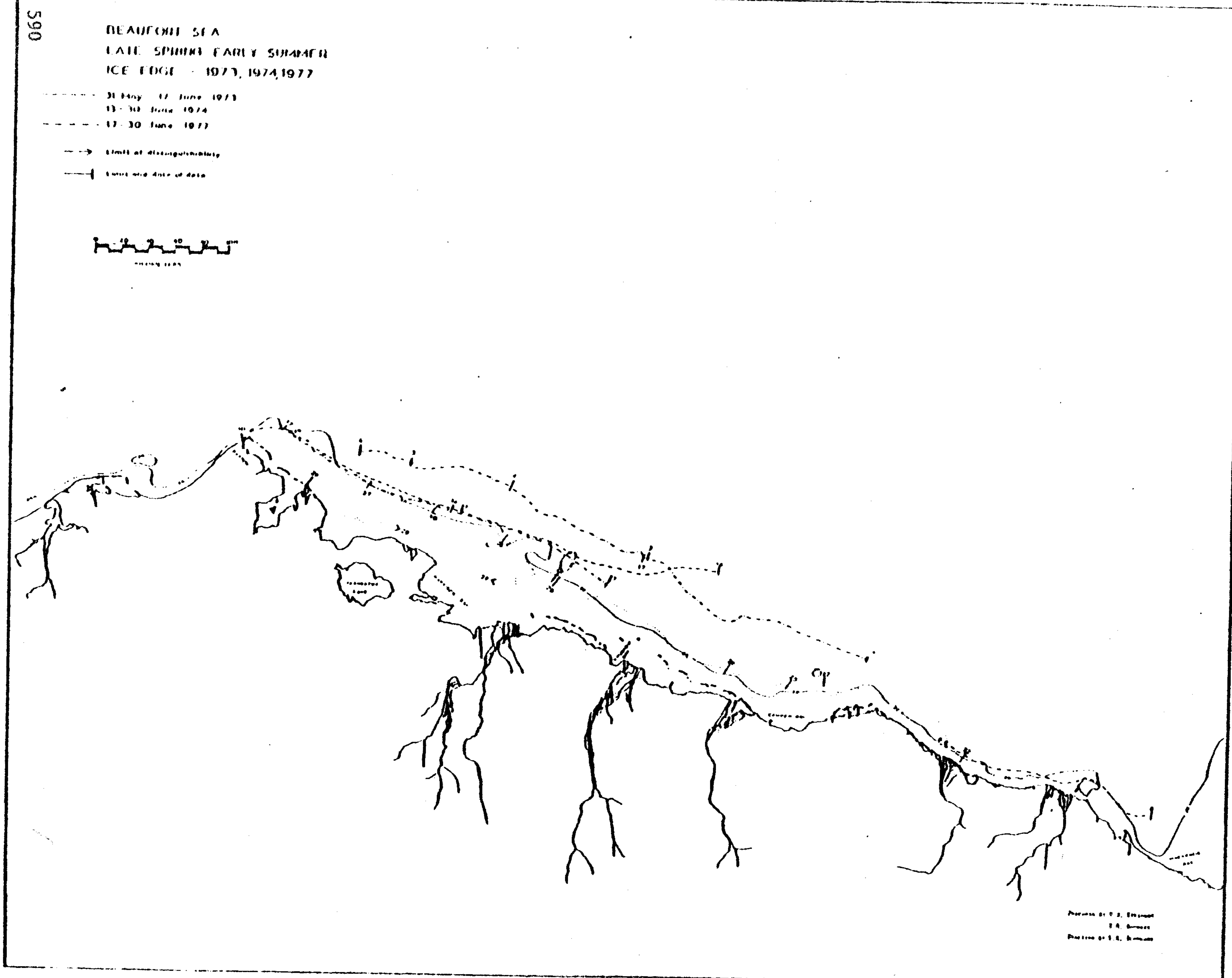

Figure 29. Seaward extent of fast ice along the Beaufort Sea coast (from Stringer, 1978).

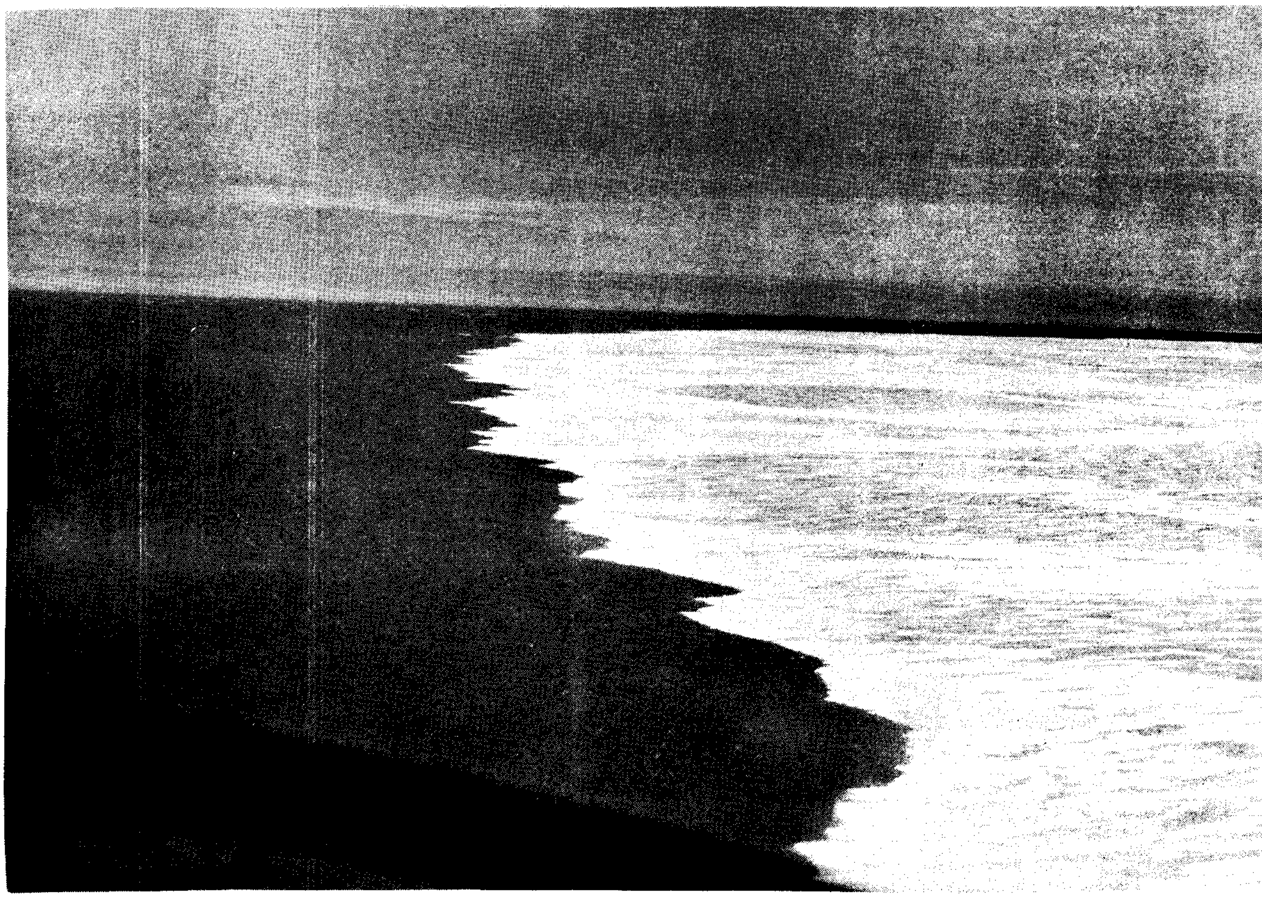

Figure 30. Low-altitude aerial view of the seaward margin of fast ice near Icy Cape, Alaska, 6 June 1978.

mainly the ice front (Burns, 1970, Fay, 1974, Braham et al. in prep.); in summer they use the ice-free coastal zone (Burns 1970). Their use of newly developing fast ice in autumn is during their southward migration. They haul out on it then in small numbers, apparently to rest, and only in periods of relative calm. The decaying fast ice in late spring-early summer is used much more intensively. In parts of the Yukon-Kuskokwim Delta region and in Norton Sound, hundreds of these seals can be seen in rather dense concentrations along that ice, (Regnart, personal communication, Burns, personal observation). It is of special importance there because of its juxtaposition with herring and capelin schools, which approach the coast prior to and during spawning. The seals feed intensively on those fishes and use the ice for basking during the final stages of their molt. Their incursions into the fast ice at that time are facilitated by its disintegration, which creates numerous openings and passages. As the fast ice disappears, spotted seals move inshore to traditional haul-out areas.

Ringed seals show the greatest dependency on, and the most prolonged use of fast ice (McLaren 1958). They are the most abundant and widely distributed seals associated with sea ice and are the best adapted for occupying regions of extensive, thick, stable ice. Their breathing and exit holes have been found in ice exceeding 2.3 m thick in the Beaufort Sea (Burns, personal observation). These seals occur in association with fast ice of the Bering, Chukchi and Beaufort Seas for as long as it persists. They make and maintain breathing holes in it throughout the winter and excavate subnivian lairs, in which they rest, give birth and nurse their pups (McLaren 1978, Smith 1976, Smith and Stirling 1975). During the molt in May through July, they bask on the fast ice.

Although ringed seals occur throughout the sea ice zone they usually occur in highest densities in the fast ice itself. This is especially true of mature adult seals and newborn pups. The ringed seal is the only seal in the northern hemisphere which regularly inhabits fast ice during the period when it is most extensive and thick. The pups are born there from late March through April (mainly early April) in prepared snow lairs or cavities and in pressure ridges (McLaren, 1958; Burns, 1970; Smith and Stirling, 1975). Stability of the ice in which these birth chambers are made is considered to be a prerequisite for survival of pups to the age of independence at 4 to 6 weeks (McLaren 1958).

Ringed seals comprised more than 99 percent of the marine mammals seen during aerial surveys over the fast ice of the Beaufort and Chukchi Seas in June 1970, 1975, 1976 and 1977 (Burns and Eley 1978). The density of these seals ranged from a low of 0.4 seals/nm^2 between Flaxman and Barter Islands in 1976 to a high of 6.2 seals/nm^2 between Wainwright and Barrow in 1975 (Table 4). Conversely the density of basking ringed seals in the pack ice in 1976 was 0.2 and 0.1 per nm^2 in the Chukchi and Beaufort Seas, respectively (Burns and Eley 1978). The area of the pack is huge, and although the density of seals there is very low, their numbers there are many times greater than in the fast ice. However, because the fast ice is important as a habitat for breeding, its use by ringed seals probably is essential for maintenance of the population.

The fast ice is utilized also by polar bears, arctic foxes, and man mainly as a relatively stable extension of land. Polar bears use the ice in transit between the pack and the shore. They cross it when they come ashore for denning or scavenging; females leaving shore with very

Table 4. Densities of ringed seals seen on the fast ice of the eastern Chukchi and western Beaufort Seas, based on aerial surveys in June 1970, 1975, 1976 and 1977. The values are the average number of seals per nm^2 in each sector (Barnes and Eley, 1978).

Sector of Coastline	1970	1975	1976	1977
Kotzebue Sound	-	-	0.7	-
Cape Krusenstern-Point Hope	-	-	2.3	-
Point Hope-Cape Lisburne	-	-	0.9	-
Cape Lisburne-Point Lay	-	-	4.9	-
Point Lay-Wainwright	5.4	2.9	1.9	3.3
Wainwright-Barrow	3.7	6.2	3.8	2.6
Barrow-Lonely	2.3	2.8	1.4	1.0
Lonely-Oliktok	1.0	1.4	1.1	0.5
Oliktok-Flaxman Island	1.4	1.0	1.4	0.7
Flaxman Island-Barter Island	2.4	1.8	0.4	1.2

young cubs frequently spend several days on the fast ice, on which they may excavate one or more temporary shelters (Lentfer, 1972; Burns, personal observation). On the extensive fast ice of the Beaufort Sea, some bears may den and give birth to their cubs (J. Lentfer, pers.comm.). In winter, polar bears are most numerous at the flaw between the moving pack and the fast ice (Lentfer 1972). This is where their main prey (ringed and bearded seals) are most accessible in the Chukchi and Beaufort Seas.

The arctic fox is the most abundant quadruped in the fast ice zone. These foxes prey on newborn ringed seals during the period when the latter are confined to their subnivian lairs in the fast ice (Smith 1976). The fast ice zone is an important part of the total habitat of Arctic foxes in northern regions, although the extent of dependence of this zone is presently unknown.

Human activity on the fast ice probably has always had an effect on certain marine mammals and fishes, if only because it made them more accessible to harvesters. Formerly, Eskimos netted ringed seals under this ice and hunted them at the flaw between the fast ice and the moving pack. Recent findings (Burns and Eley 1978) indicate that the presence of men and machinery on the fast ice has resulted in displacement of ringed seals. Aerial surveys of ringed seals in June 1976 showed that the density of seals basking on the fast ice was significantly lower in the vicinity of Eskimo villages than it was farther away (Figure 31). Similarly, in fast ice of the Beaufort Sea, the densities of basking ringed seals and of observed ringed seal holes in the ice differed between areas in which seismic exploration was conducted (disturbed areas) and those in which it was not conducted (control areas), as shown

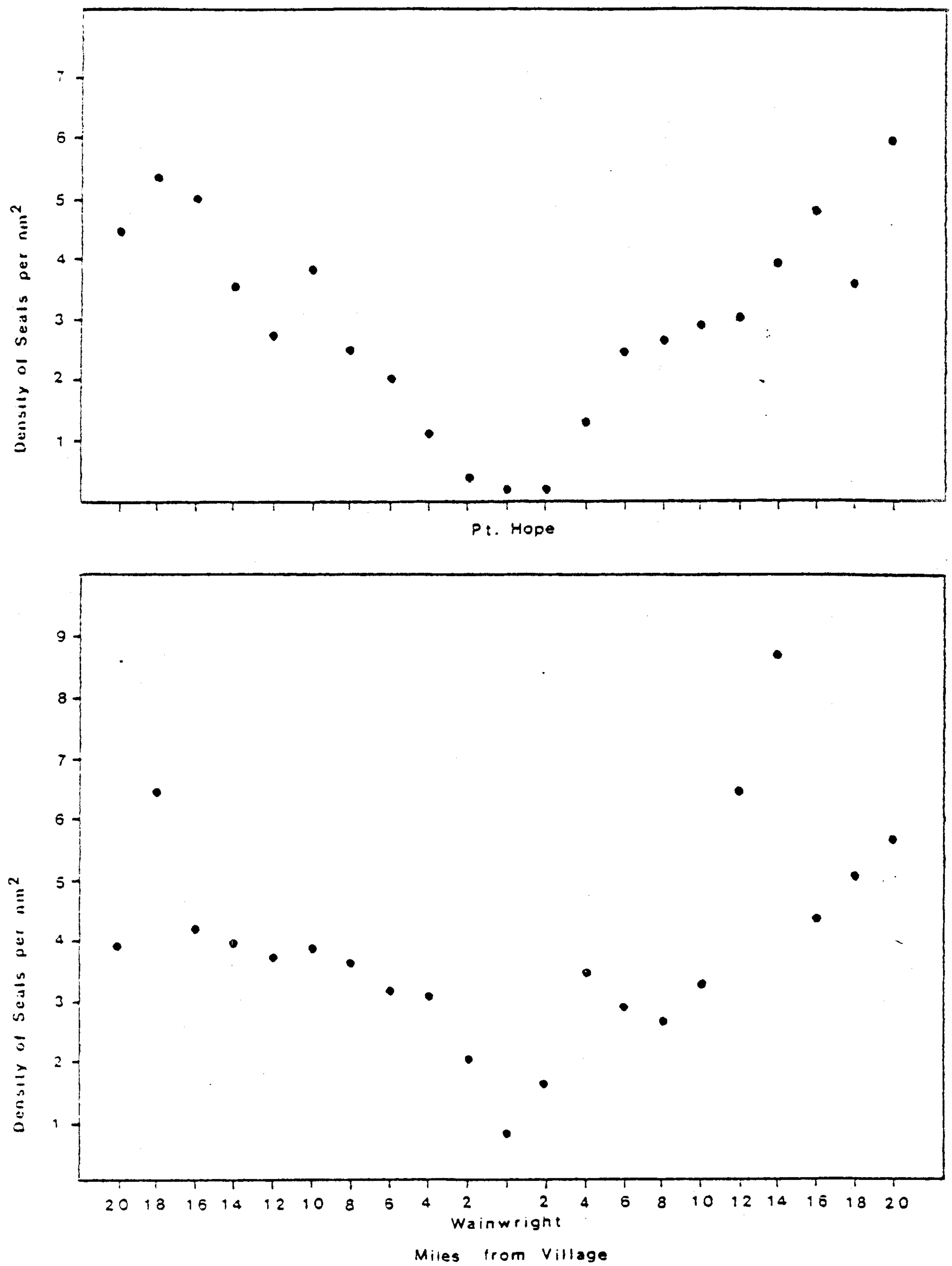

Figure 31. Densities of ringed seals on fast ice in relation to distance from two Alaskan villages as determined by aerial surveys (Burns and Eley, 1978).

in Table 5. Application of the Kruskal-Wallis H Test (Zar 1974) to these data indicates that the differences were highly significant (P > 0.025). Since in these cases removal of seals did not occur, the differences in density are presumed to be the result of displacement by disturbance alone. Disturbance from seismic exploration activities occurred between January and 2 March. Aerial surveys were conducted between June 10 and 18.

C. Characterization of Ringed Seal Habitat in Fast Ice by Side-Looking Airborne Radar (SLAR)

1. Objectives and Methods

The objective of this phase of the study was to test the hypothesis that the distribution of ringed seals on the fast ice is correlated with the surface topography of the ice. We felt that SLAR imagery would provide a more objective representation of the relative roughness of the ice than could be obtained by visual judgement. To test this, we overlaid maps of ringed seal distribution, as determined by aerial survey, on the appropriate SLAR images and compared seal numbers with SLAR film density. In the SLAR negatives, areas of high film density corresponded to rough ice and areas of low film density to smooth ice. All of the images and seal distributional data were acquired during May-June, 1976.

