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028 Distribution of Bowhead Whales in Relation to Hydrometeorological Events in the Beaufort Sea

Canada

March 1986

The Environmental Studies Revolving Funds are financed from special levies on the oil and gas industry and administered by the Canada Oil and Gas Lands Administration for the Minister of Energy, Mines and Resources, and by the Northern Affairs Program for the Minister of Indian Affairs and Northern Development.

Environmental Studies Revolving Funds
Report No. 028

March 1986

DISTRIBUTION OF BOWHEAD WHALES IN RELATION TO HYDROMETEOROLOGICAL EVENTS IN THE BEAUFORT SEA

by

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The correct citation for this report is:

Thomson, D.H., D.B. Fissel, J.R. Marko, R.A. Davis and G.A. Borstad. 1986. Distribution of bowhead whales in relation to hydrometeorological events in the Beaufort Sea. Environmental Studies Revolving Funds Report No. 028. Ottawa. 119 p.

Published under the auspices
of the Environmental Studies
Revolving Funds
ISBN 0-920783-27-9

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ACKNOWLEDGEMENTS

This project was funded by the Environmental Studies Revolving Fund and administered through the Department of Indian Affairs and Northern Development. We thank Dr. D. Stone of DIAND, who was the scientific advisor for the project, for his help and support.

We also thank Mr. N. Vanderkooy of Dome Petroleum for his assistance in obtaining oceanographic data collected from drillships, and Arctic Sciences personnel who contributed to this study, including R. Chave, computer programming, and N. Andrew, drafting.

Among employees of LGL Ltd., we thank R. Evans for compilation of the bowhead distribution maps, P. McLaren and M. McLaren who reviewed the manuscript, and W.J. Richardson for editing and critical comments. Report production was facilitated by the efforts of C. Holdsworth (proofreading), B. DeLong (drafting), B. Griffen (typing), and R. Stark (typing).

SUMMARY

Aerial surveys of the summertime distribution of bowhead whales in the southeastern Beaufort Sea have shown that the distribution of bowheads has been quite variable over the four years of study, 1980-83. This report presents the results of an investigation of the relationship between the observed distribution of bowhead whales in the Canadian Beaufort Sea and the physical and meteorological patterns that might affect the distribution of zooplankton in the Beaufort Sea. The overall aim of this study was to identify easily-monitored parameters that could be used to predict bowhead whale distribution.

This retrospective analysis was conducted for the years 1980 to 1983. All available data on bowhead whale distributions, zooplankton standing crop, temperature and salinity, wind speed and direction, and satellite imagery were compiled and analyzed.

In the southeastern Beaufort Sea, variation in the surface layer properties of much of the nearshore area and industrialized zone is determined by the location of the Mackenzie River plume. The water in areas under plume influence are warmer and less saline than the oceanic water.

Analysis of wind and physical oceanographic data and processed satellite images show that the movements of the Mackenzie River plume are determined by the wind. Under prolonged westerly winds the plume is found close inshore off the Tuktoyaktuk Peninsula, and the water in the industrialized area off Richards Island is under oceanic influences. Under prolonged easterly winds the plume extends to the north off Richards Island and to the west of Herschel Island. However, the relationship between wind and the location of the plume is not always this clear and wind cannot be used as a predictor of plume location.

Zooplankton biomass appears to be higher in the oceanic water than in the low salinity waters under the influence of the Mackenzie River plume. As a result, the location and extent of the Mackenzie River plume may be an important factor influencing the distribution and biomass of zooplankton in the southeastern Beaufort Sea. It is reasonable to assume that bowheads frequent those parts of the Beaufort Sea that contain substantial concentrations of their zooplankton food. Thus, it was hypothesized that bowhead whales avoid the low salinity waters of the plume.

At the beginning of August 1980, a plume edge was located in the industrialized area north of Richards Island. This plume edge was found farther to the northeast along the

Tuktoyaktuk Peninsula on each successive satellite image. These changes in position appear to be consistent with the expected response of the surface waters to the respective wind fields. Analysis of bowhead distributional data indicated that concentrations of whales appeared to be associated with this plume edge and that the centre of the whale concentration was found farther to the northeast as August progressed. Salinity in the area north of Richards Island decreased from early August to mid September as this area came under the influence of the Mackenzie River plume.

In 1981, salinity was low in the area north of Richards Island during the first half of August and whales were scarce in that area. Salinity increased during the middle of the month, during a period of strong westerly winds, which pushed the plume toward the coast. At this time, aerial surveys showed the presence of a large number of whales close to shore. The whales were in oceanic water and not estuarine water at this time. Later in the season, salinity decreased in the area north of Richards Island and whales were found farther to the northeast off the Tuktoyaktuk Peninsula.

The data from both 1980 and 1981 are consistent with the hypothesis that bowheads avoid the low salinity waters of the Mackenzie River plume. In 1982 whales were absent from the area north of Richards Island. This area was not under the influence of the Mackenzie River plume and salinity was high throughout the season. These findings do not invalidate the hypothesis that bowheads avoid the plume, however. Rather, they indicate that the mere absence of the plume is not enough to attract bowheads to an area.

In 1983, few bowheads occurred in the industrial zone north of Richards Island. Salinity was low throughout the observation period, indicating that the area was under the influence of Mackenzie River water. For 1983, results are consistent with the hypothesis that whales avoid the plume.

The principal objective of this study was to determine whether easily measured oceanographic parameters can be used to predict the geographic distribution and abundance of bowhead whales in and near the zone of industrial activity in the southeastern Beaufort Sea. Assuming that zooplankton distributional patterns are influenced by the Mackenzie River plume, its location is the most important natural determinant of whale distribution in the industrial zone. The relevant question is whether easily measured parameters can be used to predict the extent and location of the plume. The parameters examined included surface temperature and turbidity data from satellite imagery, salinity data from drillships, wind data from Tuktoyaktuk, and data on discharge rates of the Mackenzie River.

The most useful predictor of plume location is thermal and visible satellite imagery supplemented with salinity data. The salinity data are necessary to ground-truth satellite data and to provide the time series data that satellite data do not provide.

Ongoing studies are investigating the relationships between zooplankton and oceanography and, to a more limited extent, the relationships between whales and zooplankton. Future studies in this series should address the responses of bowheads to zooplankton concentrations.

RÉSUMÉ

Des recensements aériens de la distribution estivale des baleines franches au sud-est de la mer de Beaufort ont démontré que la distribution de ces dernières a considérablement varié pendant les quatre années de l'étude, soit de 1980 à 1983. Ce rapport donne les résultats d'une enquête sur les liens existant entre la distribution observée des baleines franches dans la mer de Beaufort au Canada et les dispositions physiques et météorologiques qui pourraient influer sur la répartition des concentrations de zooplancton dans la mer de Beaufort. L'objectif global de cette étude était d'identifier les indices facilement décelables et pouvant servir à prédire la distribution des baleines franches.

Cette analyse a été effectuée au cours des années 1980 à 1983 inclusivement. Toutes les données disponibles sur la distribution des baleines franches, la biomasse existante de zooplancton, la température et le degré de salinité, la vitesse et la direction des vents, ainsi que les images réalisées par satellite ont été recueillies et analysées.

Dans la partie sud-est de la mer de Beaufort, la variation des caractéristiques de la couche superficielle d'une grande partie de la zone du littoral et de la zone industrielle dépend de la position du panache du fleuve Mackenzie. Les eaux des zones affectées par le panache sont plus chaudes et moins salées que ne le sont les eaux océaniques.