The flight paths of ringed seal surveys were plotted on mylar overlays, at a scale of 1:500,000. Flight paths were divided into minutes of flight time and the numbers of ringed seals observed per minute were registered on the overlay. The survey observers' estimate of percent deformity (roughness) of the ice were added to the overlay for the appropriate minutes.

Table 5. Comparative densities of basking ringed seals within and outside of seismic exploration areas on fast ice of the Beaufort Sea[1].

	Survey Sectors					
	Lonely-Oliktok		Oliktok-Flaxman Is.		Total	
	Exploration Area	Control Area	Exploration Area	Control Area	Exploration Area	Control Area
1975						
No. aerial survey miles	51	119	115	162	166	287
No. seals sighted	18	117	61	189	79	306
Seal density/nm^2	0.35	0.98	0.44	1.13	0.48	1.07
1976						
No. observed survey miles	96	43	30	60	126	103
No. seals sighted	81	89	31	77	112	166
Seal density/nm^2	0.84	2.07	1.15	1.30	0.89	1.61
1977						
No. aerial survey miles	17	27	37	15	54	42
No. seals sighted	7	17	18	34	25	51
Seal density/nm^2	0.41	0.60	0.50	2.30	0.46	1.21
1975-1977						
No. aerial survey miles	164	189	182	237	346	432
No. seals sighted	106	223	110	300	216	523
Seal density/nm^2	0.64	1.18	0.60	1.27	0.62	1.21

[1] From summary of survey data analyzed by K. Frost, Alaska Department of Fish and Game.

The mylar overlays were placed over the corresponding SLAR negatives at the same scale and visually examined for relationships between seal numbers, estimates of ice deformity and image density. Actual image densities were measured for each minute of the survey flight path with a MacBeth "Quanta Log" Densitometer having an aperature setting of 1.0 mm. Densitometer readings were taken through approximately 2.0 mm circles drawn on the mylar overlay and corresponding to each minute of observation during the seal surveys.

Tests for correlation between image densities and ringed seal survey data were as follows:

a. SLAR images acquired 11-13 May 1976 and covering the landfast ice from Point Barrow to Kokruagarok (70°55'N, 153°05'W), Alaska;

(1) Image density for each minute of flight path, by number of ringed seals observed during survey flight on 6/15/76.

(2) Image densities for each minute in which one or more seals were observed, by number of ringed seals (6/15/76).

(3) Image densities for each minute in which less than 5 seals were observed, by number of ringed seals (6/15/76).

(4) Image densities for each of 38 minutes randomly chosen from the 56 original observations of one or more seals, by number of ringed seals (6/15/76).

b. SLAR images acquired 11-13 May 1976 and covering the landfast ice from Kokruagarok to Flaxman Island, Alaska;

(1) Image densities for each observation of one or more seals, by number of ringed seals (6/15/76).

(2) Image densities for each observation of less than 5 seals, by number of ringed seals (6/15/76).

(3) Image densities, by 27 observations of estimates of percent deformity of the ice.

The results of the analysis are presented in Table 6.

With one exception the correlations were weak for dispersed seals (< 5/min) and non-dispersed seals (>5/min) as these categories were defined by Burns and Harbo (1972). In the Point Barrow to Kokruagarok section (SLAR #4, Table 6), dispersed seal numbers showed a moderately strong correlation with image density (correlation coefficient = 0.98469). A larger sample of dispersed seals in the Kokruagarok to Flaxman Island section (SLAR #3, Table) showed essentially no correlation with image density (correlation coefficient = 0.01909).

Figure 32 and 33 show the number of observation points within the specified SLAR image density range when no seals, 1 to 4 seals, or 5 or more seals were seen.

The correlation coefficient for SLAR image density and the seal observers' estimates of percent deformity of the ice was 0.02390 with 95 percent confidence limits of -0.3595 and +0.4004 (i.e. a poor correlation).

2. Evaluation

The single strong correlation observed between dispersed seals and SLAR image density (Point Barrow to Kokruagarok) may be a function of the relatively small sample size (38 microdensity readings of points where seals were present). A similar random sample of 38 dispersed and non-dispersed seals showed a weak correlation with image density. Data from the Kokruagarok to Flaxman Island section, on the other hand, gave

Table 6. Results of correlation between the density of ringed seals and surface relief of fast ice as determined from side-looking airborne radar (SLAR). These data are from May-June 1976.

Identification No. of SLAR Image	Image Density in relation to	Number of Micro-Density determinations	Image Density		Number of Seals		Product Moment correlation coeff.	95 percent confidence limits	
			Mean	Std. Dev.	Mean	Std. Dev.		L1	L2
3	each observation of one or more seals	105	1.24	4.06	4.06	5.28	0.22145	0.0311	0.3963
3	each observation of less than 5 seals	78	1.22	2.06	2.06	1.32	0.01909	-0.2044	0.2406
4	each minute of survey flight	114	1.12	0.96	2.31	4.23	0.41598	0.2626	0.5656
4	each observation of one or more seals	56	1.30	1.30	4.70	5.03	0.40857	0.1631	0.6064
4	each observation of less than 5 seals	38	1.44	1.55	2.71	3.08	0.89469	0.8053	0.9443
4	38 mins. randomly chosen from 56 in which 1 or more seals were seen	38	1.45	1.55	4.82	5.59	0.44598	0.1472	0.6702

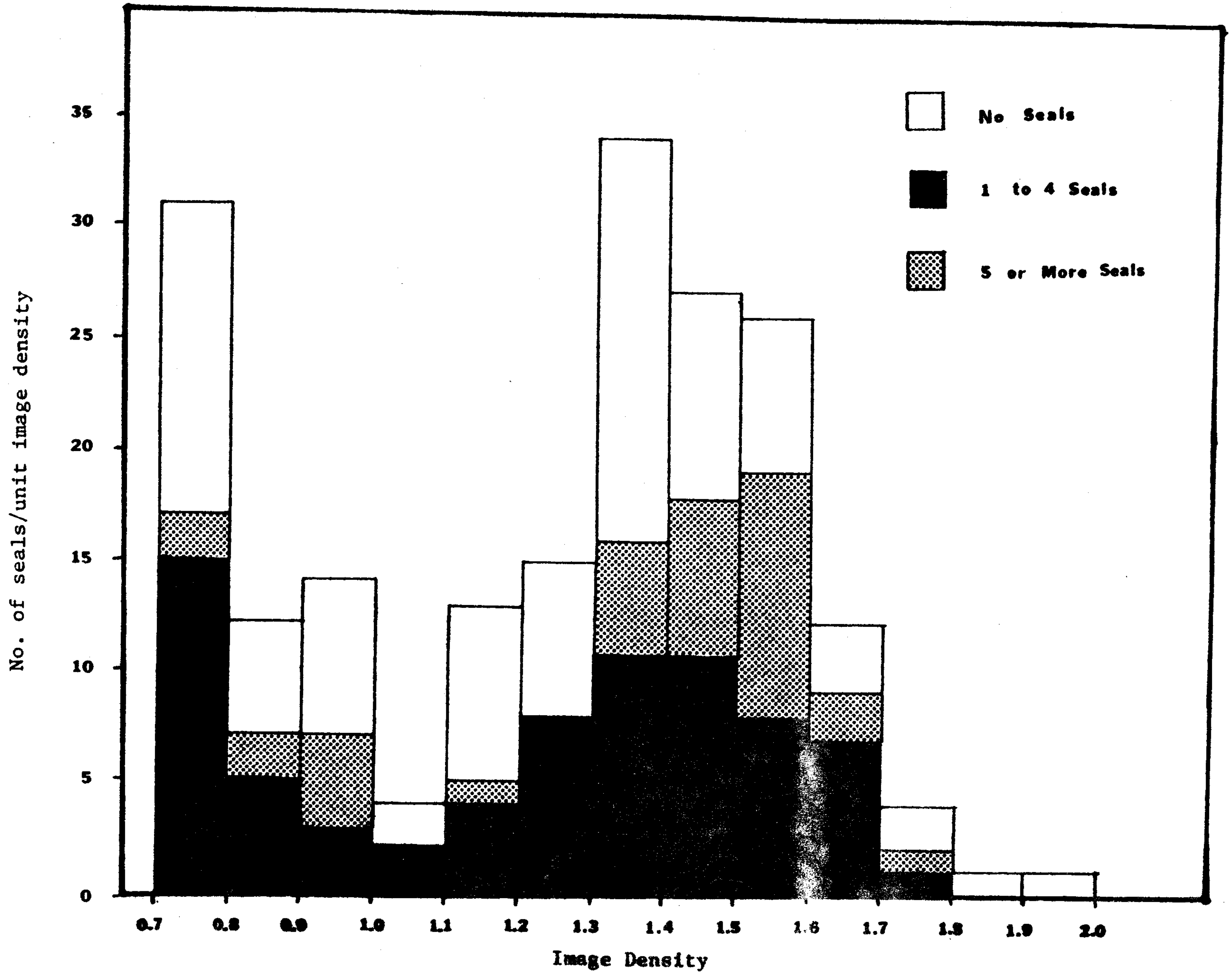

Figure 32. **Number of sightings of ringed seals in relation to the film density of images obtained by SLAR. Data from the fast ice in the area between Point Barrow and Kokruagarok, obtained May-June 1976.**

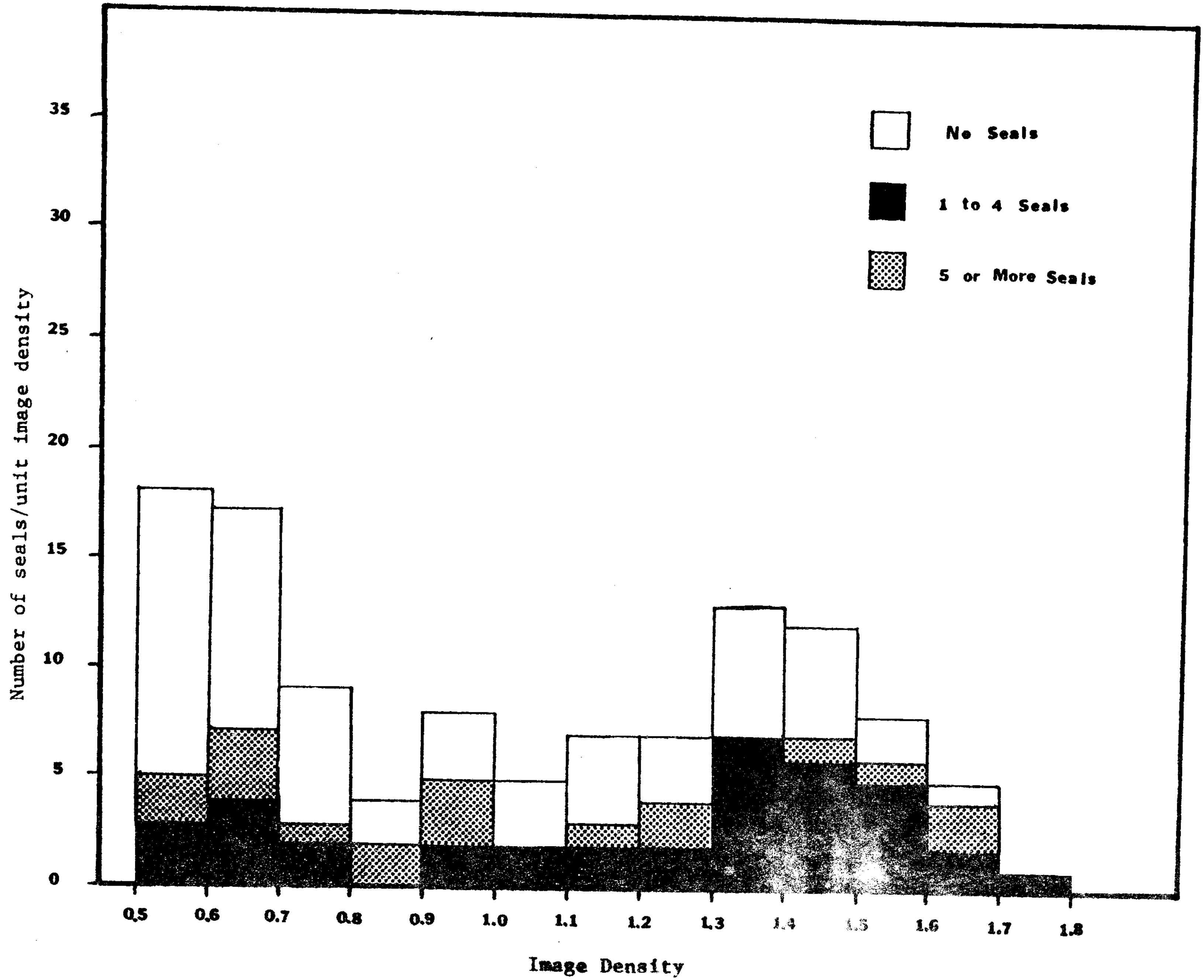

Figure 33. Number of sightings if ringed seals in relation to the film density of images obtained by SLAR. Data from the fast ice in the area between Kokruagarok and Flaxman Island obtained May-June, [illegible].

a correlation coefficient of only 0.01909 (n=78). All of the coefficients were positive suggesting that seal sightings increased with increasing ice roughness, which was contrary to field observations. Whether the difference between the correlation coefficients for the Point Barrow to Kokruagarok section and the Kokruagarok to Flaxman Island section represents an actual difference in ice types utilized in the two areas, or is merely a function of small sample size, remains in question.

We have low confidence in the findings because of several problems which, in retrospect, should have been addressed before SLAR imagery was used for characterizing ringed seal habitat. First, only two of the SLAR images had adequate temporal and spatial overlap with the seal surveys. Second, the SLAR images did not show enough of the shoreline features to allow accurate matching and scaling with the seal surveys. Third the quality of SLAR film itself was found to be variable in density. Density of the film base of images used was found to vary by up to 0.06 density units, introducing a possible 4.9 percent error rate into the measure of ice roughness. Hence, each film had to be analyzed separately, even when one was a continuation of another. Fourth, there was some distortion in the SLAR images. Fifth, there were errors inherent in the navigational system utilized during seal survey flights. Although SLAR internally adjusts for distance distortion created by its oblique angle to the terrain, some distortion was still detected. This introduced a small error with respect to locating seal positions on SLAR images. This was further compounded by aircraft navigational errors in the seal surveys. Because a relatively small shift in position can result in large differences in image density, SLAR image distortion and survey navigational errors could have obscured any actual relationships between seal numbers and image density.

The survey observers' estimates of percent deformity of the ice did not match well with the SLAR method of measuring deformity. This may have been due to the positional errors discussed above or to different levels of discrimination by the observers and the radar. Since SLAR utilizes wave lengths of approximately 3.5 cm, it "sees" texture on a finer scale than is apparent visually from the moving aircraft. A large but rounded piece of ice could return considerably less energy to the SLAR receiver than a field of small pieces having sharp angles. As a result, the larger piece would register as a lower density on the film, whereas an observer probably would register quite the opposite. Extensive snow cover, which appears flat to an observer, often overlies fields of ice with low profile roughness. Based on the capability of SLAR to discern refrozen tide cracks beneath the snow cover, we assume that it also would detect such fields and show them as rough rather than smooth surfaces. In that case, records of the survey observer and data from the SLAR would not be in agreement.

Unfortunately, little is known about the comparability of visual and SLAR registers of topography of ice or other terrain. Our results suggest that man and SLAR do not "see" ice in the same way. A similar experiment should be repeated with better controls to overcome the five problems we encountered. Such an experiment should include surface level verification of SLAR imagery and survey observer records as well as greater use of low altitude photographs.

V. Fringe and Front Zones

A. Fringe

1. Description

The ice fringe is defined here as the irregular southern margin of the main pack ice. Terms such as ice "edge" or "terminus" are less appropriate, as they imply a discrete, regular boundary, instead of the numerous wind-rafted tongues of broken, melting ice. When viewed from high altitude, these resemble a fringe (Figure 34).

In winter to early spring, the fringe of the Bering Sea pack ice usually extends from Bristol Bay to the vicinity of Cape Navarin, thence southwestward along the Siberian shore to Karaginski Bay. Since general movement of the pack is from north to south, as a result mainly of prevailing winds (Muench and Ahlnas 1976), the open ocean south of the fringe allows unimpeded drift and divergence of ice. The ice tongues of the fringe extend southward away from the main pack during periods of northerly winds (Figure 35). The area occupied by the fringe varies depending on the velocity and duration of northerly winds.

The fast-moving fringe is compacted against the slower moving pack during episodes of southerly winds. At that time, the fringe more closely approximates a definite ice "edge." Satellite images of the compacted fringe were not available because of the extensive cloud cover associated with southerly winds in the study area. Ice of the fringe probably is melting continuously, because of its contact with the warmer waters of the southern Bering Sea. Swells and chop tend to break it up into small pieces.

The general southerly drift of the pack maintains a continuous supply of ice to the winter fringe. In "average" years, the fringe west

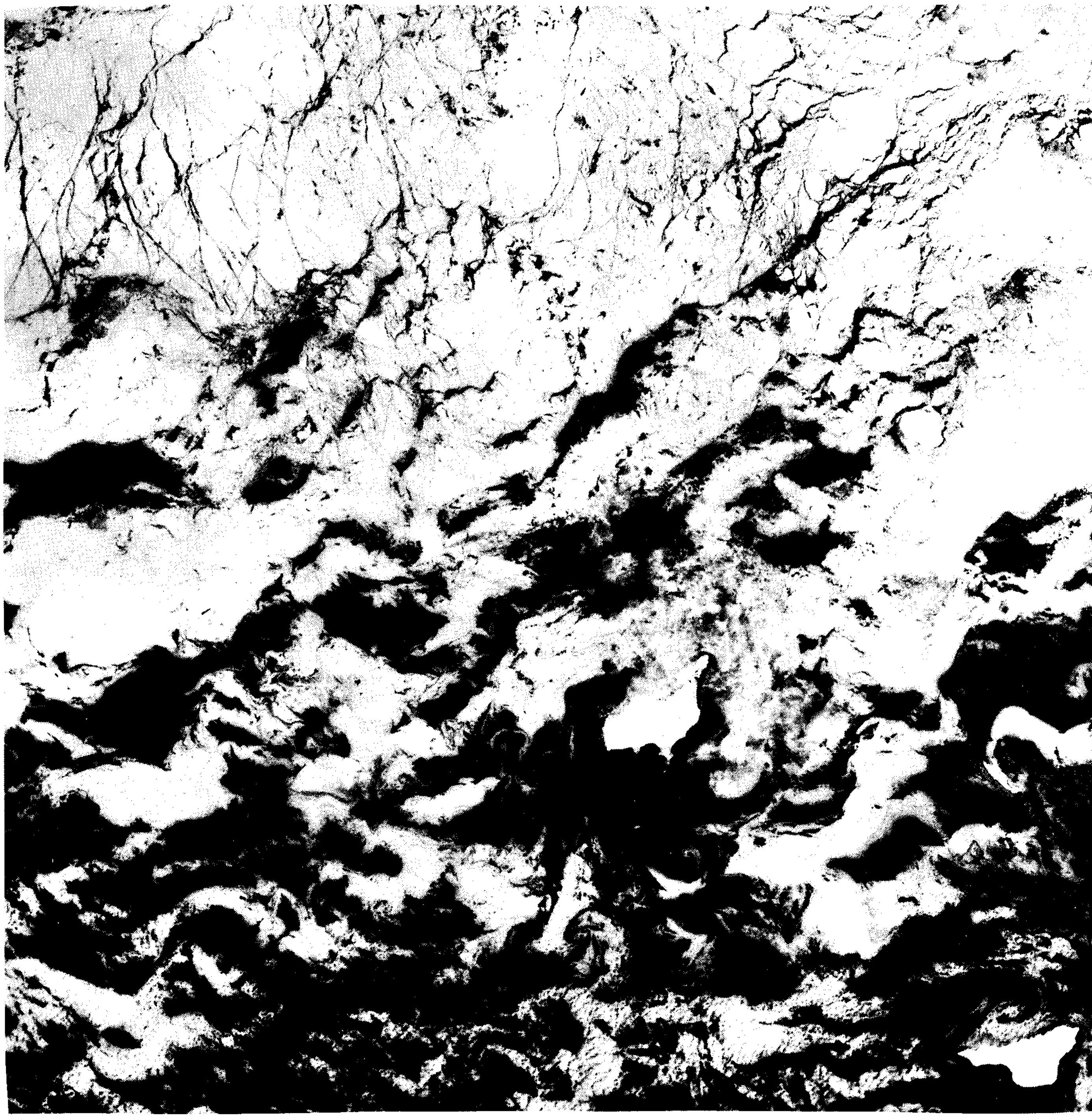

Figure 34. LANDSAT image #2453-21445, (19 April 1976) showing the ice fringe and front zone near the Pribilof Islands.

Figure 35. Low-altitude aerial view of an ice tongue of the fringe.

of St. Matthew Island occurs at or near the edge of the continental shelf, but in the eastern Bering Sea it is somewhat north of the edge. During periods of extreme cold, always associated with prolonged, northerly winds, surface water and air temperatures are lowered, new ice forms in the fringe, and the pack temporarily advances southward. On such occasions it may extend beyond the shelf break west of St. Matthew Island; in the eastern Bering Sea, it may reach the edge of the shelf. We presume that the more northern location of the eastern fringe, relative to the shelf break, is due to significant incursion of warm water into the southeastern Bering Sea, in part from the Alaska Stream (c.f. Takenouti and Ohtani 1974, fig. 2.10).

After April, in most years, the continuity of the Bering Sea pack is lost through breakup and melting. The pack as a whole no longer has any continuous fringe, for the different wind and water current regimes result in fragmentation of the main pack, rather than orderly withdrawal. Most of the large deformed floes and segments of the fast ice from the Alaskan and the Siberian coasts become entrained in rafted remnants; others drift northward through Bering Strait. Each disjunct remnant of the pack has its own "fringe" at that time.

By early June, the pack is mainly north of Bering Strait. Its withdrawal northward in the Chukchi Sea is more orderly than in the Bering, with the result that there is again a more regular fringe. This fringe, like that of the Bering Sea pack in winter, is a discrete ice zone. It is composed of thick, rafted floes, which have withstood the destructive processes of melting and wave action. By July, the fringe begins to approximate a definite edge, probably because of more southerly winds, and the persistence of deep-keeled floes which tend to drift at the same rate and in the same direction as the pack.

The period of minimal ice cover, on the average, is in late September (Brower, et al., 1977b). At that time, the fringe is most like an abrupt "edge" in the Chukchi and Beaufort Seas. Only the thickest pieces of seasonal and multi-year ice persist. Average and maximal northern retreat of the pack during the open water season in the Beaufort and eastern Chukchi Seas are shown in Figure 36. The characteristic appearance of the thick, weathered floes of the summer fringe is shown in Figure 37.

In fall and early winter (October to early January) the advancing and forming ice, like the retreating ice in late spring, has numerous indefinite fringes. These include the fringe of the irregularly developing main pack and those of the numerous separate loci of new ice formation, south of the advancing pack. Ice forms wherever air and water temperatures permit. In the coastal zone, this occurs first where there is outflow of fresh water into the sea. Major rivers such as the Noatak, Kobuk, Yukon and Kuskokwim produce plumes of ice. Ice also develops in shallow waters along the coast and drifts about in accordance with winds, remaining near shore or being blown seaward. As the processes of ice formation and southward movement continue, temporary fringes ultimately become incorporated into the advancing pack. By late January the fringe of the main pack becomes identifiable at its southern terminus.

2. Use of the fringe by mammals

The associations of marine mammals with the fringe are most apparent during periods when the pack is most stable, i.e. in late winter to spring

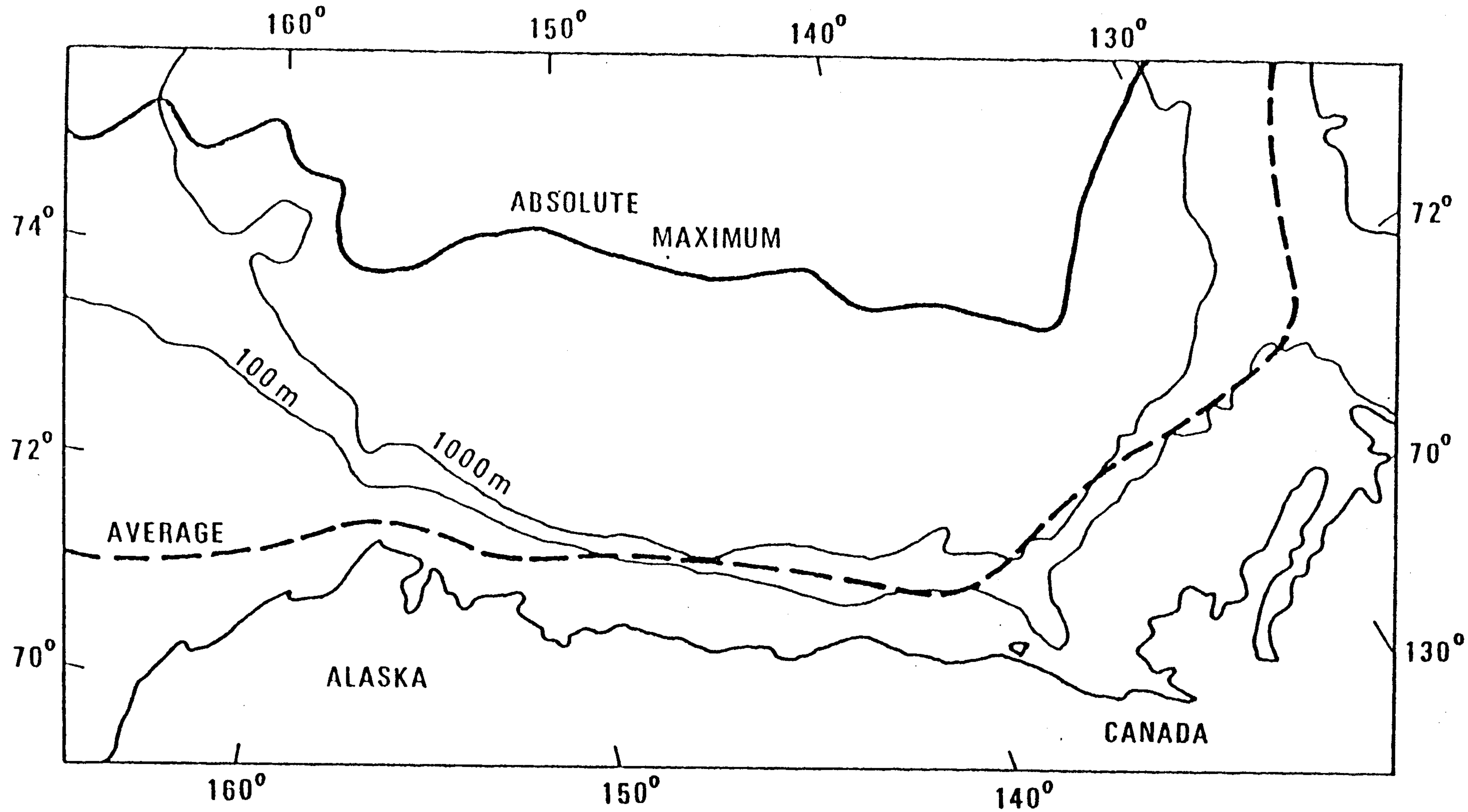

Figure 36. Average and maximum northern retreat of pack ice in the Beaufort Sea.

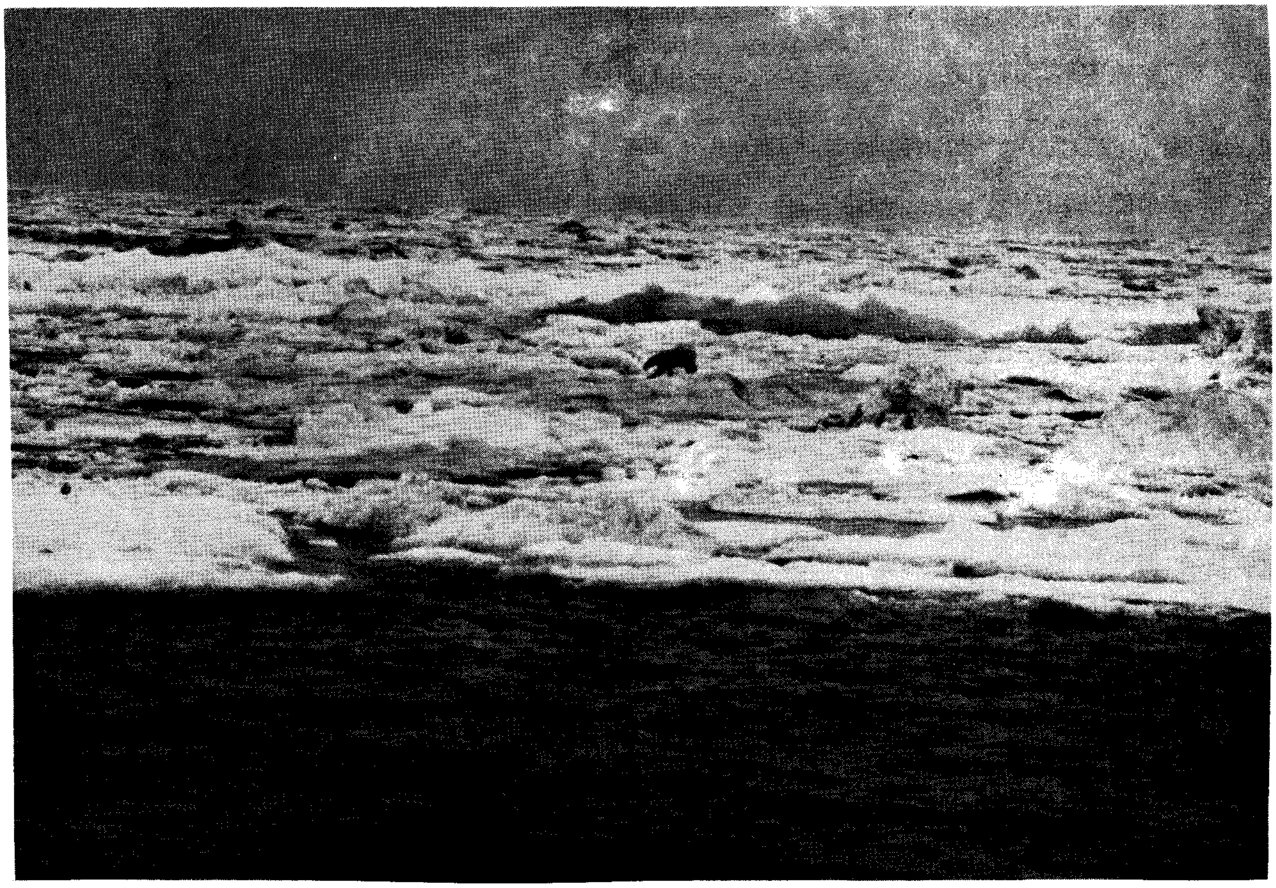

Figure 37. Thick, weathered floes of the summer fringe in the north central Chukchi Sea, 28 August 1973.

in the Bering Sea and in late summer to early fall in the Chukchi and Beaufort Seas. Seven species of pinnipeds occur in the late winter-spring fringe of the Bering Sea. Steller sea lions (Eumetopias jubatus) occur only there and in the open water south of the pack. They rarely penetrate farther into the pack than the fringe. Spotted seals and ribbon seals, on the other hand, are abundant not only in the fringe but well back into the pack as well; they are not known to range into the open water south of the fringe at that time. During April 1971, 1972, 1976 and 1977, these seals and sea lions were sighted on large tongues of ice extending as far as 21 km south of the loose pack. Walruses and bearded seals are uncommon in the fringe of the winter pack and ringed seals are rare. Harbor seals utilize the fringe during years when it is present in southern Bristol Bay (Burns and Harbo, 1977; Braham et al., in preparation; Fay and Burns, unpublished).

In late spring to early summer, during breakup and retreat of the pack, each of the above-mentioned species, except harbor seals, occurs in association with the fringes of the rafted remnants of the pack in the Bering Sea (see section on Remnants). The discontinuous and irregular northward retreat of the ice, and the generally northward migration of these animals, result in all species temporarily occupying fringe-type habitats. Spotted seals are the most abundant species in nearshore fringes, while ribbon seals occur more often in the offshore fringes. Walruses and bearded seals are common in the northern fringes. Weaned pups of bearded, spotted and ringed seals also occur in fringes close to shore.

The summer-autumn ice fringe in the northern Chukchi Sea usually is over the continental shelf, while that in the Beaufort Sea usually overlies deep water. Pacific walruses dominate the marine mammal fauna of the Chukchi Sea fringe at this time; ringed seals are dominant in the Beaufort fringe. During August-October 1973-1975, 1977 and 1978, few walruses were found in consolidated ice immediately north of the fringe, but they were more common in the open water to the south of it (Gol'tsev 1975; Estes and Gilbert 1978; Burns, unpubl.). Apparently these animals utilize ice of the fringe for resting between feeding forays in the vicinity of the pack and in the open water to the south of it. Bearded seals also are common in the Chukchi fringe, though numerous only within 50 miles of the Alaskan coast. Ringed seals are less numerous than bearded seals in the Chukchi fringe, and we presume that they are more abundant farther north, in the consolidated pack.

During aerial surveys in September 1974 and 1975, belukha whales were found in widely spaced groups along the entire fringe of the eastern Chukchi and western Beaufort Sea.

Polar bears are present in the fringe only during the summer-autumn period. As indicated by our sightings during August-September 1973, and September 1974 and 1975, they occur most often near (and among) walrus herds and in areas where bearded seals are numerous. The most intensive predation by bears on walruses and bearded seals probably takes place in this period when these three species are relatively abundant in the same areas. C. Ray (pers. comm.) reported sightings of polar bears hunting walrus calves in the Chukchi fringe during July 1977, and we observed similar situations there in August 1978.

Ringed seals and belukha whales were the most common mammals seen in the fringe of the western Beaufort Sea during aerial surveys in September 1974. In August 1977, during a traverse of the fringe by ship, marine mammals were not abundant. Bearded seals and an occasional walrus were seen northeast of Point Barrow and ringed seals were present at all locations to our easternmost station north of Demarcation Point. Apparently ringed seals were more numerous in the ice north of the fringe, as breathing holes were abundant there in newly formed ice.

Spotted and ribbon seals generally are not associated with ice in late summer and early fall. During this period, spotted seals occur mainly in the coastal zone of the Bering and Chukchi Seas in ice-free waters. The distribution of ribbon seals during this season is not known but is presumed to be mainly in the open waters of the Bering Sea (Burns 1970, Fay 1974).

In autumn and early winter, the southward migration of ice-associated marine mammals precedes the advance of the pack ice. At that time, there seem to be no strong associations of marine mammals with specific ice conditions; rather, the various species are intermixed. During October and November, the majority of walruses utilize coastal hauling grounds south of the pack, especially along the northern and eastern coasts of the Chukchi Peninsula, on islands in Bering Strait, and on the Punuk Islands, just east of St. Lawrence Island (Gol'tsev 1968, 1975; Fay and Kelly, in press). Spotted, ringed and bearded seals also are numerous nearshore, south of the advancing pack. The nearshore abundance of ringed and bearded seals increases as new ice forms. Their presence in areas of grease and slush ice appears to anticipate the development of ice types which they will occupy during the winter months when they mostly inhabit fast ice and flaw zone, respectively.

Spotted and ribbon seals also move southward, mainly ahead of the advancing seasonal pack. These seals continue their southward movement into the Bering Sea, remaining mostly close to the fringe. In autumn, at St.

Lawrence Island, an influx of spotted and ribbon seals occurs with the first ice. In Norton Sound this influx is of spotted seals alone, followed closely by ringed and bearded seals.

B. The Ice Front

1. Description

The "front" is a zone of transition between the fringe and the heavier, consolidated pack. It is one of the most labile segments of the winter pack of the Bering Sea. It is strongly affected by both surface weather and sea state, and for that reason its character can change rapidly.