Ces analyses des données physiques éoliennes et océanographiques ainsi que celles des images réalisées par satellite démontrent que les mouvements du panache du Mackenzie sont déterminés par les vents. Sous des conditions persistantes de vents d'ouest, l'on constate que le panache se trouve près des côtes de la Péninsule Tuktoyaktuk et les eaux de la zone industrielle près de l'île Richards subissent des influences océaniques. Sous des conditions persistantes de vents d'est, la plume s'étend jusqu'à l'île Richards au nord et jusqu'a l'île Herschel à l'ouest. Cependant, les rapports entre la direction du vent ent la position du panache ne sont pas toujours aussi clairs; dès lors, la direction du vent ne peut pas être utilisée afin de prédire la position du panache.

La biomasse de zooplancton semble être plus dense dans les eaux océaniques que dans les eaux à moindre salinité et dépendant du panache du Mackenzie. Par conséquent, la position et l'étendue du panache du Mackenzie pauvent être un facteur important influençant la répartition et la biomasse de zooplancton dans le sud-est de la mer de Beaufort. Il est raisonnable d'en déduire que les baleines franches fréquentent les parties de la mer de Beaufort ayant des concentrations importantes de leur alimentation, le zooplancton. Ainsi, l'on a postulé que les baleines franches évitent les eaux du panache à moindre salinité.

Au début d'août 1980, l'on avait repéré un biseau du panache dans la zone industrielle au nord de l'île Richards. Sur chaque image successive de satellite, l'on a retrouvé ce biseau du panache plus loin au nord-est, près de la Péninsule de Tuktoyaktuk. Ces changements de position semblent coincider avec la réaction prévue des eaux superficielles aux champs éoliens respectifs. L'analyse des données sur la distribution des baleines franches révèlait qu'il y aurait un rapport entre la concentration des baleines et le biseau, et que le centre de la concentration des baleines se déplaçait de plus en plus vers le nord-est au dur et à mesure que le mois d'août avançait. Le degré de salinité dans la zone au nord de l'île Richards diminuait à partir du début août jusqu'a la mi-septembre, à mesure que cette zone tombait sous l'influence du panache du Mackenzie.

Pendant la première moitié du mois d'août 1981, le degré de salinité était bas dans la zone au nord de l'île Richards et les baleines y étaient rares. Vers le milieu du mois, le degré de salinité augmentait pendant une période de vents d'ouest violents, qui avaient poussé le panache vers la côte. A ce moment-là, des recensements aériens montraient la présence d'un grand nombre de baleines près de la côte. Celles-ci se trouvaient alors dans les eaux océaniques et non pas dans celles de l'embouchure. Plus tard dans la saison, le degré de salinité diminuait dans la zone du nord de l'île Richards, et l'on trouvait des baleines plus au nord-est, près de la Péninsule de Tuktoyaktuk.

Les données recueillies à la fois en 1980 et en 1981 coincident avec l'hypothèse que les baleines franches évitent les eaux à moindre salinité du panache du Mackenzie. En 1982, les baleines étaient absentes de la zone au nord de l'île Richards. Cette zone n'était pas sous l'influence du panache du Mackenzie et le degré de salinité demeurait élevé pendant toute la saison. Ces conclusions cependant n'annullent point l'hypothèse que les baleines franches évitent le panache. Au contraire, elles indiquent que seule l'absence du panache dans une zone donnée ne suffit pas à y attirer les baleines franches.

En 1983, peu de baleines franches étaient repérées dans la zone industrielle au nord de l'île Richards. Le degré de salinité était resté bas pendant la période d'observation, indiquant ainsi que la zone était sous l'influence des eaux du Mackenzie. En 1983, les conclusions coincidaient avec l'hypothèse que les baleines évitent le panache.

L'objectif principal de cette étude était de déterminer si l'on pouvait se servir de paramètres océanographiques facilement mesurables pour prédire la distribution géographique et l'abondance de baleines franches dans et près des zones d'activités industrielles dans la partie sud-est de la mer de Beaufort. Si l'on suppose que la disposition de la répartition du zooplancton dépend du panache du Mackenzie, alors sa position est l'élément naturel le plus important qui déterminera la distribution des baleines dans la zone industrielle. La question importante est de savoir si des paramètres facilement mesurables peuvent aider à prévoir l'étendue et la position du panache. Les paramètres examinés comprenaient les données sur les températures en surface et la turbidité observée à partir des images prises par satellite, les données sur le degré de salinité recueillies par les navires de forage, les données éoliennes de Tuktoyaktuk et les données sur les taux de décharge du Mackenzie.

L'élément de prédiction le plus utile dans la position du panache est constitué par les images réalisées par satellite sur les données thermiques et la visibilité en plus des données sur la salinité. Ces dernières sont indispensables afin de confirmer la véracité des images par satellite et pour livrer des données de série dans le temps non fournies par satellite.

Des études en cours recherchent les rapports entre le zooplancton et l'océanographie et, dans une moindre mesure, les liens entre les baleines et le zooplancton. Des études ultérieures dans cette même série devraient résoudre le problème des baleines franches et des concentrations de zooplancton.

INTRODUCTION

The bowhead whale, Balaena mysticetus, is a large baleen whale that inhabits cold northern waters. The bowheads of the Western Arctic (= Bering Sea) population winter in the Bering Sea and migrate around western and northern Alaska to and from summering grounds in the Canadian Beaufort Sea. The size of this population was much reduced by intensive commercial whaling between 1848 and 1914 (Bockstoce and Botkin 1983). The Western Arctic population is now estimated to number only about 4417 individuals (I.W.C. 1985). Bowheads are classified as endangered under U.S. legislation and are also considered endangered in Canada (Committee on the Status of Endangered Wildlife in Canada).

From late May to early September, the great majority of the Western Arctic bowheads are in Canadian waters (Fraker 1979; Fraker and Bockstoce 1980; Davis et al. 1982). Offshore hydrocarbon exploration, including drilling from drillships and artificial islands, has been underway in the central part of the bowheads' summer range (especially the waters north of Richards Island [Mackenzie Delta] and the western Tuktoyaktuk Peninsula) since the early 1970's. The intensity of offshore industrial activity has generally increased since then.

Systematic aerial surveys of the summer range of the Western Arctic bowhead began in 1980. The results of these surveys and of other non-systematic coverage indicate that there have been substantial annual differences in bowhead distribution. There has been a decrease in the numbers of whales present during the summer in the industrialized areas of the Canadian Beaufort Sea. Two hypotheses have been put forward to explain these changes in distribution (BEMP 1984): (1) bowhead whales are avoiding the industrial areas because of noise and disturbance, and/or (2) bowhead whales are responding to changes in the distribution patterns of their primary food, zooplankton. These hypotheses are not mutually exclusive. The present study is the first stage of a test of the second hypothesis. It investigates the relationships between the observed distributions of bowhead whales in the Canadian Beaufort Sea and the physical and meteorological features that might affect the distribution of zooplankton in the Beaufort Sea. If there is a close relationship between bowhead distribution and inferred zooplankton concentrating mechanisms, then it may be possible to predict bowhead distribution by monitoring easily measured surface hydrological phenomena. Only when the roles of natural phenomena are understood will it be possible to determine whether observed distribution changes are caused by, or influenced by, industrial activities. The overall aim of the present study, then, is to determine whether easily measured parameters can be used to predict bowhead whale distributions.

In this report, we first review the general features of the southeastern Beaufort Sea, including physical oceanography and meteorology, zooplankton communities, mechanisms associated with zooplankton patchiness, and the distribution and feeding habits of bowhead whales. We then analyse satellite imagery, sea ice data, physical oceanographic and meteorological measurements, and bowhead whale distribution in 1980-1983. These data are then correlated in an attempt to explain the observed distributions of bowhead whales in terms of the hydrometeorological phenomena operating in the Beaufort Sea.

The geographic area considered during this study is the southeastern Beaufort Sea, from the Alaska/Canada border (141°W) to Cape Bathurst (128°W) and north to 72°N (Fig. 1).

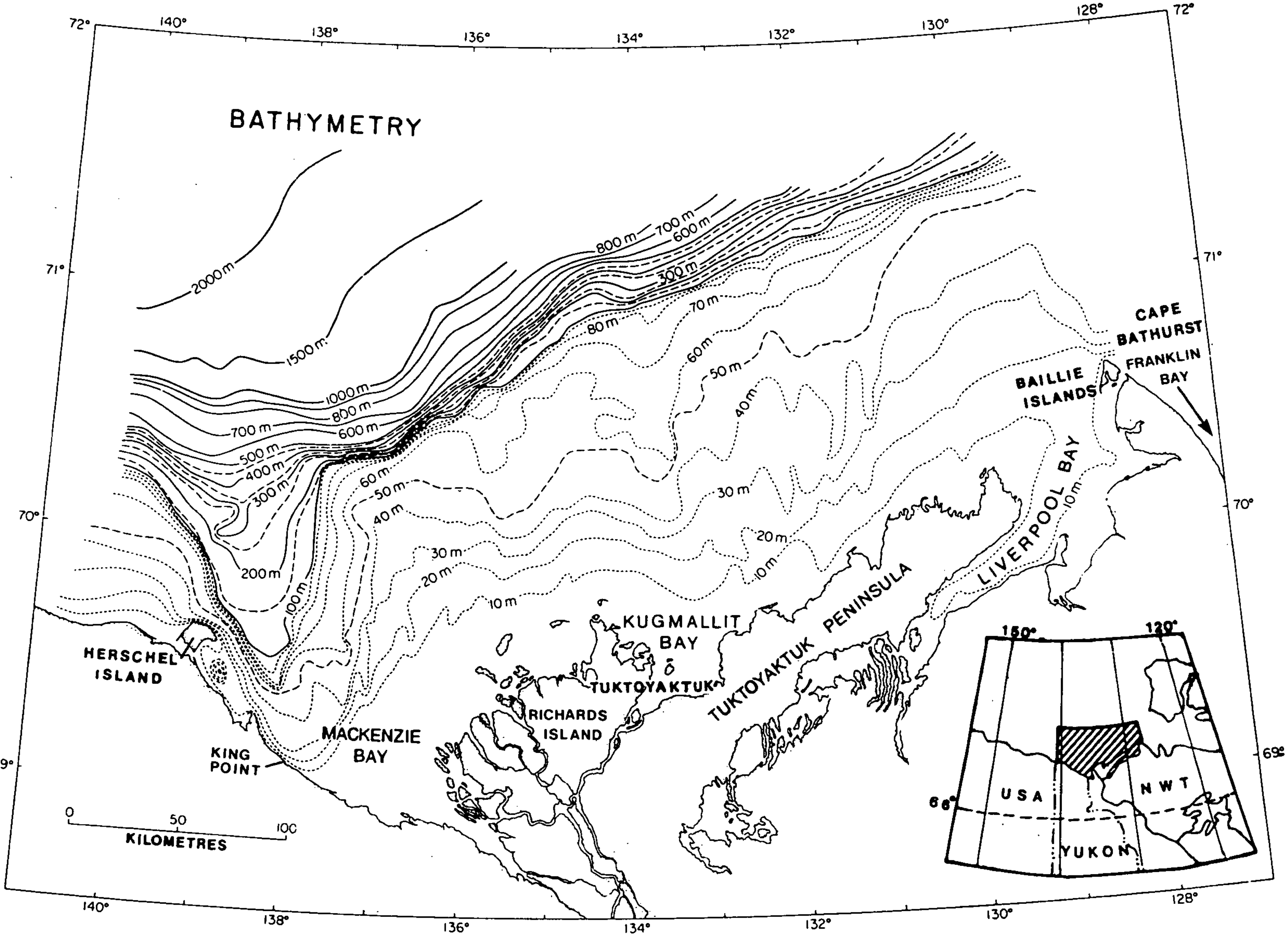

Figure 1. The bathymetry of the study area in the Canadian Beaufort Sea (from Pelletier 1975).

BACKGROUND

There have been a few studies of the relationships between whales (both toothed and baleen whales) and oceanographic conditions on the major whaling grounds in non-arctic parts of the world ocean. Most of this work is from the Japanese Whales Research Institute and was conducted during Japanese whaling operations in the 1950's and 60's (Uda and Nasu 1956; Nemoto 1963; Nasu 1966; Kawamura 1973). In a review of much of this work, Nasu (1966) classified baleen whale feeding grounds at high latitudes into three major kinds: (1) fronts separating major water masses; (2) 'eddy grounds', where eddying circulation is common either due to instabilities along frontal boundaries or because of topographic effects of islands, capes, promontories or seamounts; and (3) upwelling areas, either topographic or wind induced. Gallardo et al. (1983) recently described an upwelling zone off the coast of Chile that exhibited lowered surface temperature, increased salinity, elevated chlorophyll concentrations, abundant birds and high densities of Bryde's whale (*Balaenoptera edeni*). Many other whale species were also observed. Gallardo et al. (1983) made the point that the distribution of Bryde's whales in the area appeared to show more correlation with the presence of food of the right kind and in adequate quantities than with a given range of temperature.

Although the distribution and abundance of bowhead whales, white whales (*Delphinapterus leucas*) and other marine mammals in the Beaufort, Chukchi and northern Bering Seas have been studied since 1975, few studies have attempted to relate whale distributions to oceanography (Griffiths and Buchanan 1982; Borstad 1984; Thomson and Martin 1984). There is evidence from elsewhere that the energy requirements of baleen whales in general are such that they must feed on concentrated patches of zooplankton (Brodie et al. 1978; Brodie 1981). Using conventional *in situ* sampling and acoustical remote sensing from a small vessel, Griffiths and Buchanan (1982) were able to show correlations between the presence of bowheads and the abundance of their zooplankton food supply. However, they were unable to sample large areas, and there is very little information concerning either the standing stocks and production of zooplankton in the Beaufort Sea, or their temporal and spatial variability. Because of the logistical problems and cost of such a study, there has been no attempt to relate bowhead whale distribution to food abundance over a large area, or to the physical factors that might partly determine the distribution of zooplankton. However, the U.S. Minerals Management Service is sponsoring a project of this nature; it will start in September 1985 in part of the Alaskan Beaufort Sea. A related study funded by DIAND will be conducted along part of the Yukon coast in the Canadian Beaufort Sea in August 1985.

PHYSICAL OCEANOGRAPHY OF THE SOUTHEASTERN BEAUFORT SEA

Bathymetry

The southeastern Beaufort Sea features a wide, shallow continental shelf extending up to 130 km offshore, with maximum depths of 60 to 100 m (Fig. 1). The shelf break is of varying steepness and generally spans depths of 60-1000 m. Beyond the shelf break and continental slope is the continental rise and abyssal plain of the Canada Basin.