The existence of the front is dependent on a balance between factors which contribute ice to southern parts of the pack and those acting to destroy it. The former include low temperatures and prevailing northerly winds. The latter are warmer water and frequent North Pacific storms. The front is a zone of dynamic equilibrium between regions of cold, windy and warmer, stormy conditions.

Since there is great annual variation in extent of ice cover in the Bering Sea, there are major annual differences also in location of the fringe and front zones. Figure 38 illustrates the location of the fringe and front zones in March-April 1960-1979. Late winter-spring 1976 was a period of prolonged northerly winds, lower than normal temperatures (especially in April) and extensive ice coverage, with a front zone in excess of 130 km wide in the vicinity of the Pribilof Islands. In the same period in 1979, the pack was much less extensive, and the front zone was unusually narrow, being less than 30 km wide. The ice coverages in 1976 and 1979 were not maximum and minimum extremes, although they did approach the extremes.

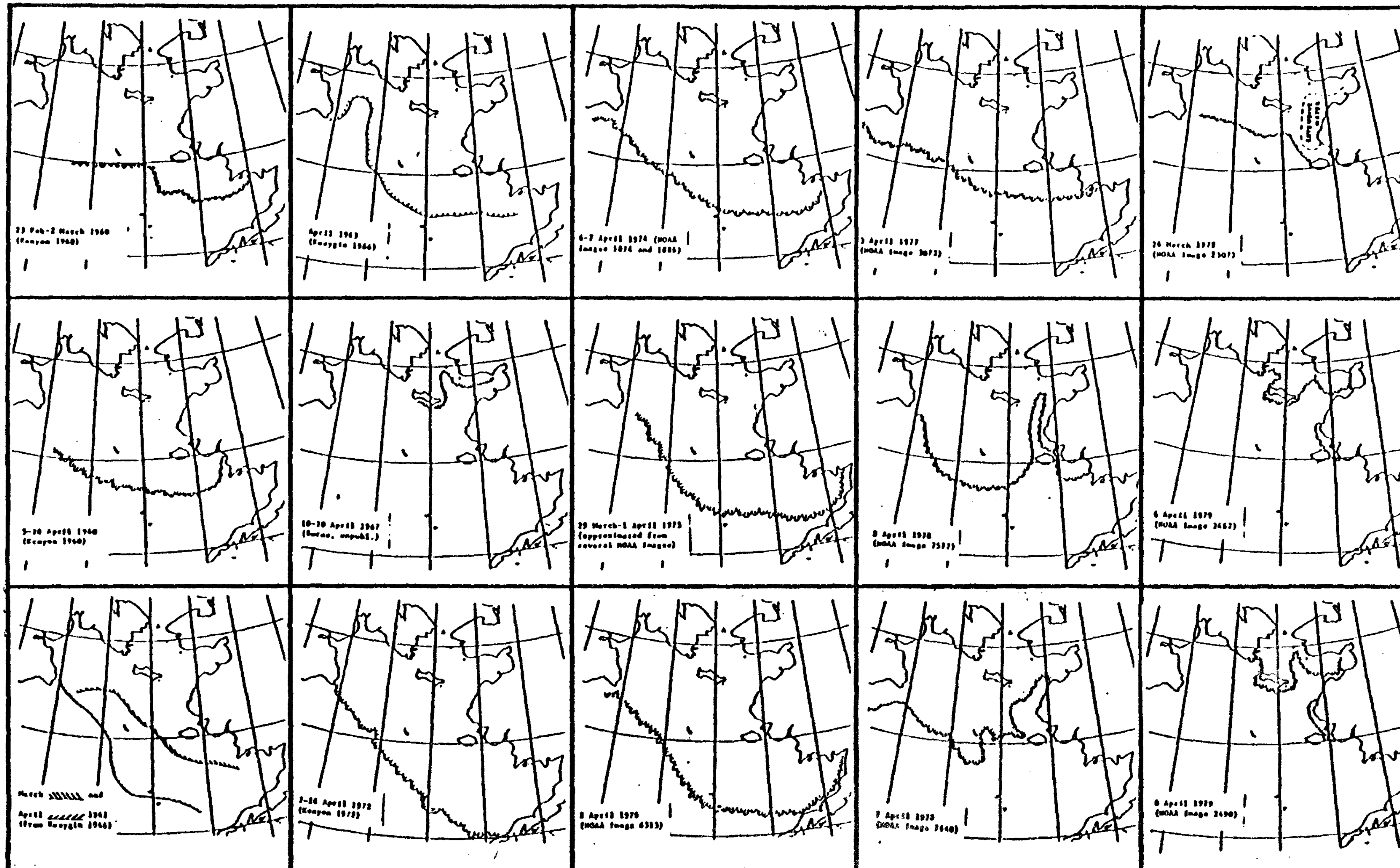

Figure 38. Annual differences in location of the fringe and front zone in the Bering Sea, March-April, 1960-1979.

In our experience, the maximal extent of the pack ice occurred in 1972. In March and April of that year, the southern margin reached Unimak Island (55°N) and exceeded the maximum reported by Wittmann and MacDowell (1964). Conditions were almost as extreme during the previous year. In both years, ice resulted in significant mortality of sea otters, (Enhydra lutris) in Bristol Bay; these animals are little adapted to ice (Schneider and Faro 1975). The minimal extent of ice occurred 1967. In mid-April, that year it was just south of St. Lawrence Island and central Norton Sound (63°N) and the ice-associated marine mammals were distributed much farther north than usual. Walruses were abundant around St. Lawrence Island in March of that year. In normal winters the majority of the walrus population is well south of that location, at that time.

The difference between maximal and minimal limits of the eastern Bering Sea pack in April of those extreme years was approximately 870 km.

We have made shipboard excursions into the front on seven occasions in March and April since 1968. Our most extensive study and repetitive coverage of it was in March-April 1976, when shipboard (NS SURVEYOR, ZRS ZAGORIANY) and aerial surveys were conducted throughout this zone from eastern Bristol Bay to about 179°E. As in other years, the front was composed mainly of small floes, less than 20 m in diameter, separated by water, slush ice and brash for most of that period. Occasionally, during brief periods of calm, it refroze into a consolidated unit. In stormy periods, it converged or dispersed depending on wind direction and velocity. During or just following each storm, the refrozen units were broken up by swells moving in from the open sea (Figure 39). Indeed, it appeared that the depth of the front was a function of the depth of penetration into the pack by those swells, and the size of the floes

Figure 39. Surface level view of floes in the front after an episode of penetration by ground swells.

was a result of the wavelength and amplitude of the swells. Under the influence of the swells, ice of all thicknesses was broken into units of about 20 m or less.

East of 160°W longitude, in inner Bristol Bay, the ice cover in March-April 1976 was made up predominantly of rafted new ice in floes mostly larger than 100 m in diameter and with rough surfaces. Ice ridges were of very low profile, apparently resulting from refreezing of rafted pancake ice rather than from pressure of convergence. All visible surfaces were covered with silt, which also appeared to be incorporated into the ice. The latter probably was derived from the turbid waters of this part of the bay and from windblown sediments off the land.

The ice of the front from 160°W to approximately 169°W was quite uniform. A south-north gradation in coverage from open water to nearly 8 oktas occurred there over an average distance of 25 km in the eastern part of the area, 40 km in the central part and 60 km in the western part. Maximal width of the front was 84 km in the vicinity of 166°W. There was a clear trend of increasing thicknesses and deformity of floes from east to west, although floe diameter was similar in all areas. In the east, the floes were mainly of thin, gray ice, while those in the west were thicker (about 0.7 m) and had more accumulated snow. The degree of deformation (pressure ridging) also increased from east to west.

West of 169°W, ice conditions in the front in March-April 1976 were markedly different from those described above. Although, the majority of floes were about the same size ($\sim$ 20 m in diameter), they were made up of thicker (0.7 to 1.0 m) ice, even to the southern limit of the zone. Snow cover appeared to be much thicker, the degree of deformation was between 15 and 50 percent, and there was a strikingly higher proportion of clear, blue ice in the pressure ridges than was seen farther to the east. The ice edge extended south of the shelf margin in this region, from 174^{O}W at least to 179^{O}E, which was the western limit of our aerial surveys.

The motion of ice in the front, particularly vertical motion produced by the penetrating swells, appears to be the most important factor in periodically shaping the characteristics of this zone. Swells break up the ice cover and, in turn, are damped as they pass north into the pack. While surface chop acts on the fringe to reduce floes to a very small size, its energy is rapidly dissipated; only the ground swells penetrate far into the front. During periods of ice formation, surface chop, because of the characteristically short amplitudes and frequencies, results in slush and small pancake floes often less than 1 m in diameter. A gradient from slush and small cakes of the fringe to the larger floes of the front usually occurs over less than 10 km. The ground swells penetrate the pack up to 80 to 90 km beyond that, however, producing floes of relatively uniform size that make up the front. The point where the swells are no longer of an amplitude sufficient to fracture the ice marks the inner edge of the front and the beginning of the consolidated pack. In the latter, floe size tends to be much larger and more variable.

During a 6 week shipboard penetration of the pack in southeastern Bering Sea during March and April 1976, refreezing of the front into broad, unbroken ice fields occurred repeatedly. Breakup of this refrozen ice cover due to swells coming from the southwest, was noted on 25 March at 56°48'N, 165°58'W, on 30 March at 57°02'N, 166°15'W, and on 7 April at 57°21'N, 165°16'W. Based on the known position of the ice fringe on those dates, penetration of the pack by swells was approximately 74 km, 96 km and 133 km, respectively.

Waves and swells also affect the form of floes making up the fringe and front. The horizontal and vertical motion of floes grinding against each other results in rounding of their edges and in the production of brash between them. On thicker floes, undercutting (melting) takes place at the water surface, and the submerged rams (feet) tend to pump and dip brash and water onto the floes as they rise and fall. During periods of strong southerly winds or swells from a distant storm, sea water may wash over the floes, intensifying melting when weather is warm or adding further ice to the exposed parts, when weather is cold. In the latter case, refrozen water or slush forms a raised rim at the perimeter of low, flat floes (Figure 39).

The action of waves and swells in the front apparently does not result in the kinds of deformation produced by overriding and pressure ridging farther inside the pack. The deformation and massiveness of heavy ice in the front are mainly expressions of forces operating much farther north, during the formation and movement toward the front. Formation and drift of ice in the north usually are not accompanied by significant vertical motion. New ice formed in the pack usually is rather flat. It is broken and deformed, mainly through stress from surface winds and interaction with adjacent land masses or major ice massifs. The thick, pressure-ridged floes that occur in the front are brought there by southerly drift of the pack. Their location in the front is a function of their place of origin in, and their route of drift from, more northerly regions. The heaviest ice is derived from areas of repeated convergence in the central and northern Bering Sea. The much lighter ice in the front of the southeastern Bering Sea and Bristol Bay is derived mainly from centers of formation in Bristol and Kuskokwim Bays and south of Nunivak Island. This lighter ice is less deformed than that in the central Bering Sea because of its origin relatively close to the front in areas mainly of ice divergence.

2. Use of the front by mammals

Regular mammalian occupants of the front of the eastern Bering Sea include most of the spotted and ribbon seal populations and, during February, March, and early April many walruses, bearded seals and belukha whales (Kenyon 1960, 1962; Kosygin 1966; Gol'tsev 1976; Braham et al., 1977). Some ringed seals also are present, as are bowhead whales. Minke, gray and killer whales, and sea lions penetrate the front in spring as it disintegrates and recedes. Harbor seals utilize the front occasionally when it extends into their late winter-spring range, mainly around the Pribilof Islands and in Bristol Bay.

Spotted and ribbon seals show the strongest association with the front and are found there during February to late April (or to mid-May in years of late disintegration of the pack). In February and March, they mainly appear to be feeding; at the same time, they are distributing themselves into habitats suitable for events which follow in April to June. They give birth to pups on the ice of the front, mainly during the first half of April. Pups of both species, born as lanugo-clad "whitecoats," are weaned after 3 to 4 weeks. Although these pups "paddle" through water or brash between floes, they do not normally swim or dive until they are weaned and have shed most of the lanugo. They seek protection from the wind by utilizing cavities and depressions in ridged ice. On floes of the eastern part of the front, such protection often is not available, and pups are protected by their mothers.

Adult spotted and ribbon seals mate in the front during April and early May. Individuals of all ages begin their annual molt there in April and spend an increasing proportion of time basking on the ice.

The molt continues into June and July, with the subadults completing the molt before the adults. In May and June when the front no longer exists, both species are concentrated in the wind-rafted "remnants" of the pack. After disintegration of the eastern remnants, spotted seals complete their molt on land, while ribbon seals continue to occupy the western remnants.

Bearded seals and walruses in the front occur most often during February to early April. However, the centers of abundance for both are farther north. Both species begin to migrate out of the front in April although some male walruses remain in Bristol Bay all summer utilizing ice as long as it is present. Bearded seals give birth from late March through early May with the peak occurring about 20 April. Thus, some bearded seal pups are born in the front. These pups swim almost from birth and move with their mothers, mainly vacating the front by late April. Walrus calves are born mainly in May, well north of the front.

Our most intensive and quantifiable surveys of marine mammals in the front were conducted in March and April of 1976 to 1979. These surveys were made from a Bell 206 helicopter based aboard the NOAA ship Surveyor. The comparative densities of walruses and seals in the front during the 1976-79 surveys are indicated in Table 7. The comparative densities of the seals, by species,are presented in Table 8. Locations where surveys were conducted are shown in Figure 40. These data indicate that spotted seals had the broadest general distribution in the front with highest concentrations near Bristol Bay (up to 6.78 per nm^2 in 1976 and 6.72 per nm^2 in 1967). Ribbon seals also occurred throughout the front, mostly in low numbers. Ribbon seals were found to be highly clumped, mainly west of the Pribilof Islands. Bearded seals were more uniformly distributed in low numbers throughout the front (except in 1979 , when this zone

Table 7. Relative abundance of seals and walrus sighted during aerial surveys in the front, 1976 to 1979.

Year	Station No.[1]	Date	Area Surveyed (nm^2)	Total No. of seals and walrus counted	Density of seals & walrus ($/nm^2$)	Density of Walrus	Density Seals
1976	1	27 March	82.7	560	6.77	0	6.77
	2	20 April	40.0	1	0.03	0	0.03
	3	23 April	27.5	87	3.16	0	3.16
	4	24 April	26.0	151	5.81	0	5.81
	5	24 April	13.0	11	0.93	0.10	0.85
	6	25 April	24.5	81	3.31	0	3.31
	7	25 April	24.5	186	7.59	0	7.59
1977	8	28 March	103.3	253	2.45	0.65	1.80
	9	30 March	81.2	249	3.07	2.82	0.25
	10	21 April	40.5	287	7.09	0.15	6.94
	11	23 April	85.0	14	0.16	0	0.16
	12	23 April	85.3	18	0.21	0.01	0.20
	13	24 April	15.0	8	0.53	0.06	0.47
	14	24 April	30.6	28	0.92	0	0.92
	15	25 April	43.9	20	0.46	0.03	0.43
	16	27 April	31.2	35	1.12	0	1.12
	17	27 April	24.7	31	1.26	0	1.26
1978	18	5-6 April	94.5	136	1.44	0	1.43
	19	7-9 April	211.0	668	3.17	2.46	0.71
	20	10-13 April	177.0	652	3.68	2.79	0.89
1979	21	15 April	67.0	150	2.24	1.79	0.45
	22	18 April	51.0	132	2.59	0	2.59
	23	20 April	60.0	113	1.88	0.43	1.45
	24	21 April	59.0	923	15.64	12.95	2.69
	25	22 April	44.0	129	2.93	0.18	2.75
	26	24 April	49.0	266	5.43	2.12	3.31
	27	25 April	49.0	374	7.63	4.16	3.47
	28	27 April	48.0	166	3.46	0.52	2.92

[1] See Figure 40

Table 8. Species composition and relative densities of seals seen during aerial surveys in the ice front, 1976 to 1979.

Year	Station No.[1]	Date	Ribbon Percent	Ribbon Density	Spotted Percent	Spotted Density	Ringed Percent	Ringed Density	Bearded Percent	Bearded Density
			Species Composition and Density ($/nm^2$) for seals							
1976	1	23 March	0	0	99.9[2]	6.77	0	0	0	0
	2	20 April	100	0.03	0	0	0	0	0	0
	3	23 April	0	0	100.0	3.16	0	0	0	0
	4	24 April	0	0	100.0	5.81	0	0	0	0
	5	24 April	0	0	27.0	0.23	0	0	45.0	0.38
	6	25 April	0	0	94.0	3.10	0	0	0	0
	7	25 April	0	0	89.0	6.78	0	0	1.0	0.04
1977	8	28 March	1.0	0.01	62.0	1.13	0	0	37.0	0.66
	9	30 March	0	0	20.0	0.05	0	0	80.0	0.20
	10	21 April	0	0	97.0	6.72	0	0	3.0	0.22
	11	23 April	7.0	0.01	79.0	0.13	0	0	7.0	0.01
	12	23 April	41.0	0.08	24.0	0.05	0	0	35.0	0.07
	13	24 April	0	0	86.0	0.40	0	0	14.0	0.07
	14	24 April	4.0	0.03	96.0	0.88	0	0	0	0
	15	25 April	0	0	84.0	0.36	0	0	16.0	0.07
	16	27 April	26.0	0.29	74.0	0.83	0	0	0	0
	17	27 April	6.0	0.09	94.0	1.17	0	0	0	0
1978	18	5-6 April	54.0	0.77	45.0	0.65	0	0	1.0	0.01
	19	7-9 April	9.0	0.07	75.0	0.53	1.0	0.01	15.0	0.11
	20	10-13 April	1.0	0.01	44.0	0.39	10.0	0.09	45.0	0.40
1979	21	15 April	0	0	50.0	0.22	0	0.	50.0	0.22
	22	18 April	0	0	78.0	2.02	16.0	0.41	6.0	0.16
	23	20 April	9.0	0.13	22.0	0.32	0	0	69.0	1.00
	24	21 April	10.0	0.27	58.0	1.56	0	0	32.0	0.86
	25	22 April	29.0	0.80	55.0	1.50	1.0	0.02	14.0	0.39
	26	24 April	8.0	0.27	42.0	1.39	1.0	0.04	49.0	1.61
	27	25 April	15.0	0.53	19.0	0.65	1.0	0.02	64.0	2.20
	28	27 April	29.0	0.83	25.0	0.73	0	0	46.0	1.35

[1]See Figure 40.