Ice Cover

Ice cover varies seasonally over the continental shelf and slope. In May, the sea ice begins to melt and retreat to the offshore under the combined warming from solar insolation and the comparatively warm waters of the Mackenzie River freshet. Between July and September, most of the shelf is ice free, although incursions of ice from the permanent Arctic Ocean pack ice located farther offshore can occur at any time. Local ice begins to form in September, and from November onward the Beaufort Sea is largely ice covered.

Circulation

The ocean circulation of the Beaufort Sea is generally dominated by the forcing of the surface wind field, particularly over the shallow continental shelf. Recent studies of the variability of currents at sites in the shallow (depth <100 m) waters off the Mackenzie Delta and Tuktoyaktuk Peninsula reveal that the currents are significantly correlated with the local winds (Fissel 1981; Fissel and Birch 1984). On average, the surface current is 0.5 to 2% of the wind speed, although the response to individual winds can be 2-3 times greater. While highly variable, wind driven ocean currents can attain speeds of up to 50-75 cm/s. The relationship of currents to winds in a shallow shelf sea are complex and non-linear. In the Beaufort Sea, the wind forcing is mediated by three highly variable quantities: (1) the degree of surface layer stratification due to the presence (or absence) of the Mackenzie River plume (discussed below); (2) the varying wind fetch of offshore winds which depends, in turn, on the location of the offshore pack ice; and (3) the duration over which strong winds blow.

An eastward flowing current offshore near the shelf break has been described (Huggett et al. 1977; Melling 1983). This current appears to persist in the absence of local wind forcing, and has typical mean flow speeds of 5-15 cm/s. This current may extend into Franklin Bay. Strong eastward flow entering Franklin Bay, off Cape Bathurst, has been measured from satellite-tracked drifter and ice velocity observations (Dome Petroleum et al. 1982). Along the shelf off the Yukon coast, stronger wind-independent currents have been observed having speeds of up to 75 cm/s; however, the sparsity of current data precludes any attempt to determine the spatial characteristics of the flow regime in this area.

Over the ice-infested deeper waters of the continental rise and abyssal plain, the circulation is weak (less than 5-10 cm/s) and directed westward. This motion is part of the Beaufort Gyre, the large clockwise circulation pattern that dominates flow in the Canadian Basin of the Arctic Ocean.

Surface Layer and Stratification

A considerable number of temperature and salinity profiles have been collected during the open water season over the past 35 years in the study area (see Cornford et al. 1982). Recently, surface temperature data have been obtained through satellite imagery. These data indicate that the spatial distribution of temperature and salinity are the combined results of two primary sources: the locations of freshwater discharge from the Mackenzie River, and marine water from the Arctic Ocean.

The horizontal extent of the Mackenzie River outflow, as defined by surface salinities of 5 °/oo or less and high sediment concentrations, is often confined to within 50 km of the coasts of Mackenzie Bay, Richards Island and Kugmallit Bay and within the 10 m isobath (Marko et al. 1983; Fissel and Birch 1984). However, on other occasions, satellite imagery reveals [faintly] turbid river water extending up to 100 km from the nearest shoreline (Borstad 1984). The boundary between the concentrated plume water and the offshore waters is usually characterized by very large horizontal gradients and frontal characteristics. Because of this, the extent of the concentrated plume is apparent from satellite imagery and during aircraft overflights.

A much larger river-influenced area characterized by reduced but non-zero suspended sediment concentrations, surface salinities of 20 °/oo or less, and a pronounced halocline lies beyond the river water. This zone covers much of the area off the coast between Herschel Island and Cape Bathurst and has been observed as far east as southwestern Banks Island. Its extension into the eastern Alaskan coastal zone is suspected on the basis of satellite observations of turbid water (Marko et al. 1983). The locations of zones under the influence of riverine outflow are strongly influenced by the wind, and to a lesser extent by levels of river flow, sea state and the sea-ice distribution (MacNeill and Garrett 1975).

Temperature and salinity at the surface are determined by the location of the Mackenzie River plume which, in turn, is largely determined by the wind (MacNeill and Garrett 1975) (Fig. 2). During steady northwest winds, offshore water movements are toward the southeast, and nearshore (within 10 km) water movements are eastward, in alignment with the coastline. Two days after cessation of these winds, currents gradually veer to the north and east (MacNeill and Garrett 1975). Under conditions of westerly or northwesterly winds, movement of the pack ice has an onshore component caused by rotational effects. This reduces the amount of open water in the area. Rotational effects on the movement of the river plume complement wind-induced surface water motions that cause the plume to turn eastward along the shore. The net result, for westerly or northwesterly winds, is a concentration of the river water along the coast east of Mackenzie Bay.

The response of nearshore waters to strong easterly winds is a current flow to the northwest. At the same time, the ice pack tends to drift offshore, expanding the area of open water. The easterly wind also counteracts the tendency of the river plume to turn to the east along the coastline; instead, the plume extends much farther offshore and remains in the western portion of the area (MacNeill and Garrett 1975; Herlinveaux and de Lange Boom 1975).

Upwelling

Under easterly winds a net transport away from the coast occurs in the surface layer. The replenishment of this water from below results in upwelling of the deeper water with a compensating shoreward transport at depth. The upwelled water is evident as a coastal band of cold, relatively high salinity water. The depth from which water is upwelled is difficult to determine from existing data. However, results of an oceanographic survey in 1952 (Fig. 3) reveal the effects of one coastal upwelling event driven by easterly winds in late August. An upward tilt of the salinity (and hence density) contours toward the coast indicates that cold, saline Arctic water normally present at depths of 60 m or greater near the shelf break was displaced upward along the coast of the Tuktoyaktuk Peninsula.

Over the Alaskan slope, upwelling has been reported by Hufford (1974) from depths of 125 m. Aagaard (1981) observed frequent upwelling from depths of 200 m at the shelf break in the Alaskan Beaufort Sea. Melling and Lewis (1982) suggest that in early autumn a substantial amount of upwelling of deeper Arctic Ocean water onto the continental shelf may occur. Upwelling would account for increased salinities observed in the upper 50 m of the water column from the summer months to November. Upwelling may be enhanced at the shelf break in a manner similar to that described in other areas (e.g., Scotia Shelf; Fournier 1978).

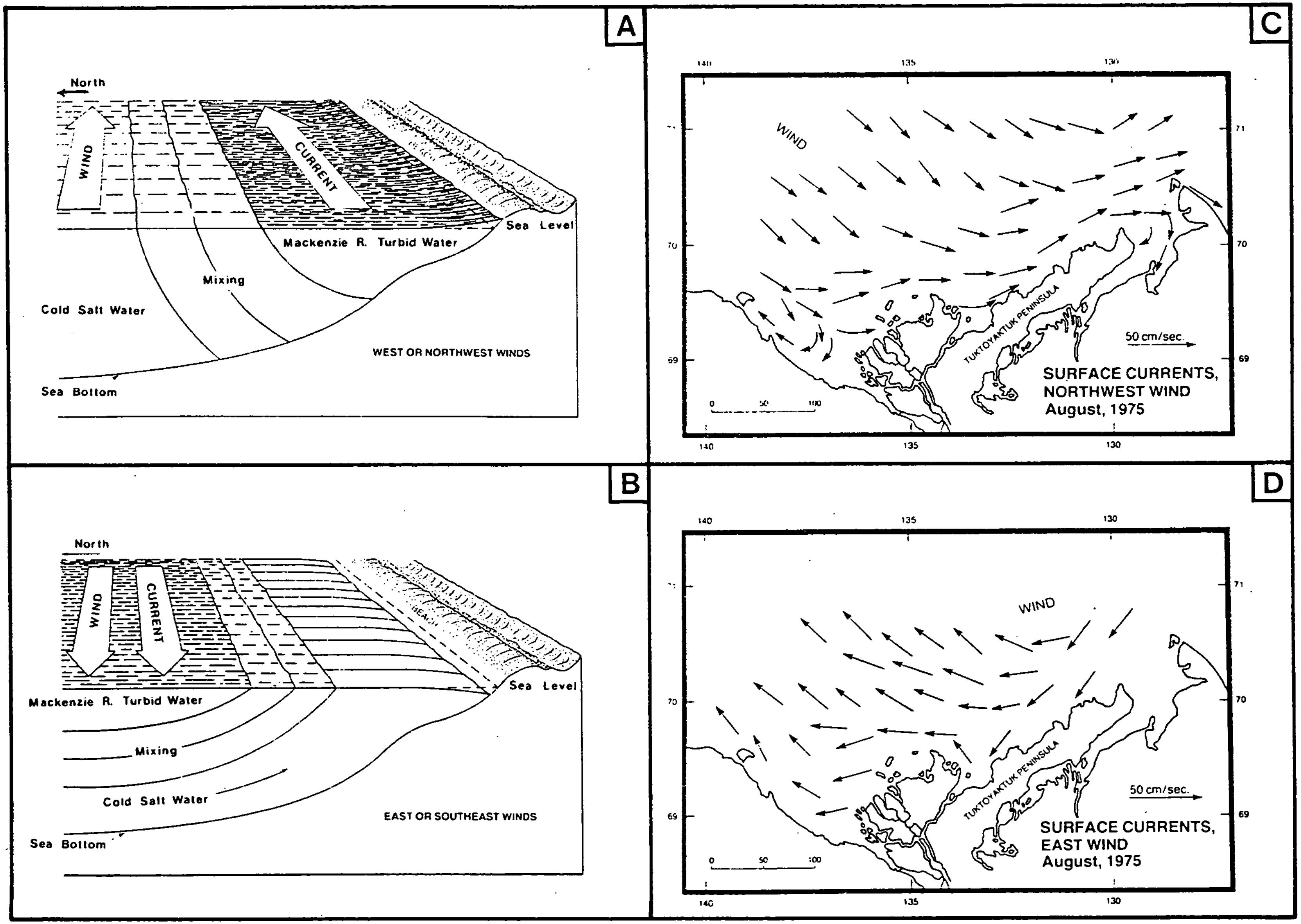

Figure 2. Illustrations of the response of the southeastern Beaufort Sea to wind forcing. The advection of the Mackenzie River plume in response to winds is illustrated (A,B) along with a generalized pattern of surface currents under prevailing wind conditions (C,D). (From the results of the Beaufort Sea project of 1974-1975; Herlinveaux and de Lange Boom 1975; McNeill and Garrett 1975).

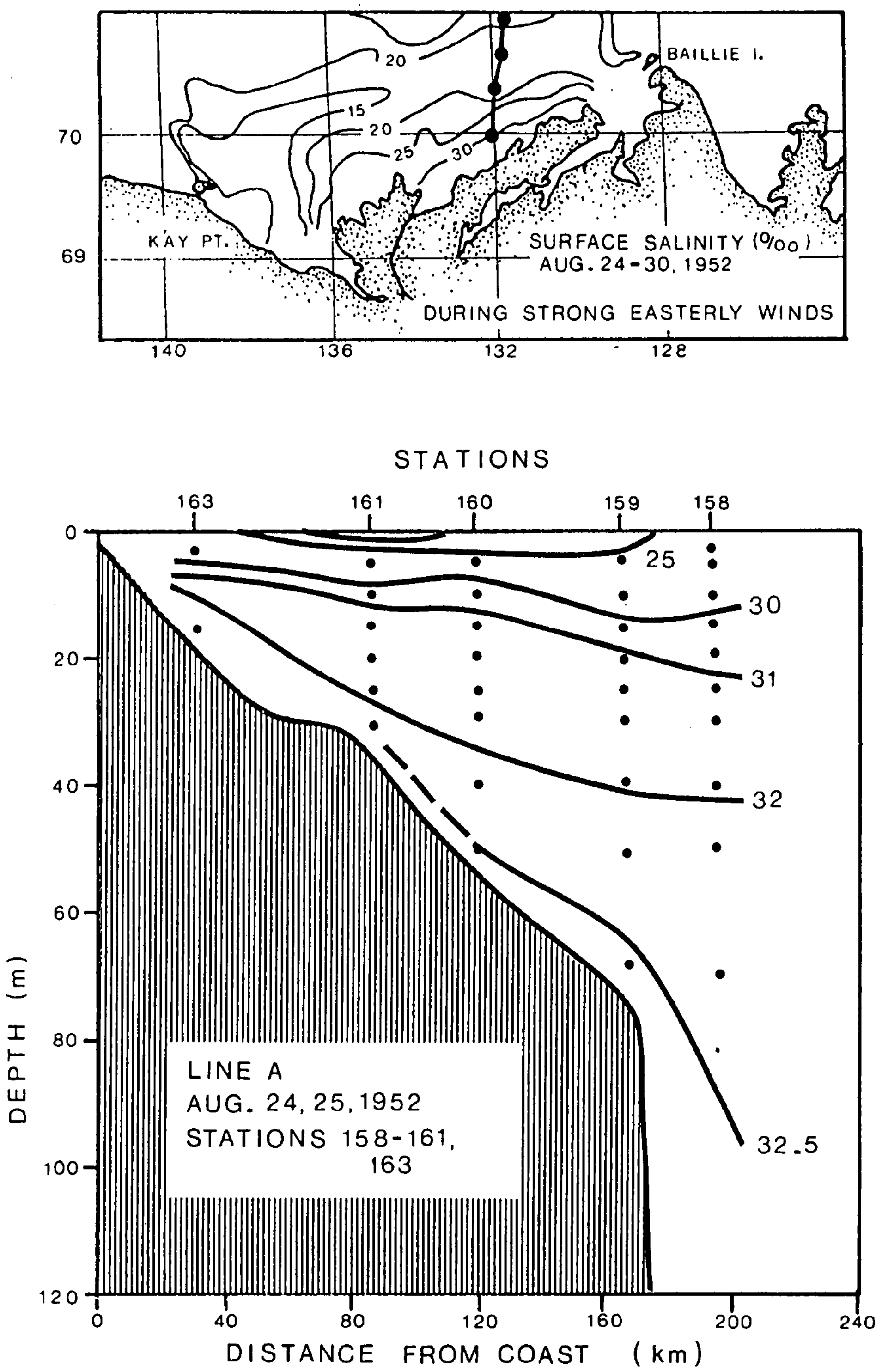

Figure 3. A coastal upwelling event over the continental shelf, inferred from the data of Cameron (1953).

SURFACE WINDS

Wind directions over the Beaufort Sea are markedly bimodal. The most frequent winds are from the northerly to westerly sector and from the southeasterly to northeasterly sector.