[2]The other animals seen were sea lions.

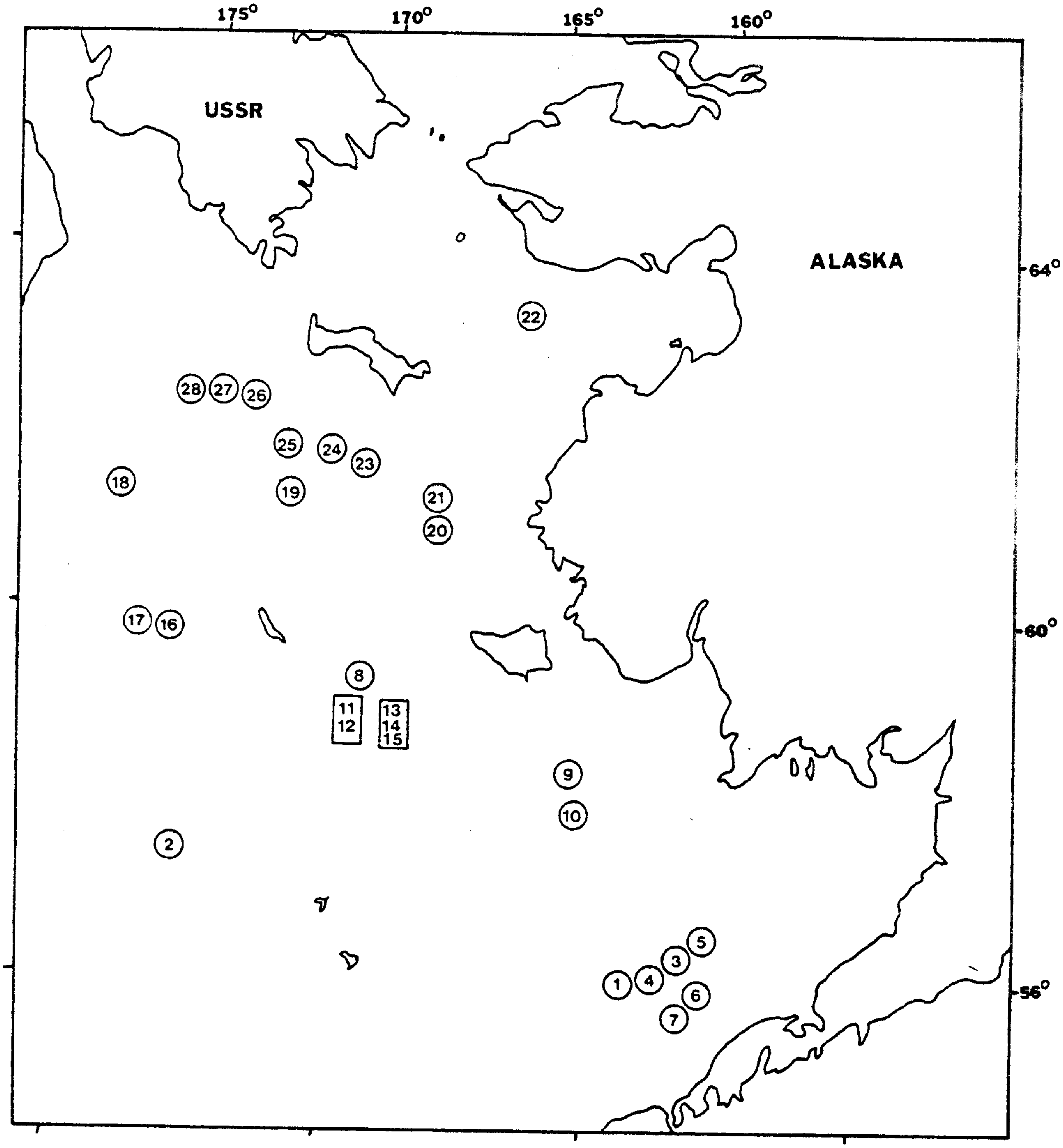

Figure 40. Locations of aerial surveys in the ice front.

was further north than in the previous 3 years). Ringed seals seldom were seen in our surveys south of Norton Sound except relatively near shore (Braham et al., in preparation). Walruses showed a highly clumped distribution but they usually were the most abundant animals seen during each survey. Highest densities were 2.8 per nm^2 in 1977, 2.79 per nm^2 in 1978 and 12.95 per nm^2 in 1979. Our data suggest that, in many instances the density of seals (except for bearded seals) tended to be inversely related to the density of walruses.

As the retreat and disintegration of the front proceed, the ice-associated marine mammals migrate northward (walruses, bearded and ringed seals) or become temporarily redistributed in the rafted remnants of the pack (ribbon and spotted seals); many spotted seals move into the ice-free coastal zone.

VI. SPRING REMNANT-ICE

A. Introduction

Our observations prior to 1968 of the breakup and disintegration of the pack, as seen from shore stations at St. Lawrence Island, Nome, and in Bering Strait, led us to believe that by late May and early June the only ice remaining in the Bering Sea usually was situated between eastern St. Lawrence Island and Bering Strait. During a multidisciplinary cruise of the R/V Alpha Helix in early June 1968, Burns (1969) observed "the occurrence of a disjunct band or remnant of seasonal ice, far south of the normally receding ice edge". Associated with that remnant were numerous ribbon seals, which were utilizing it as a place to rest while undergoing their annual molt. Burns speculated that the presence of such rafted remnants of ice might be an annual feature of the spring pack that is of critical importance to those seals as molting habitat. However, it was not until high resolution satellite imagery became available to us some years later (1974) that the possibility for further investigation of that point became feasible. Our findings since then have confirmed the presence annually of several large masses of wind-rafted ice in the Bering Sea that persist well into June and July and that these are heavily utilized by the seals.

B. Characteristics of the Remnant Ice- Bering Sea

Using principally the NOAA/VHRR visible band imagery, we have followed the development of the rafted remnants each spring since 1974, with the objectives of (a) tracing their origin and duration and (b) determining whether there is any predictable pattern to their size, form, and location. Further, we have examined some of them in closer view from ships, aircraft, and small boats, in order to assess their mammalian fauna and the quality of their constituent ice.

A series of comparative views of the development, extent, and distribution of the major rafted remnants of seasonal pack ice in the northern Bering Sea, each year from 1974 to 1978, is shown in Figure 41. These cover the period from 21 May to 20 June. Prior to that period, the ice was much more extensive; after 20 June in most years, clouds obscured the view of the remaining ice. From these comparative views, it is apparent that:

1. In four of the five years, there was remarkable uniformity in timing of development and disintegration of the remnants.

2. The basic pattern of development was set in most years by late May and was remarkably similar from year to year.

3. While there was considerable variation in shape and size of the remnants, the major deviations in location usually took place in mid- to late-June.

The remnant ice originated each year as two major massifs. One of these (Alaskan Massif) extended from Bering Strait to eastern St. Lawrence Island and southern Norton Sound, thence southward toward St. Matthew and Nunivak islands. The other (Anadyr massif) extended in most years from southwestern Gulf of Anadyr generally southeastward, toward St. Matthew Island. In 1974, the identity of the southern parts of these two massifs was lost in early May, when the southern end of the Alaskan massif moved westward and combined with the southeastern part of the Anadyr massif (Muench and Ahlnas, 1976: figs. 2, 3). In 1975-78, they remained clearly distinguishable well into early June. Parts of both

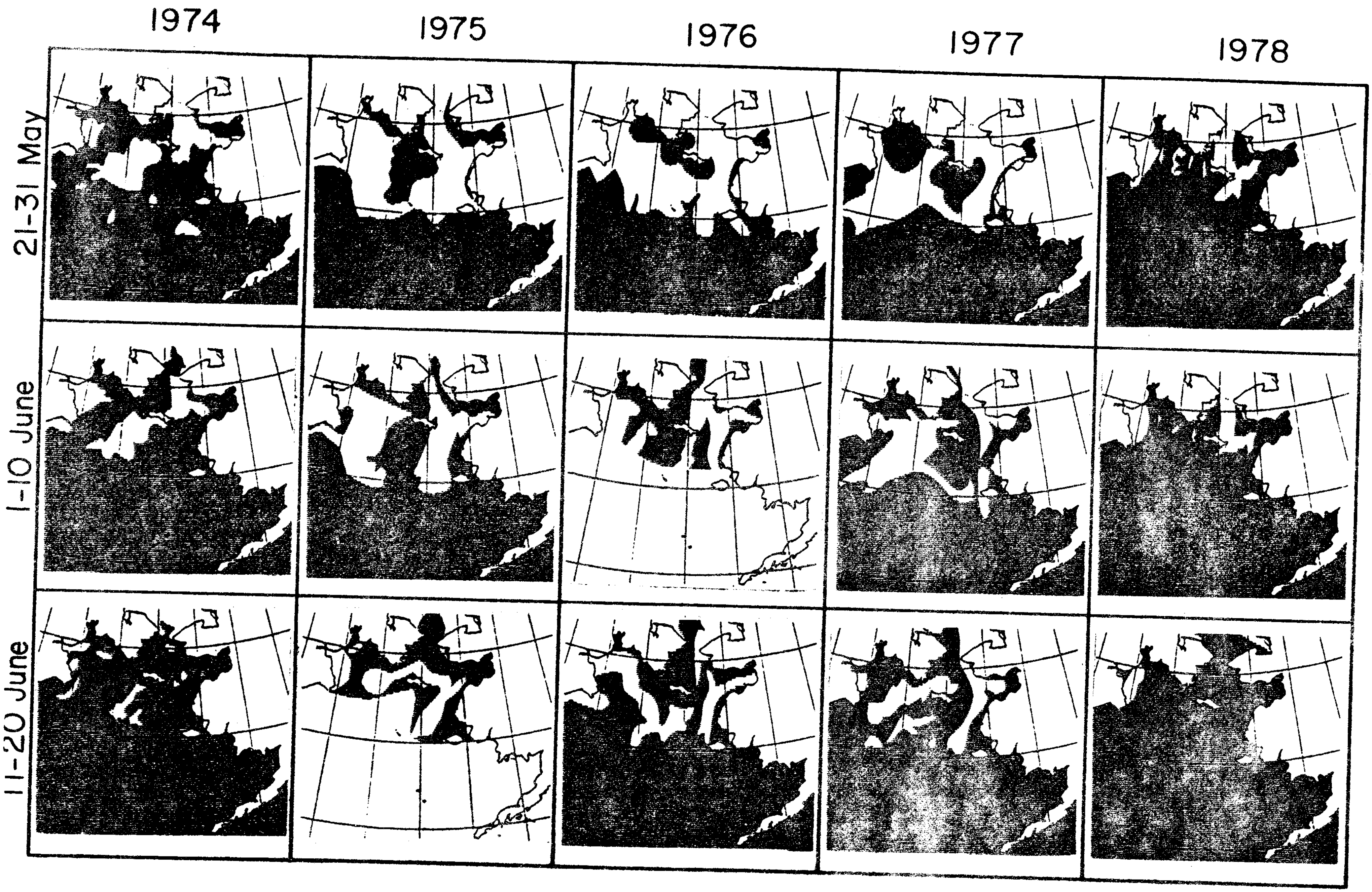

Figure 41. Shape, location, movement and degeneration of rafted remnants of the Bering Sea pack ice, 1974-1978.

persisted until late June in 1974-1977; in 1978, only a portion of the Anadyr massif persisted that long. In 1979 (not shown), the Alaskan and Anadyr massifs were clearly separate, the former being less extensive than in 1978 and the latter more extensive.

During our probes into the Alaskan massif and some of the small remnants between it and the Anadyr massif in late May to early June 1968, 1977, and 1978, we observed that many floes were larger (up to 30 m in diameter), rougher (50 to >80% deformation), and stood higher out of the water (hence also deeper underwater) than the flat, small floes usually found in the southeastern ice front (cf. Figures 42 and 43). Frequently, the pressure ridges also contained numerous chunks of clear, blue ice, not seen in the southeastern front. This ice closely resembled that formed in the northern Bering and Chukchi seas in winter when there is little particulate matter in the surface water and epontic algae are absent. These massive floes were deeply undercut as a result of melting; where lighter, thinner floes were present, they were very fragile and were rapidly disintegrating.

The persistence of the Alaskan massif well into June and the Anadyr massif into July, long after the locally formed ice had disintegrated, appeared to be mainly a function of the enormous mass of these heavy, deformed floes. Simply because of their greater mass, they are more resistant to melting than the thinner, less deformed floes that are generated, for example, in the broad areas of divergence south of St. Lawrence Island and in Bristol Bay. Even by early June in the southern edge of the remnants, many of the floes were 20 x 30 m in diameter and at least 10 m deep. Their occurrence as rafts seems to be mainly a

Figure 42. Typical floe in the Bering Sea spring remnants. front.

Figure 43. Typical floes in the southeastern Bering Sea ice front.

result of their comparatively uniform quality. That is, because of their great mass and deep keels, they tend to move slowly and as a group.

Considering the quality of this ice and its distribution, we hypothesized that the two massifs must be derived from the parts of the winter pack that are made up of the thickest, most deformed ice, i.e. that they do not develop at random but in specific loci from specific parts of the pack. We presumed that those parts would be in the areas of greatest convergence and downstream from them. To test this hypothesis, we selected the clearest NOAA/VHRR satellite views of the winter pack at its annual maximum in late March, and using standard base maps, sketched an outline of the whitest (presumably thickest) ice (Figure 44). We compared these with sketched outlines of the limits of remnant ice in late May, also derived from NOAA visual imagery. The results, while crude, tend to support the hypothesis.

Each year, the distribution of remnant ice in late-May was sufficiently similar to the pattern of white ice in late-March to indicate a distinct positive relationship (Figure 45). The correlation was closest in 1975, 76, and 77, which were the years with the heaviest winter ice and most persistent spring remnants; it was least satisfactory in 1974, 1978 and 1979. In each of the latter years, the pack was lighter and broke up a little earlier than in 1975-77 and, by late-May, was more advanced in its degradation. In all years, the area occupied by the late-May remnant ice was mainly within the same area that had been occupied by the late-March white ice (Table 9).

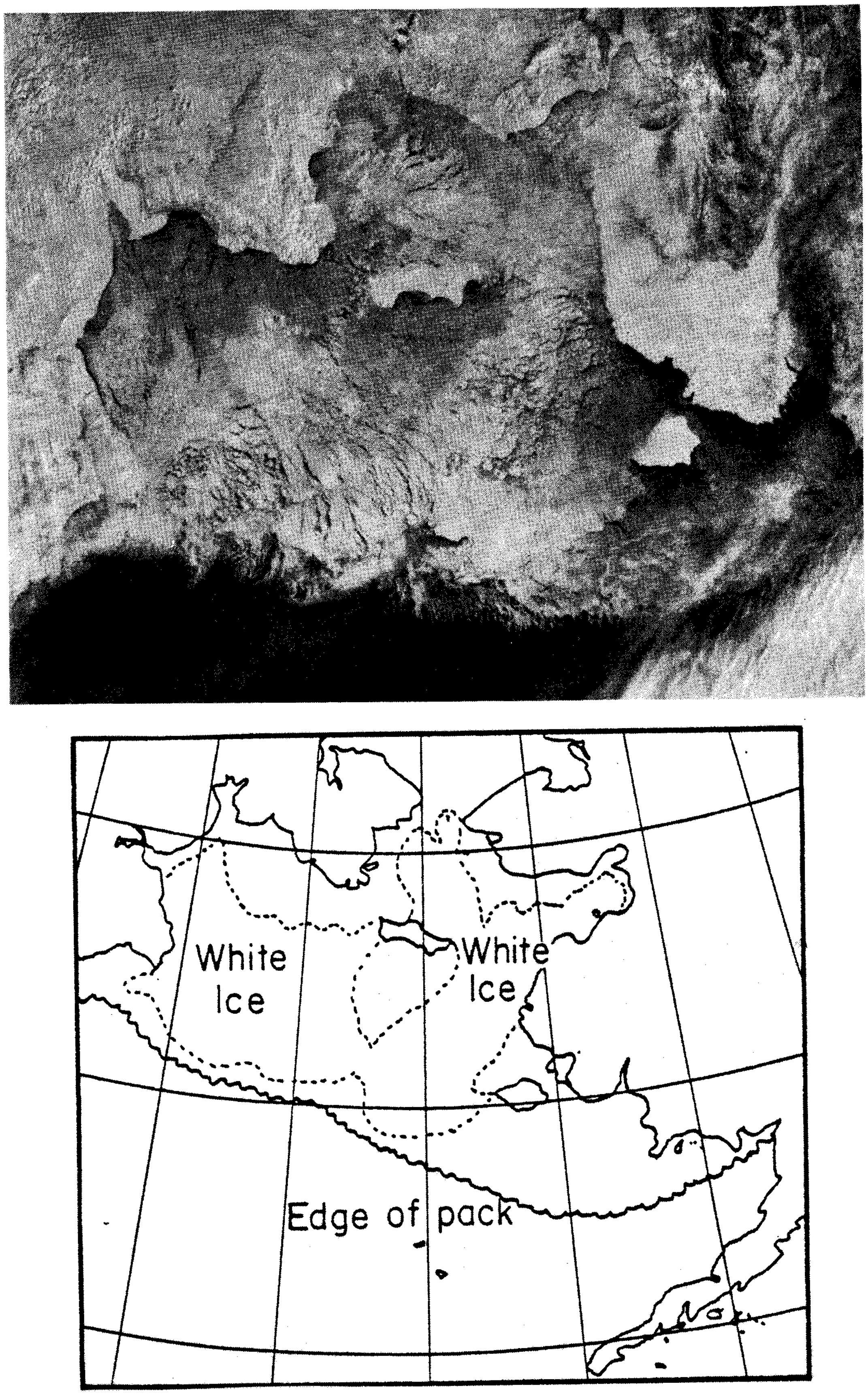

Figure 44. Example of satellite view and sketch of the extent of white ice, Bering Sea, 18 March 1978.

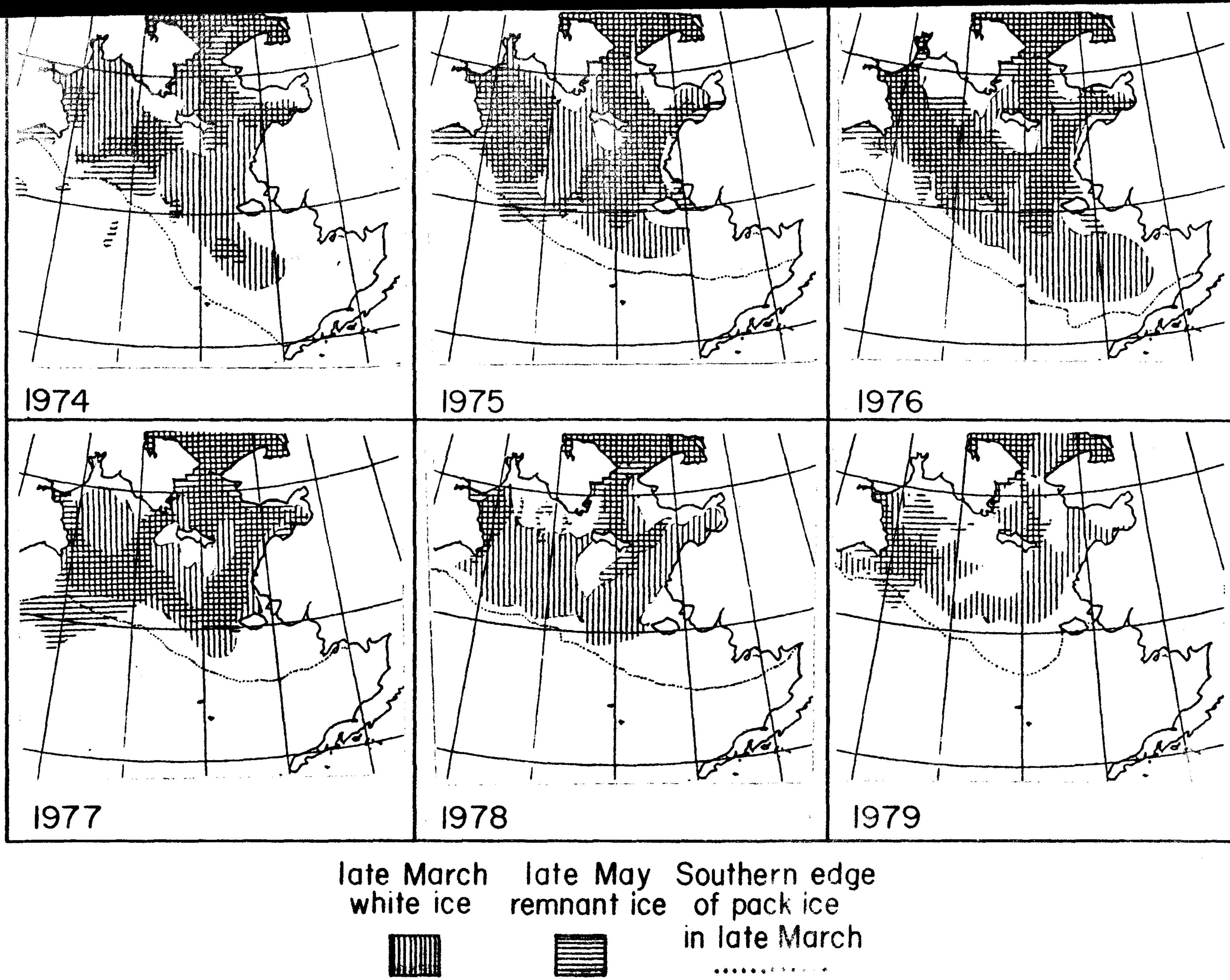

Figure 45. Overlay of remnant ice of 21-31 May on white ice of 17-29 March in Bering Sea, 1974-1979.

Table 9. Proportion of area of late-May remnant ice situated within same area as late-March white ice, Bering Sea 1974-1978

Year	Area of white ice in March ($km^2 x 10^3$)	Area of late-May remnant ice in location of March white ice ($km^2 x 10^3$)	Percentage
1974	194	155	80
1975	348	276	79
1976	358	281	78
1977	319	225	70
1978	83	60	72
1979	89	51	57

The relationship between the extent of white ice in late-March (km^2 of coverage) and that of total remnant ice in late-May was remarkably close (Figure 46). That is, as the area of white ice in late March increased, so did the area of remnant ice in late-May. This relationship lends further support to our hypothesis and indicates that even with wide variation in extent and quality of the pack and of the attendant weather, it may be feasible to predict the size and location, and to some extent, the shape of the spring ice remnants at least two months in advance, by extrapolation from the distribution of white ice in late winter. In general, it seems that the white ice south of 60° N lat and immediately to the west and southwest of St. Lawrence Island is the least likely to persist beyond mid-May; the western part of the Anadyr massif and the northern part of the Alaskan massif are the most likely to persist beyond 1 June (Figure 45).

C. Use of the Remnants by Mammals - Bering Sea

Our aerial surveys of the distribution of seals in the ice front of the Bering Sea in March and April consistently showed a high proportion of ribbon seals in the west and of spotted seals in the east. Furthermore, Kosygin (1966) indicated that in the Gulf of Anadyr, ribbon seals comprised 90 percent of the seals available to Soviet sealers, whereas in the eastern Bering Sea, spotted seals comprised 50 percent of the catch. On this basis, we hypothesized that the distribution of ribbon and spotted seals in the remnants in May and June as molting areas would be comparable, i.e. that ribbon seals would tend to be most numerous in the Anadyr and spotted seals most numerous in the Alaskan massif. Unfortunately, we were not able to sample the Anadyr massif adequately, but we did acquire

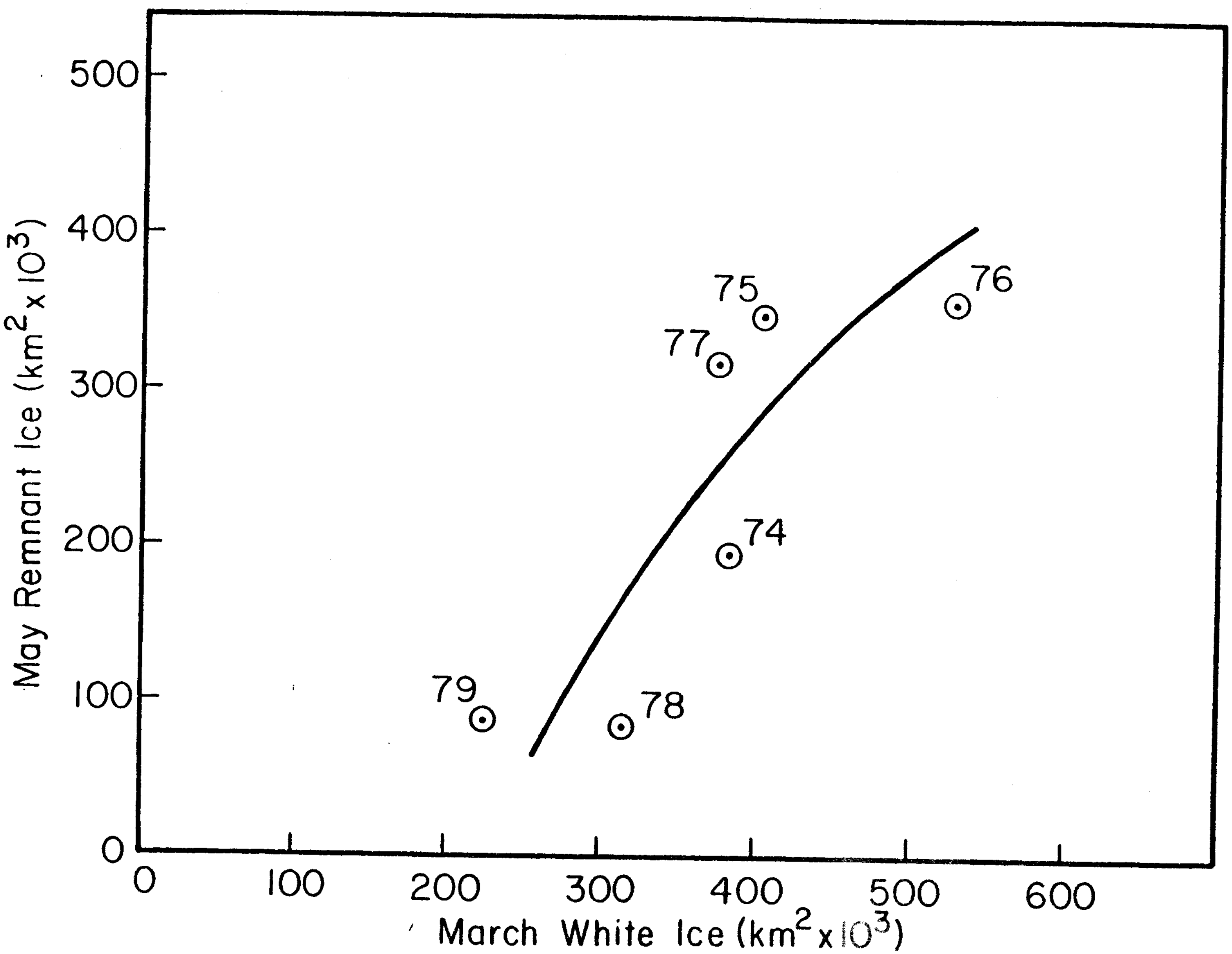

Figure 46. Approximate relationship between total areal coverage of white ice in late-March and total areal coverage of remnant ice in late-May in the Bering Sea, 1974-1979.

some data from the Alaskan massif and from a few areas between with which to test that hypothesis. We conducted two probes into the Bering Sea remnants by ship. These were limited for political reasons to the Alaskan massif and some portions between it and the Anadyr massif, east of the International Convection Line. On each occasion, surveys were conducted in an effort to assess the kinds and abundance of mammals utilizing the remnants.

In the first instance (24 May-6 June 1977), surveys were conducted from the NS Discoverer while in transit between oceanographic stations, as well as from small boats in the vicinity of each station (i.e. within a radius of about 5 km of the ship). In the shipboard surveys, the observers stood on the flying bridge (approx. 18 m above the water) and counted all mammals by species sighted within about .5 km of the ship using 7 x 35 binoculars for visual aid. At the same time, the ship's command determined the location of the cruise track and distance covered. In the small boat surveys, the approximate area covered was estimated by the observers, who also recorded the number of mammals of each species sighted within it.

In the second instance (28 May-9 June 1978) the surveys were conducted via ship-based (NS Surveyor) Bell 206 helicopter, flown at an altitude of approximately 500 ft (152 m) at speeds ranging from about 35 to 85 kt (approx. 65-160 km/hr). The observers (one forward, next to the pilot; one behind the pilot) recorded the number and species of all mammals sighted within 1/4 nm (.46 km) to each side of the flight track (i.e. the total width of the survey track was approximately .93 km). The flight tracks for each survey were pre-determined, based on the distribution of ice in the area and the wind direction and velocity. The surveys were designed to sample as much of the remnant ice area as possible within 30 nm (55km) of the ship (including several replicates) at each oceanographic station. The position of each station had been selected for the purpose of sampling different portions of the remnant, without prior knowledge of ice conditions or mammal distributions there.

The approximate areal coverage by the surveys, relative to the total area of the remnants, and their location is shown in Figure 47. In 1977, one station was in the eastern edge of the Anadyr massif, just west of St. Matthew Island; one was in the link between the Anadyr and the Alaskan massifs; and three were in the southern end of the Alaskan massif. The numbers of seals in the two stations west of 170°W were low (approximately 0.5 seals/km^2); the numbers in the three stations east of 170°W were significantly higher (approximately 2 to 6 km^2). At all stations, spotted seals predominated (80 to 94%); ribbon seals made up about 5% overall and bearded and ringed seals about 1% each.

The surveys in 1978 were of the various parts of the main Alaskan massif and of one small, linear remnant directly west of St. Lawrence Island. The densities of seals utilizing these remnants, as indicated by the survey data, ranged from about 1 to 5/km^2. Densities were lowest in the western part of the Alaskan massif (1 to 2/km^2) and were highest (2.75 to 5/km^2) along the eastern margin. Bearded seals predominated in the west (74%) and spotted seals in the east (69%); ribbon seals made up about 12% overall and ringed seals about 4%. Walruses and gray whales also were abundant in and near the eastern and southern margins, respectively, of the massif.

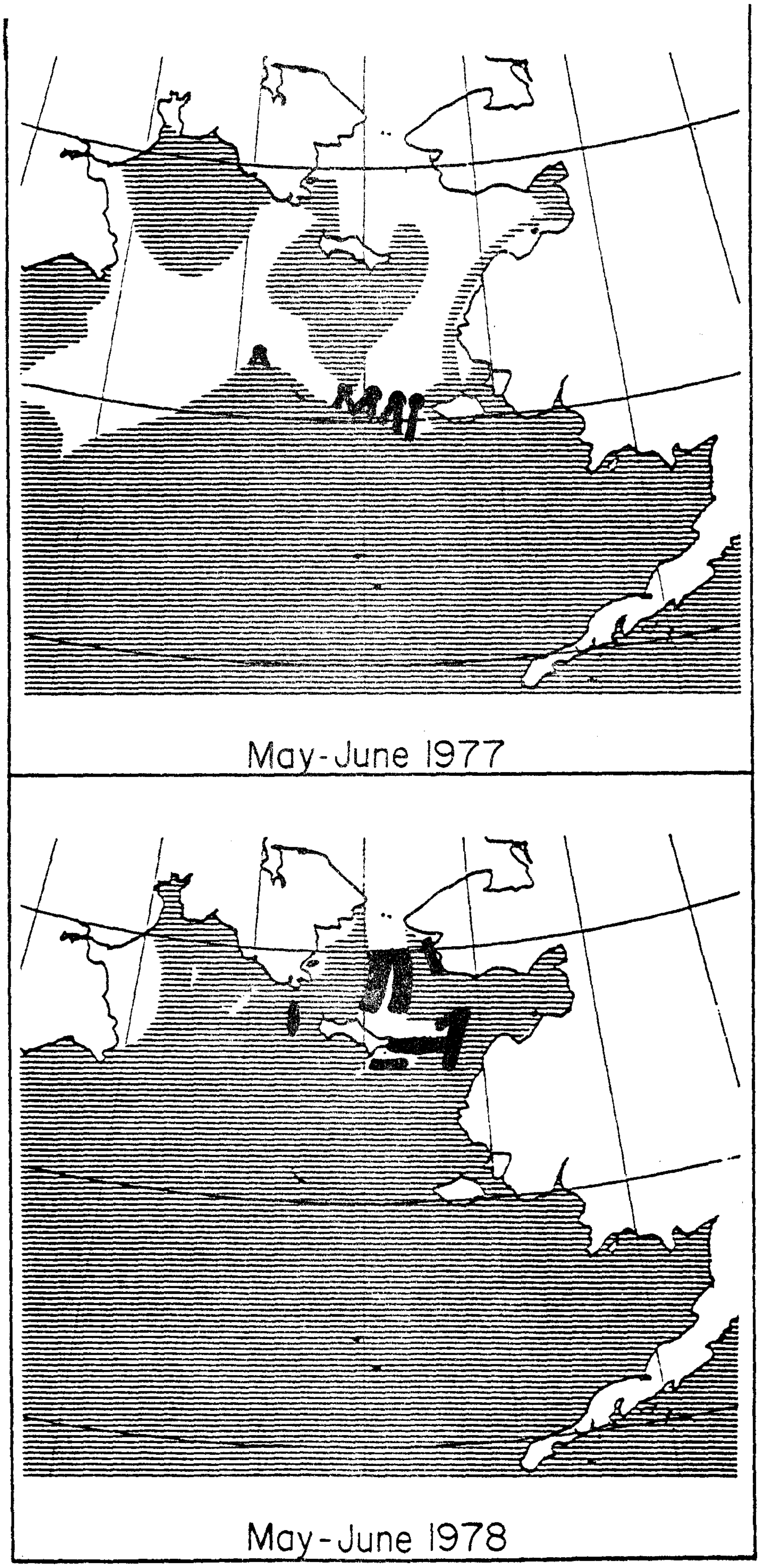

Figure 47. Survey coverage of the Spring remnant ice of the Bering Sea in May-June, 1977-1978.

While the probes were not adequate comparisons of the distribution of seals in the Anadyr versus Alaskan massifs, the findings do indicate that ribbon seals tended to be more abundant in the western than in the eastern parts of the remnants examined:

1. In the southern edge of the remnant ice on 24 May-6 June 1977, a total of 363 seals were sighted from the ship and small boats. The ratio of spotted to ribbon seals sighted in and near the two stations west of 170°W was 30:4 (7.5:1), whereas in those east of 170°W, it was 293:14 (21:1). This difference is significant (X^2=3.18) at the 90% confidence level.

2. In the remnant about St. Lawrence Island and northward toward Bering Strait on 28 May-6 June 1978, the aerial survey results showed a ratio of spotted to ribbon seals on the western side of 39:35 (1:1), whereas on the eastern side it was 376:75 (5:1). This difference is highly significant (X^2=36.1).

D. Chukchi-Beaufort Remnant Ice

The seasonal pack ice of the Chukchi Sea usually retreats northwestward in a regular fashion, without any recurrent pattern of remnants to the south other than persistence of ice for some time in the larger bays, such as Kotzebue Sound. Occasionally, slender remnants of former shorefast ice occur along the coasts, or a tongue from the main pack may be detached and rafted. The remnant ice in the bays is not ordinarily utilized by seals, though any offshore remnants that develop may be used opportunistically by walruses and by spotted, bearded, and ringed seals for completing their molt. Most of the Chukchi pinnipeds at this time are found in association with the main pack.