Directional distributions of winds based on measurements from coastal stations (Harper and Penland 1982) suggest that virtually all strong winds with speeds in excess of 40 km/h (11.1 m/s) are from the northwest (i.e. northwesterly) (Fig. 4). However, a survey of summer winds at offshore locations shows considerable interannual variability at high wind speeds (Fig. 5). In some years (e.g., 1979 and 1982) strong winds are more commonly from the east than from the west, whereas in other years strong easterly winds are virtually non-existent.

The dominant wind conditions in the Beaufort Sea are associated with the passage of large-scale weather systems. The weather systems result in wind events with typical periodicities ranging from 2.5 to 30 days. Strong westerly winds are often associated with low pressure systems travelling from west to east, often centered over the pack ice edge. Prolonged periods of easterly winds usually result from the establishment of a large high pressure system over the Arctic Ocean pack ice.

Wind patterns are similar in different seasons. Average monthly wind statistics collected over many years at Tuktoyaktuk (Fissel and Birch 1984) show that mean monthly wind speeds remain virtually constant throughout the year. However, there is evidence of a modest increase in the frequency of occurrence and mean strength of westerly and northwesterly winds in the autumn and winter months.

ZOOPLANKTON IN THE BEAUFORT SEA

In terms of biomass, copepods and hydrozoans were the dominant zooplankters collected with net tows in the Canadian Beaufort Sea (Griffiths and Buchanan 1982). Species composition of the zooplankton varies with hydrographic conditions. Grainger (1965) has identified three major groups: one group, characterized by the copepods *Calanus hyperboreus* and *C. glacialis* and other species, is important in both offshore and nearshore areas; a second, which includes the copepods *Gadius tenuispinus* and *Spinocalanus magnus*, is restricted to offshore areas; and a third, characterized by *Limnocalanus grimaldi* and two species of *Acartia* among others, is restricted to shallow coastal waters.

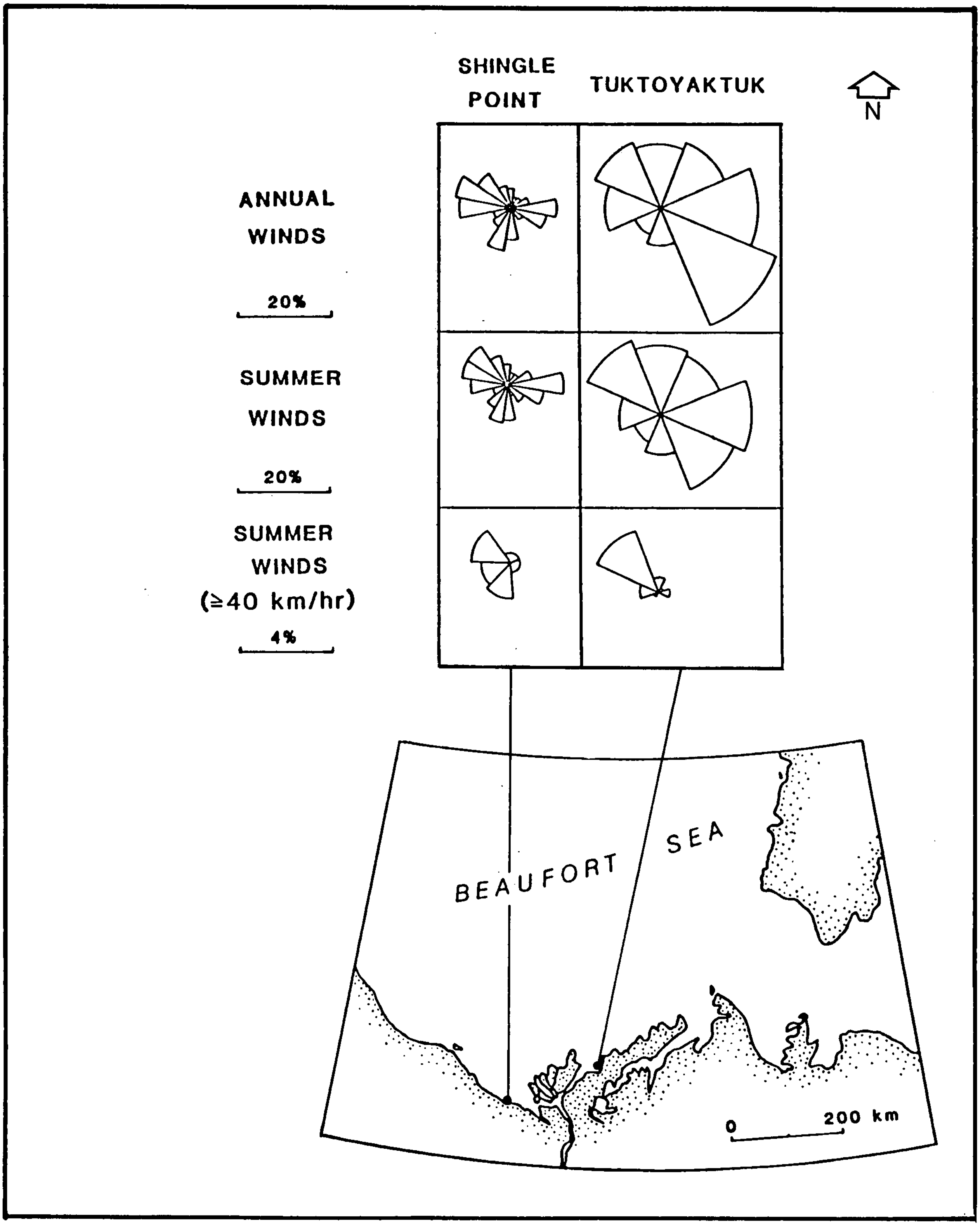

Figure 4. The directional distribution of winds at stations along the Beaufort Sea coast (from Harper and Penland 1982). The radii of the pie shaped areas denote the percentage of time when winds blow from the directional sector indicated. The number of years of data used in constructing these distributions is not stated.