Conditions in the Beaufort Sea are similar, in that there is generally an orderly retreat of the pack from the shore during July to September, without any regular occurrence of remnants in particular areas. Frequently, in late August and September, a broad tongue of ice extends southward toward the shore in the area between Harrison and Camden Bays (as it did in 1976, 77, and 78), and it is conceivable that small parts of that tongue might occasionally become separated as "remnants". Diffuse nearshore remnants occurred in August 1976 between Thetis and Barter islands; a similar remnant occurred in the vicinity of Barter Island in August 1978. The most outstanding coastal remnants developed in August 1974 between Cape Halkett and Flaxman Island and from Camden Bay to Herschel Island, and in July 1977 between Harrison and Camden Bays. In both of the latter years, these remnants persisted at least through early September, in and just north of the proposed Beaufort Sea oil lease area (Figures 48, 49). These apparently formed by entrainment of drifting ice around persistent, grounded ice masses of the stamukhi zone, as described by Reimnitz, et al., (1977).

The nearshore remnant in August 1977 contained higher numbers of seals than did the offshore pack. The highest densities were in the vicinity of Harrison Bay, where surveys via small boats yielded sightings of from 5 to 15 seals per hour. Comparable surveys in the offshore pack showed counts of from less than one to about 3.5 seals per hour in 1977 and from 0.3 to 3.4/hr in 1978. Both ringed and bearded seals occurred in the nearshore ice, whereas only ringed seals were present offshore, over deeper water. Since this was well after the molting season, seals were seldom out on the ice; they were mainly sighted in the water where

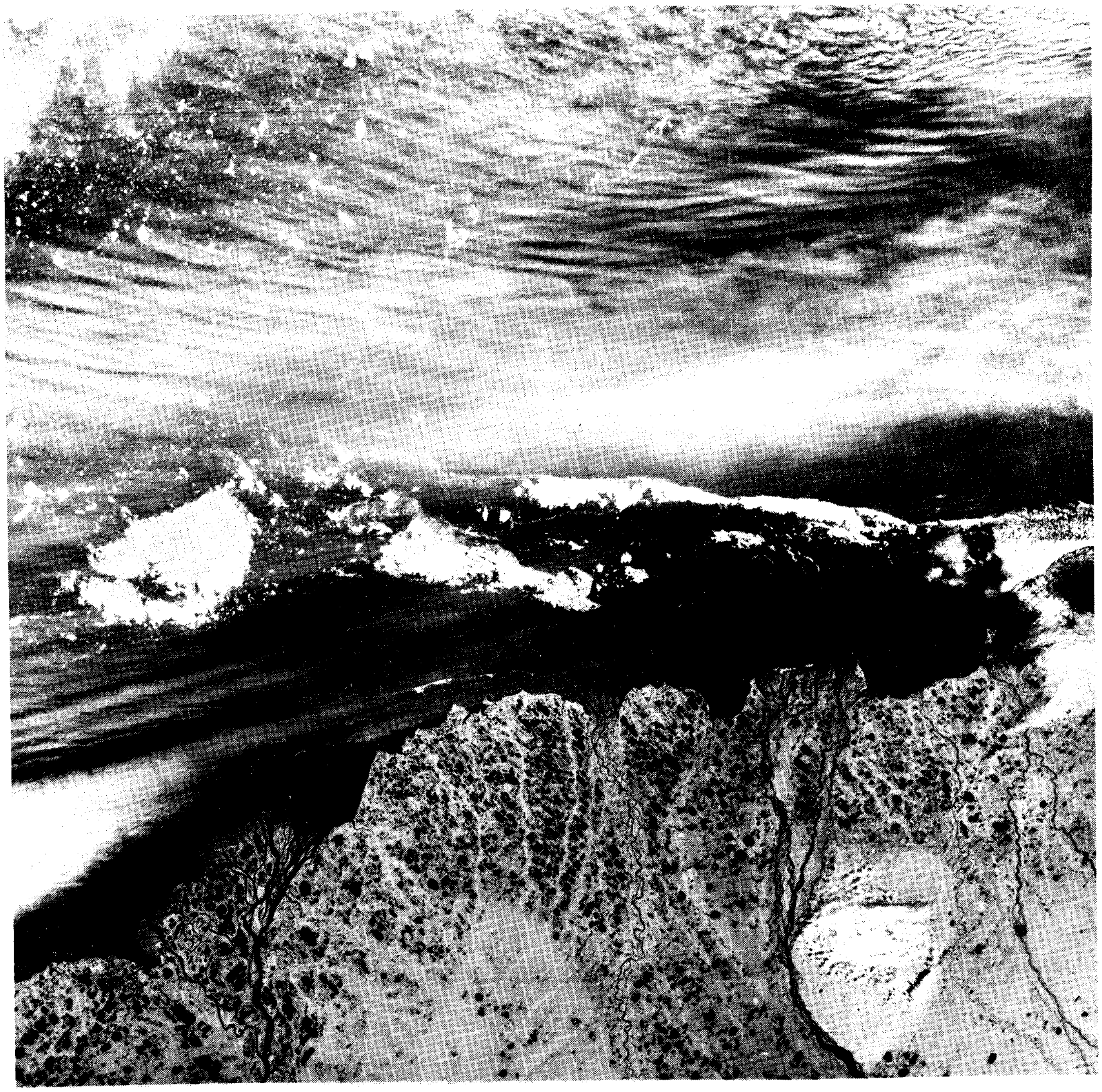

Figure 48. LANDSAT image #2933-20473 showing nearshore remnants in the area between Harrison Bay and Flaxman Island, 12 August 1977.

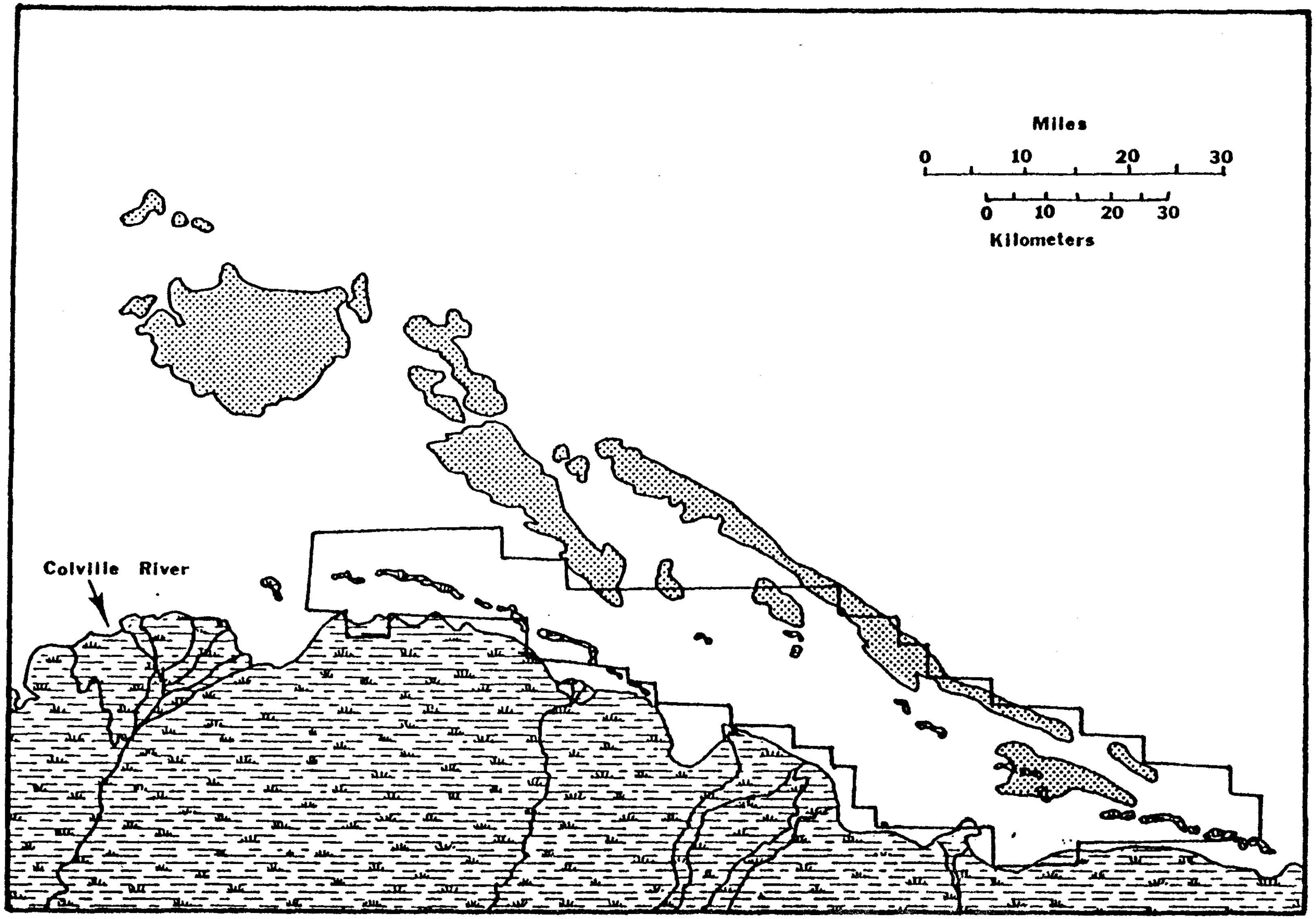

Figure 49. Schematic of the ice remnants of Figure 48 in relation to the Beaufort Sea lease area.

they were feeding. No seals were sighted in the open sea between the remnant and the offshore pack.

E. Discussion

The presence in the Bering Sea in late spring and early summer of two or more extensive, rafted remnants of the winter pack ice is now known to be a feature that occurs annually with a high degree of reliability. These remnants are situated in approximately the same locations each year, and the ice of which they are composed is some of the heaviest, most deformed ice that develops in the entire region. This massiveness certainly is one of the major reasons for their persistence; another is the seasonal change in climate, in which surface winds diminish greatly in velocity and become more variable in direction, tending to allow the remaining ice to disintegrate more or less _in situ_ during May to July.

This extra-heavy ice apparently is a product of the net southward movement of the winter pack. Ice from the Chukchi Sea moving southward through Bering Strait and that formed locally in the northern Bering Sea is greatly deformed where it impinges on the northern coasts of the islands and mainlands of Alaska and eastern Siberia. The product is two major massifs of heavy, pressure-ridged ice, one extending southeastward from the Gulf of Anadyr, and the other essentially from Bering Strait to Nunivak and St. Matthew Islands. The western part of the Anadyr massif and the northern part of the Alaskan massif are the most reliably persistent. The Anadyr massif persists the longest; usually into July.

Each of these major remnants, as well as a number of smaller, more irregularly situated ones, is utilized intensively by pinnipeds of the Bering Sea, which rely on them as haulout areas on which to rest and, especially, to complete their annual shedding and replacement of hair. On that account, these remnants in late May and June contain some of the greatest concentrations of seals ever formed during the year (Shustov, 1965, 1969; Tikhomirov and Kosygin, 1966). Our observations, and those of Soviet biologists, indicate that the western ice (i.e. west of about 172°W) is utilized mainly by ribbon seals and the eastern ice (east of 172°W) mainly by spotted seals. Bearded and ringed seals inhabit the western and northern remnants, walruses occur principally in northern parts. There is not perfect geographical segregation of any of these species, only a tendency for the majority of individuals of each to be situated in those areas.

The observed tendency toward geographical clumping probably does not occur by chance alone. The predictability of location and persistence of the various remnants probably has played a selective role in the evolutionary adaptation of each of these pinnipeds to the Bering Sea pack ice. The ribbon seal's closer association with the western than with the eastern ice appears to be related to the more regular occurrence and duration of the Anadyr than of the Alaska massif. Since these seals do not ordinarily haul out on land (Tikhomirov, 1964; Shustov, 1965) and since they probably must come out of the water in order to complete their molt (Feltz and Fay, 1966; Ling, 1970, 1974), they appear to be dependent on the persistence of remnant ice well into July. Spotted seals, on the other hand, appear to be more adaptable in that they utilize the remnants as available but often complete their molt on shore (Tikhomirov, 1961, 1964; Burns and Fay, unpublished). Because the spotted seals are not wholly dependent on remnant ice for molting sites, and because the eastern remnants often are nicely juxtaposed beside the spring migration route of an important food supply (spawning herring), most of the adult spotted seals tend to concentrate in the eastern Bering Sea.

We suspect that the distribution of ribbon and spotted seals in the ice front during the breeding season (which just precedes the molt) and their apparent selection there of different qualities of ice as haulouts are linked to their differential dependence on the remnants as molting sites. Ribbon seals in the front tend to utilize larger, thicker floes than do the spotted seals (Shustov, 1965; Burns and Fay, unpublished). That is, they appear to selectively occupy those floes that, because of their greater mass, will be most likely to persist as a component of the remnants. While such floes are abundant near the southern edges of both the Alaskan and Anadyr massifs in April-May, the ribbon seals concentrate in the western ice, as if in anticipation of having access to the most extensive and persistant remnant.

In years of minimal extent of ice such as 1979, the Alaskan massif is absent south of 64°N by late May. In that case, spotted seals probably dispersed early, mostly moving inshore while the ribbon seals travelled northward to the Anadyr massif, which persisted through June. In the spring of 1967, however, ribbon seals occurred in enormous numbers on remnant ice between St. Lawrence Island and Bering Strait (Burns, 1968). That instance was unique in our experience (1952 to present) as well as in that of the Eskimos of St. Lawrence, King, and Little Diomede islands. We suspect that the Anadyr massif did not persist in that year alone, and that the ribbon seals were obliged to seek ice elsewhere, farther north, on which to complete their molt.

The ice cover in the eastern Bering Sea was extremely light also in the springs of 1955, 1959, and 1979, but ribbon seals were not unusually abundant in the St. Lawrence-Bering Strait region in those years. At least for 1979, the Anadyr massif still was very extensive in early June and persisted for some weeks longer.

For bearded and ringed seals and walruses of the Bering Sea, the presence of remnant ice after late May appears to be a convenience but not a necessity for their existence. Usually, by that time, most have already migrated into Bering Strait or on northward into the Chukchi Sea, where the presence of ice always is reliable. When remnants of the Anadyr and Alaskan massifs persit to that time or longer, they are heavily utilized by these animals in prodigious numbers. Neither bearded nor ringed seals of the Bering-Chukchi region haul out on land ordinarily, and walruses seem always to use ice in preference to land as a haulout. In June, each of these species is well along in its molt, and the walruses are in the final stages of their calving season.

The Beaufort Sea remnants, appear to be utilized intensively by bearded and ringed seals during the summer, but this is more a relationship with feeding than with breeding or molting. The juxtaposition of floating ice over shallow water probably is particularly advantageous for bearded seals, which are bottom-feeders not known to dive to great depths. The importance of the relationship for ringed seals is less certain but may be connected with the nearshore migration of Arctic cod, a major forage fish utilized by those seals. At any rate, it seems that the presence of such remnants near shore does lead to concentration of both of these species of seals in and near the Beaufort lease area, well after their molt has been completed.

VII RELATIONSHIP TO OCS DEVELOPMENT

A. Introduction

There are nine species of mammals which are strongly and positively linked with the occurrence of sea ice in western and northern Alaska. These are the arctic fox, polar bear, belukha and bowhead whales, the walrus, and the bearded, ringed, spotted, and ribbon seals. Our interpretations of their relative abundance and activities in each of the potential oil-producing basins of the Bering, Chukchi, and Beaufort seas (Figure 50) are summarized in Table 10. Major parts of the populations of each species are found in one or more of those basins in all or a significant part of each year.

Within the ice, there is unequal distribution of these species, as the table indicates. Where two or more occur together in a given basin at the same time, there is partitioning of the available habitats and other resources, as exemplifed by their different feeding habits, birth times, choice of birth sites, and the relative precocity of their young (Table 11). At the same time, each is constrained to a considerable extent by the ice itself, which prevents most of them from advancing far northward in winter and restricts some of them to certain narrow corridors for migration in spring.

The risks of impact on these mammals by OCS oil development in the seasons when pack ice covers the Bering, Chukchi, and Beaufort seas will differ with each phase of that development. Seismic surveys probably will be conducted mainly on fast ice in winter and spring and from vessels at sea in the ice-free summer. In that case, the most important considerations of mammal-ice relationships will be in the fast ice itself and in the adjacent flaw zone. Probably, exploratory drilling

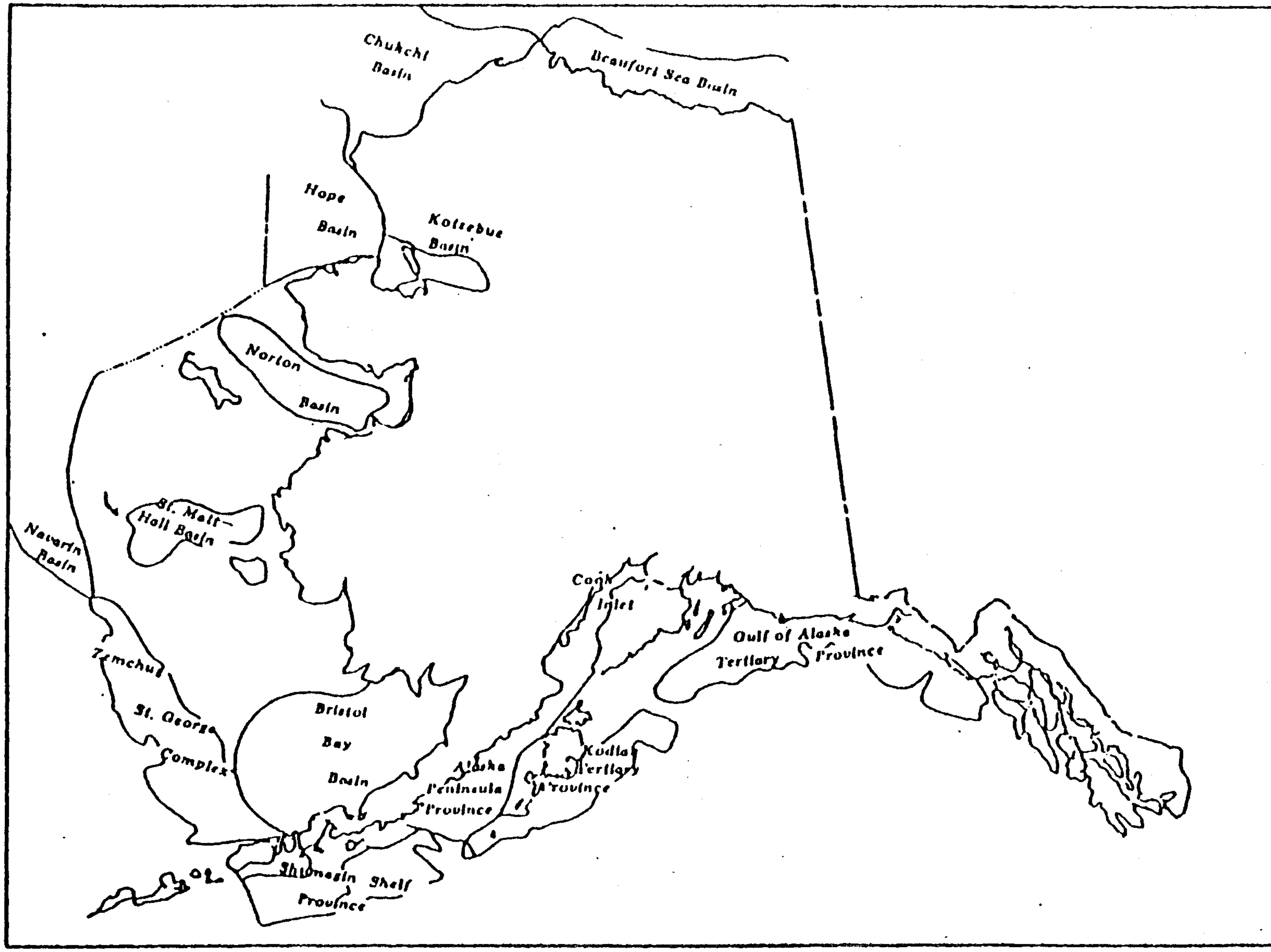

Figure 50. Geologic basins of the Alaskan Continental Shelf.

Table 10. Relative Abundance and Activities of Ice-Associated Marine Mammals in the Geological Basins of the Alaskan Outer Continental Shelf.

Species	Ice type	BRISTOL	ST. GEORGE	NAVARIN	ST. MATTHEW	NORTON	HOPE	CHUKCHI	BEAUFORT
ARCTIC FOX	Consol. pack & fast	Rare-winter, spring	Uncommon-winter, spring	Rare-winter, spring	Few-winter, spring	Abundant-winter, spring Feeding Travelling	Abundant-winter, spring Feeding Travelling Mating	Abundant-winter, spring Feeding Travelling Mating	Abundant-winter, spring Feeding Travelling Mating
POLAR BEAR	Consol. pack & fast	Rare-late winter,spring	Rare-late winter, spring	Rare-late winter,spring	Rare-late winter,spring	Few-late winter, spring Feeding Travelling	Abundant-fall, winter,spring Feeding Nurture Mating Travelling	Abundant-all yr Mating Birth Nurture Feeding Molt	Abundant-all yr Mating Birth Nurture Feeding Molt
BELUKHA	Open pack, flaw, & fringe	Abundant-all yr Feeding Mating Birth Nurture	Uncommon-winter Feeding Travelling	Common-winter Feeding Travelling	Uncommon-winter Common-spring Migrating Mating Feeding	Rare-winter Abundant-spring Migrating Mating Feeding Common-summer Birth Nurture Feeding Abundant-fall Migrating Feeding	Absent-winter Abundant-spring Migrating Mating Feeding Common-summer Birth Nurture Feeding Abundant-fall Migrating Feeding	Absent-winter Abundant-spring, summer,fall Migrating Mating Birth Nurture Feeding	Absent-winter Abundant-spring, summer,fall Migrating Mating Birth Nurture Feeding
BOWHEAD	Open pack, flaw & fringe	Rare-winter	Uncommon-winter	Abundant-winter, spring Migrating Birth Nurture Feeding(?)	Uncommon-winter, spring	Absent-winter Abundant-spring Migrating Birth Nurture Feeding(?) Rare-summer Abundant-fall Migrating Feeding(?)	Absent-winter Abundant-spring Migrating Birth Nurture Feeding(?) Rare-summer Abundant-fall Migrating Feeding	Absent-winter Abundant-spring Migrating Birth Nurture Feeding Rare-summer Abundant-fall Migrating Feeding	Absent-winter Abundant-spring, summer,fall Migrating Nurture Mating Feeding

Table 10. continued

Species	Ice type	BRISTOL	ST. GEORGE	NAVARIN	ST. MATTHEW	NORTON	HOPE	CHUKCHI	BEAUFORT
WALRUS	Open pack & front (winter); Flaw & remnants (spring); Fringe (summer-fall)	Abundant-all yr Feeding Mating Molt Nurture	Common-winter Feeding	Uncommon-winter	Common-winter Feeding Abundant-spring Migrating Feeding Birth Nurture	Uncommon-winter Abundant-spring, summer, fall Migrating Birth Nurture Feeding Molt	Rare-winter Abundant-spring, summer, fall Migrating Birth Nurture Feeding Molt	Rare-winter Abundant-spring, summer, fall Migrating Nurture Feeding Molt	Uncommon-spring, summer, fall
BEARDED SEAL	Open pack, flaw & front (winter,spring) & remnants (spring); Fringe (summer - fall)	Common-winter, spring Feeding Mating Molt Birth Nurture	Common-winter, spring Migrating Feeding Mating Molt Birth Nurture	Rare-winter	Common-winter Feeding Abundant-spring Migrating Feeding Birth Nurture Mating Molting	Common-winter Feeding Abundant-spring Migrating Feeding Birth Nurture Mating Molting Few-summer Feeding Abundant-fall Migrating Feeding	Common-winter Feeding Abundant-spring Migrating Feeding Birth Nurture Mating Molting Few-summer Feeding Abundant-fall Migrating Feeding	Common-winter Feeding Abundant-spring, summer, fall Migrating Feeding Birth Nurture Mating Molting	Rare-winter Common-spring, summer, fall Feeding Birth Nurture Mating Molting
RINGED SEAL	Consol. pack & fast (all yr); open pack, fringe, & remnants (spring, summer)	Few-winter, spring	Few-winter, spring	Few-winter, spring	Common-winter, spring Migrating Feeding Birth Nurture Mating	Abundant-fall, winter,spring Migrating Feeding Birth Nurture Mating Molting Uncommon-summer	Abundant-fall, winter,spring Migrating Feeding Birth Nurture Mating Molting Uncommon-summer	Abundant-all yr Feeding Birth Nurture Mating Molting	Abundant-all yr Feeding Birth Nurture Mating Molting
SPOTTED SEAL	Front, fringe, & remnants (winter, spring)	Abundant-winter, spring Feeding Birth Nurture Mating Molting	Abundant-winter, spring Feeding Birth Nurture Mating Molting	Few-winter, spring	Abundant-winter, spring Migrating Feeding Birth Nurture Mating Molting	Abundant-spring, summer, fall Migrating Feeding Molting	Abundant-spring, summer, fall Migrating Feeding Molting	Abundant-spring, summer, fall Migrating Feeding Molting	Uncommon-summer

Table 10. continued

Species	Ice type	BRISTOL	ST. GEORGE	NAVARIN	ST. MATTHEW	NORTON	HOPE	CHUKCHI	BEAUFORT
RIBBON SEAL	Front & remnants (winter, spring)	Common-winter, spring Feeding Birth Nurture Mating Molting	Abundant-winter, spring Feeding Birth Nurture Mating Molting	Few-winter, spring	Abundant-winter, spring Feeding Birth Nurture Mating Molting	Common-spring, fall Feeding Molting Migrating	Common-spring Feeding Molting Uncommon-summer, fall	Uncommon-spring, summer, fall	Rare-summer

Table 11. The birth period, characteristics of birth sites, duration of dependency and mobility of the young of nine species of ice-associated mammals.

Species	Birth Period	Characteristics of Birth Site	Duration of Dependency	Mobility of Dependent Young
Arctic Fox	May-June	Subsurface Den on land	3-5 mos.	Restricted to densite until independent.
Polar Bear	Nov-Dec	Subnivian den mainly on land	24-28 mos.	2-3 mos. restricted to densite; then travel with mother
Belukha	June-Aug	Near shore-open water	24 mos.	Mobile - travel with mother
Bowhead	March-May	Leads in pack	24 mos.?	Mobile - travel with mother
Walrus	April-June	On pack	18-24 mos.	Mobile - travel with mother
Bearded Seal	March-May	On pack	2-3 weeks	Mobile - travel with mother
Ringed Seal	March-April	Subnivian lair on fast ice and heavy pack	4-6 weeks	Restricted to lair until weaned
Spotted Seal	March-April	On ice of front zone	3-4 weeks	Passive drift on ice
Ribbon Seal	March-April	On ice of front zone	3-4 weeks	Passive drift on ice

will be conducted mainly during the ice-free period, except in the western Beaufort Sea, in which case mammal-ice relationships only in the latter locality will require some consideration. For the production phase, in which permanent offshore platforms, shore camps, shipping, air traffic, and potential spills are among the factors to be considered, a much broader variety of mammal-ice relationships must be reckoned with, since this phase will affect greater areas and persist for a much longer period of time.

It is perhaps most useful to consider each of the major ice-habitats of these mammals that exist within the geological basins and to point out some of the known and potential impacts that could occur with the different phases of oil development.

B. Fast Ice

Fast ice of sufficient extent and stability for exploratory operations occurs in or adjacent to the Norton, Hope, Kotzebue, Chukchi and Beaufort basins. As an annual, relatively stable extension of land, it is a convenient platform for conducting many operations connected with nearshore petroleum development. Its stability and thickness are generally related to latitude. Thus, it is of greatest utility to man in the most northerly latitudes.

To date, fast ice has provided a useful platform on which to construct temporary roads and to conduct exploratory seismic and drilling operations. For local residents of coastal areas, fast ice provides an excellent route of travel and a platform important in fishing and hunting. It is anticipated that human activity in the fast ice zone, especially from Norton Sound northward, will intensify as development progresses from the exploratory stage.

The principal mammalian inhabitants of the fast ice are ringed seals, for whom it is the primary habitat for birth and nurture of their young. Its degree of stability seems to be the principal factor affecting the success (or lack thereof) in the annual production of young by this species (McLaren, 1958). That is, the best production of ringed seals takes place in the most stable ice, which also will tend to be the most useful ice for seismic surveys and exploratory drilling. Polar bears and arctic foxes also occur on this ice, probably in numbers proportional to the density of ringed seals, since the latter are their main reason for being there. The bears and foxes feed on ringed seal pups, and the bears also take older seals, the remains of which are fed on by the foxes after the bears are sated.

As we have demonstrated earlier in this report, seismic surveys conducted on the fast ice do have a displacing effect on ringed seals, hence, presumably on polar bears and foxes, as well. While we assume that this effect is temporary, i.e. that they are displaced only in the year when the disturbance occurs, it is conceivable that repetitive disturbance over several years, or disturbance causing activities covering great expanses of the available ringed seal habitat, could have very significant effects on the production of young by this species and, in turn, on the availability of food for the bears and foxes. Probably the establishment of permanent camps, platforms, shipping centers, etc. will have long-term displacing effects, but these will be local. Unless such facilities are numerous along a large part of the coast, the impact on the ringed seal population as a whole probably will not be significant.

We suspect that, in the production phase, the probability of petroleum spills will be greater under the fast ice than farther from shore. Under-ice releases probably will be contained in the immediate area, as long as the ice remains stable, for it will be temporarily trapped in pockets in the irregular undersurface of the ice. We think that there is low probability of recovery of such entrapped oil from the fast ice zone, because of that irregularity. At any rate, it is likely to have an adverse impact on the resident ringed seals, before it can be recovered. Since the oil will tend to rise and accumulate in the breathing holes of the seals, and since most of those holes do not penetrate completely through the snow to the air above, there will be a tendency for the volatile fractions to be released and accumulate in the air pockets and subnivian lairs used by the seals. We expect that most of the adult seals in the area so affected would depart at once. Some females might remain, but on emerging into their lairs to nurse their pups, they would become coated with oil and, ultimately transfer it to the inside of the lair and the pups themselves. This would cause reduction in insulative value of the pup's woolly lanugo coat, on which it relies for warmth. Probably, some oil from the mothers body surface would be ingested during suckling. We anticipate that, in the area of a spill under fast ice, all of the ringed seal pups would be lost, either from desertion, excessive heat loss, oil ingestion, or any combination of these. The extent of this impact would be dependent on the extent of the spill.

C. Flaw Zone

Flaw zones of major importance to mammals occur in the St. Matthew, Norton, Hope, Chukchi, and Beaufort basins. Of these, we regard as most important the persistent flaw along the northwestern coast, between

Point Hope and Barrow. This flaw is frequented throughout the winter by ringed and bearded seals and because of the latter's abundance, by polar bears and arctic foxes. A large proportion of the bear population of the Chukchi Sea resides in this area in spring. At that time also, the flaw becomes the migration corridor for practically all of the bowheads, belukhas, walruses, and bearded and ringed seals moving northward from their wintering grounds in the Bering Sea to their summer feeding areas in the Chukchi or Beaufort seas. En route to the flaw, these animals come around the eastern and western ends of St. Lawrence Island, then through Bering Strait, and northward through the broken pack to the vicinity of Point Hope. The period of greatest mammal numbers along that route and in the flaw between Point Hope and Barrow is from March to July. It is probable that any seismic activity, drilling, shipping, or heavy aircraft traffic it, especially its narrower parts, will discourage if not prevent those mammals from completing their normal migrations in timely fashion, for they seem to have no alternative routes.

D. Fringe and Front

The fringes and front may occur annually in most of the proposed lease areas north of the Alaska Peninsula and Aleutian Islands. Exceptions are the southwestern part of the Navarin Basin, over which sea ice usually does not occur, and the St. George Basin, where ice is present only during years of maximal extent of the pack. The front is a feature of the pack during February through April. It occurs almost annually in Bristol Bay and less regularly over the St. George Basin. In occasional winters of minimal ice cover, it may occur in the Norton Basin.

The front is of critical importance to virtually the entire populations of spotted and ribbon seals from March to late April. This zone also is

This zone also is utilized by some bearded and ringed seals, walruses and, depending on its location, harbor seals. Almost the entire annual production of spotted and ribbon seal pups is born in the front and fringe. Pups of both species remain on the ice until weaned and are dependent on their woolly hair (lanugo) for insulation. The importance of the lanugo for thermoregulation decreases as thickness of the blubber layer increases (e.g. see Davydov and Makarova 1965). The young of bearded seals and walruses are born mainly north of the front. Unlike those of spotted and ribbon seals, the young of these two species are swimmers (though they swim poorly and for short periods of time), and they move with their mothers soon after birth.

Vessel traffic in the front probably would result in direct mortality of some young seals in areas of high seal density. The number of cases of pups being forced into the water for prolonged periods of time also will be increased, thus contributing to increased mortality through thermal stress.

The motion and structure of ice comprising the front are such that oil in the water will become concentrated in the openings between floes. Through the dipping and pumping action of floes rising and falling with waves and swells, this oil would be deposited on the ice. Lanugo-clad pups, may become coated by this oil, largely destroying the insulative qualititi̇es of their hair. Adults surfacing through a slick or moving on the oil-covered floes likewise would become coated. Contact of oil-covered females with their pups may lead to the pups being coated, as well as to ingestion of oil by the pups while nursing. Oiling of molting seals might increase skin irritation, possibly increasing the probability of infection by other agents.

E. Remnants

The presence of the spring remnant ice in the Bering Sea is of critical importance for the seals that do not haul out on land and must haul out on ice in order to complete their molt. Judging from the reactions of seals held in captivity, the molt itself causes considerable metabolic and psychological stress to the animals, who show this through their irritability, general lethargy, and disinterest in food (Ronald et al., 1970). At the time of hair loss and shedding of the outer protective layer of cornified epidermis, there is loss of serum and electrolytes, and the skin is particularly vulnerable to infection by microbiological agents (Greenwood et al., 1974). Probably, the affected skin is equally vulnerable to irritation by toxicants. This, then, is a period when further stresses, by disturbance or introduction of chemical irritants may have especially deleterious, direct effects on the seals. For the majority of seals in this region, the period of greatest vulnerability is during May and June, though some individuals are molting as early as April or as late as July. Molt in the walrus is more prolonged, extending mainly from April to August.

Use of the remnant ice by walruses in May and June is connected also with their annual calving season, which lasts from about mid-April to mid-June (Burns, 1965; Krylov, 1969). At that time, the females haul out on ice, especially in the northern remnants (i.e. north of 62°N), where they give birth to their calves and suckle them. Although the calves quickly become capable of sustained immersion in the cold water, they are ill-prepared for this at birth and apparently rely on spending a large amount of time on the ice, where they can be warmed by the sun and by contact with the mother (Fay and Ray, 1968; Ray and Fay, 1968). Disturbances resulting in prolonged immersion at this early age may take a considerable metabolic toll. While that is not necessarily lethal in itself, it may contribute to calf mortality in combination other stresses and pathogens.

G. General

Some polar bears will be attracted to sites of human activity, requiring removal. However, most (particularly pregnant sows or sows with cubs) will be displaced. Because of displacement, petroleum development probably will reduce the extent of available habitat for polar bears, in direct proportion to the extensiveness of development activities.

Arctic foxes are attracted by and can be expected to congregate near sites of human activity. This will result in an increasing incidence of their predation on ringed seal pups in those areas and an increase in the public health hazard to humans through diseases transmitted by foxes (i.e. rabies and alveolar hydatid disease).

Impacts on the more aquatic mammals of the ice zone probably will be mainly effects of sight, sound, and odors, plus some direct and indirect effects of oil spills per se. The acoustical and olfactory senses of marine mammals appear to be especially keen, and it is probable that the main effects will be through those receptors. Our experience indicates that continuous, low frequency sounds such as those made by heavy machinery seem to be least deterring; irregular or intermittent sounds and high frequencies seem to be more deterring. Fumes from combustion and other strong odors clearly elicit fright reactions in most species, as do sight and sound of low-flying aircraft and outboard-powered small boats. Large vessels seem to be less frightening than small boats, though recent studies in Japan and in southeastern Alaska have suggested that large whales respond more adversely to large than small vessels (Nishiwaki and Sase, 1977; Jurasc and Jurasc, unpublished).

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