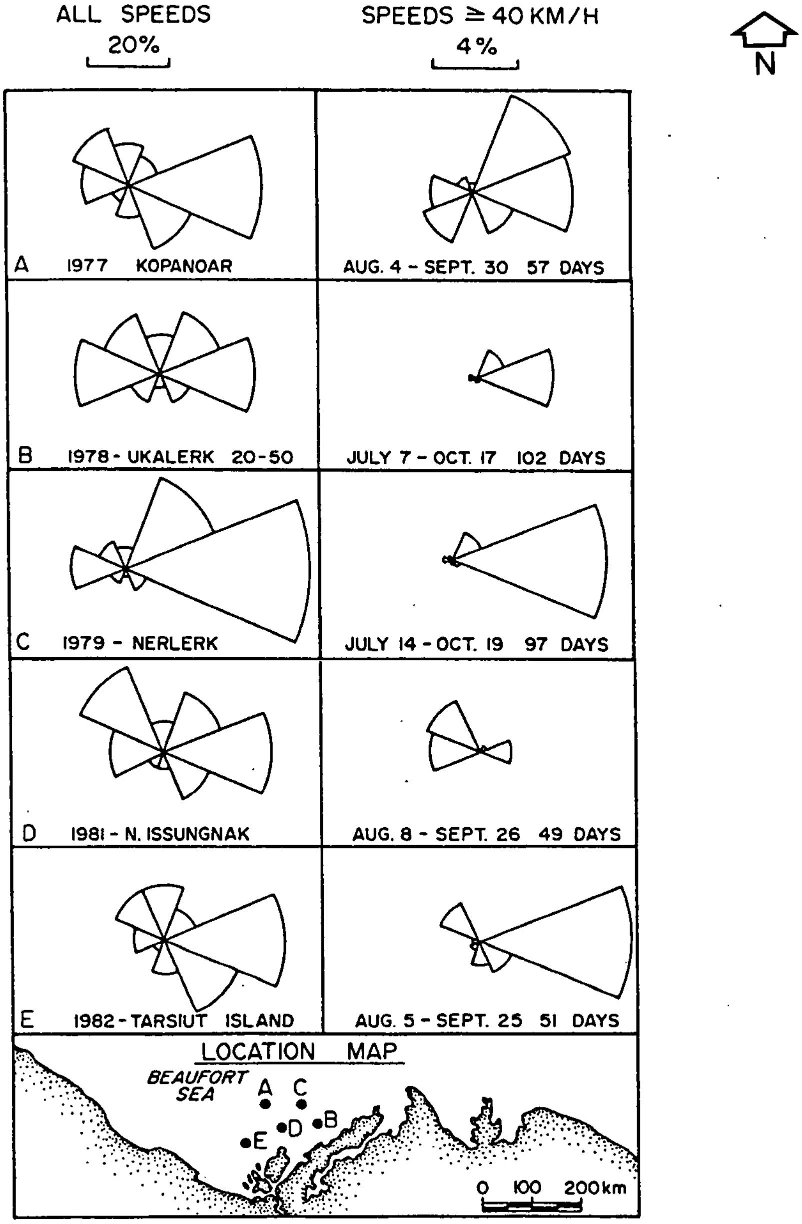

Figure 5. The directional distribution of summer winds for offshore locations in the Canadian Beaufort Sea (Fissel and Birch 1984).

Euphausiids were not abundant in tows made in the southeastern Beaufort Sea by Grainger (1965) or Griffiths and Buchanan (1982), nor were they abundant in tows made by Horner (1979) in the Alaskan Beaufort Sea. However, stomach contents of bowheads taken near Kaktovik in the Alaskan Beaufort Sea in autumn indicate that euphausiids may be an important component of zooplankton and of the bowhead diet (Lowry and Frost 1984). Euphausiids constituted 31% by volume of all items in eight bowhead stomachs from the Kaktovik area. Euphausiids in both the northern and southern hemisphere are found in discrete layers and/or patches, and these fast swimmers can avoid most nets (Brodie et al. 1978; Sameoto 1983; Nicol 1984; Klindt and Zwack 1984). The methods and gear used in most studies in the Beaufort Sea have been inadequate for sampling euphausiids. Because of the local nature of euphausiid swarms, an unguided net may miss them entirely, even if it is capable of catching them (Sameoto 1983).

Grainger and Grohe (1975) provide plankton data from vertical tows taken from 1951 to 1975 in the Canadian Beaufort Sea. Grainger and Lovrity (1975) obtained associated physical oceanographic data for samples taken after 1960. Fifty-two of the zooplankton samples taken in the study area (north to 71°) had matching physical oceanographic data. Zooplankton densities were highest in samples taken in 20 m or less of water and lowest over deep water (Table 1).

Zooplankton densities were not significantly correlated with surface salinities in any of the three water depth ranges examined (Table 1). Salinity at 10 m depth was a significant predictor of zooplankton density only at water depths of 20 m or less (Table 1). There was little variability in salinity at 10 m depth in deeper water; salinity at 10 m was higher in deeper water. Low surface salinities may have been due to melting ice; melting ice did not affect salinity at depth.

Griffiths and Buchanan (1982) provided estimates of zooplankton biomass for some nearshore areas in the Beaufort Sea. In 1980 they took six vertical tows at each of 10 stations at water depths of 5.5 to 25.7 m. In 1981 they took three replicate horizontal tows, usually at each of three depths, at each of 18 stations over water depths of 5 to 40 m. The stations were off Richards Island and the Tuktoyaktuk Peninsula as far north as 70°10'N, and off the Yukon coast at King Point. Zooplankton biomass was highest during 1980 when salinity at 0 and 5 m depth was high, and lowest during the first half of August 1981 when salinity was low (Table 2). Over the two years, integrated zooplankton biomass (log transformed) at 19 stations north of Richards Island and off the Tuktoyaktuk Peninsula was not correlated with surface salinity ($r = 0.34$, $t = 1.46$, $p = 0.15$) but was correlated with salinity at 5 m depth ($r = 0.65$, $t = 3.56$, $p = 0.003$).

TABLE 1

Salinity, zooplankton densities and their correlation over three ranges of water depth in the Canadian Beaufort Sea. Data from Grainger and Grohe (1975) and Grainger and Lovrity (1975)

	Shallow 2-20 m	Mid-depth 21-100 m	Deep Water 100-720 m
Mean Salinity ± s.d. (°/oo)			
at 0 m	6.5 ± 6.4	10.4 ± 7.2	4.0 ± 2.2
at 10 m	14.7 ± 10.7	28.7 ± 1.7	28.6 ± 2.0
Zooplankton (no./m^3) ± s.d.	6193 ± 12,157	3537 ± 3679	498 ± 322
Correlation Coefficients			
Salinity (0 m) vs. zooplankton[a]	0.25 ns	0.04 ns	-0.07 ns
Salinity (10 m) vs. zooplankton[a]	0.47 *	-0.09 ns	-0.40 ns
Sample size	22	20	10

ns is $p>0.05$; * is $p<0.05$

[a] Zooplankton density (no./m^3) was log-transformed prior to product-moment correlation analysis.

TABLE 2

Salinity measurements and biomass of zooplankton (mean ± s.d.) in vertical tows (1980), and mean integrated biomass from horizontal tows (1981) from the southeastern Beaufort Sea. Data from Griffiths and Buchanan (1982)

	Zooplankton Biomass (mg/m^3)	Salinity °/oo		No. Stations
		at 0 m	at 5 m	
1980	632 ± 357	18.7 ± 5.8	28.7 ± 1.1	8[a]
1981 1-15 Aug	150 ± 128	12.7 ± 3.8	19.3 ± 7.5	6
16-30 Aug	340 ± 195	21.3 ± 2.6	22.7 ± 3.1	5

[a] Not including samples taken off King Point.

Therefore the existing limited zooplankton data for the southeastern Beaufort Sea appears to suggest that biomass may be higher in the oceanic water than in waters under the influence of the Mackenzie River plume. As a result, the location and extent of the Mackenzie River Plume may be an important factor influencing the distribution and biomass of zooplankton in the southeastern Beaufort Sea.

Changes in the distribution of salinity and zooplankton could affect very large portions of the southeastern Beaufort Sea. Observed changes in the distribution of bowhead whales are also large and could be related to large-scale changes in the distribution of zooplankton, their primary food source.

Zooplankton Patchiness

A dominant characteristic of the distribution of zooplankton is its patchiness (Mackas and Boyd 1979; Omori and Hamner 1982). Zooplankton occur in discrete regions of high and low standing crop; concentrations are generally associated with specific circumstances or areas. Within such areas or circumstances, zooplankton may be concentrated in layers, for example at a pycnocline, and may in fact be patchy within these layers. Zooplankton aggregations may remain cohesive over time intervals of minutes to months, and may occupy spaces ranging from as little as a few cm^3 to thousands of m^3 (Omori and Hamner 1982). Ueda et al. (1983) observed copepods aggregated in ball-shaped swarms ranging in size from a few cm to more than a metre in diameter. Klindt and Zwack (1984) found that Antarctic krill sometimes occurred in swarms up to 250 m in length; Thomson (LGL Ltd., in prep.) found euphausiids concentrated in an even longer band just above the ocean floor in the Bering Sea.

Several physical oceanographic mechanisms may cause zooplankton to aggregate and thus provide good feeding habitat for baleen whales. Some of these mechanisms have been shown to operate, or at least have the potential to operate, in the Beaufort Sea.

The complicated coastal morphology, steeply sloping bottom topography along parts of the shelf break, enormous freshwater discharge, and periodic coastal upwelling found in the southeastern Beaufort Sea are all conducive to the formation of oceanic fronts between water masses of dissimilar properties. Physical fronts are marked by strong vertical motions and a sharp horizontal gradient in temperature, salinity and/or velocity (Bowman and Esaias 1978). Eddies may be formed along fronts. Eddies consist of water surrounded by water of differing physical properties. Fronts and eddies have been observed in the Beaufort Sea (Herlinveaux and de Lange Boom 1975; Marko 1975; Griffiths and Buchanan 1982; Borstad 1985; W.J. Richardson, LGL Ltd., pers. comm.). However, because of the small spatial scale of these features they are not well resolved in oceanographic data; their vertical structure in the Beaufort Sea, therefore, remains unknown.

Convergent fronts are often recognizable at the surface by lines of flotsam or changes in sea state, and are often the sites of intense biological activity (Bowman and Esaias 1978). Plankton, fish, seabirds and whales may concentrate along certain types of fronts (Pingree et al. 1974; Fournier 1978; Brown 1980; Gaskin 1982). In many areas, a front between coastal and oceanic waters occurs at the shelf break at depths of 100 to 300 m. Shelf break fronts are also recognized as areas of intense biological activity (Fournier 1978; Owen 1981).

Frontal eddies, such as those generated by the Gulf Stream, are characterized by a cold core of upwelled water up to 1000 km^2 in area. This can cause a 10- to 100-fold enhancement of chlorophyll concentrations (Yoder et al. 1981). Eddies have been noted along the edge of the Mackenzie River plume by Borstad (1985), who speculates that the assumed increase in productivity could attract secondary and higher level consumers.

Complex biological and physical interactions also occur at estuarine fronts. On the continental shelf of temperate seas, the front of a freshwater discharge propagates slowly across the shelf until it reaches the shelf edge, where eddies and instabilities may develop (Kao 1981). In Georgia Strait, the plume edge is an aggregation point for zooplankton and their food; however, Mackas et al. (1980) point out that the relationship is not a simple one. Seliger et al. (1981) investigated the mechanisms that lead to patchiness of phytoplankton in estuarine frontal regions. They identified the interfrontal region, shoals and areas with rapid shallowing as regions where phytoplankton growth and standing crop were enhanced.

Tidal fronts between water masses of differing characteristics are also zones of convergence that concentrate flotsam at the surface and zooplankton below (Pingree et al. 1974). Tide-forced internal waves may also generate surface slicks and concentrate zooplankton (Shanks 1983). This phenomenon requires a shelf, pycnocline and tides; all are present in the Beaufort Sea. Tides and tidal currents are weak in the Beaufort Sea; however, other currents are present that can generate internal waves.

Zooplankton patchiness has been observed in and near the Beaufort Sea. Hansen et al. (1971) found pteropods concentrated in a thin layer at the pycnocline at 50 m depth in the Arctic Ocean north of the Beaufort Sea. In the Beaufort Sea itself, Griffiths and Buchanan (1982) used an echosounder to find patches of zooplankton from several to hundreds of metres across. Feeding bowheads were sometimes associated with the appearance of the patches on the echosounder.

Average concentrations of zooplankton as shown by net tows appear to be insufficient to meet the energetic requirements of bowhead whales (Griffiths and Buchanan 1982). These whales must feed on concentrations of zooplankton that are above average. The distribution of these concentrations may be an important determinant of the distribution of bowhead whales. In this study we have hypothesized that zooplankton is concentrated at estuarine fronts and at other fronts evident on airborne remote sensing data and satellite imagery.

BOWHEAD WHALES

Breiwick et al. (1980) estimated that the original stock size of the Western Arctic bowhead population was between 14,000 and 26,000 animals. The Scientific Committee of the International Whaling Commission considers the best estimate of present population size to be 4417 with 95% confidence limits of 2613 and 6221 (I.W.C. 1985).

The Western Arctic bowheads winter in the Bering Sea. In spring, they enter the Canadian Beaufort Sea through recurring leads that are far offshore. Some animals move into Amundsen Gulf in June and early July (Fraker 1979; Braham et al. 1980). In late July and early August, there is a westward movement of bowheads out of Amundsen Gulf (Fraker 1979; Davis et al. 1982) and a southward movement out of the northern Beaufort Sea into the southeastern Beaufort Sea (Davis et al. 1982). During August and the first half of September, animals are present in the vicinity of the Mackenzie Delta and the Tuktoyaktuk Peninsula (Renaud and Davis 1981; Davis et al. 1982; Harwood and Ford 1983; McLaren and Davis 1985). Westward migration from Canadian waters into the Alaskan Beaufort Sea occurs during September and early October.

Several species of baleen whale including the bowhead and gray whale (*Eschrichtius robustus*) migrate long distances to feed in cool waters at high latitudes during the summer. It has been assumed, with some evidence, that these whales fast during winter and therefore must store sufficient energy during summer to meet their energetic needs in winter. Bowhead whales apparently feed very little during winter and during the spring migration (BEMP 1984; Lowry and Frost 1984). They spend much of their time feeding in summer in the southeastern Beaufort Sea (Würsig et al. 1985a,b), and also do some feeding during their westward migration along the Alaskan coast (Lowry and Frost 1984; Ljungblad et al. 1984a).

The bowhead has very long and relatively fine baleen, and is believed to be adapted for filtering zooplankton from large volumes of water (Nemoto 1970; Mitchell 1975; Pivorunas

1979). Stomachs of bowheads taken in the eastern Alaskan Beaufort Sea (off Kaktovik) in autumn show that bowheads feed mainly on copepods and euphausiids (Lowry and Frost 1984). Many other taxa are also taken, but they do not appear to contribute much to total energy intake (Lowry and Frost 1984).

The feeding behaviour of bowheads in the Canadian Beaufort Sea in summer has been studied in some detail (Würsig et al. 1985a,b). The feeding mode is variable and apparently opportunistic. Bowheads occasionally feed at or just below the surface, sometimes in coordinated echelons of up to 14 whales. Copepods were unusually abundant in surface waters on an occasion when 20-30 bowheads were observed skim feeding (Griffiths and Buchanan 1982). Observers in aircraft have not seen bowheads feeding in patches of plankton dense enough to be visible (cf. Watkins and Schevill 1979 for right whales [Eubalaena glacialis]). Near-bottom feeding has been noted on numerous occasions when bowheads surfaced with mud streaming from their mouths or bodies. It is possible that near-bottom feeding is confined to young bowheads; in the Beaufort Sea in 1983 and 1984, bottom feeding was observed in areas occupied primarily by immature whales. In Alaska, the few bowheads whose stomachs contained mainly benthic organisms were small individuals (Hazard and Lowry 1984; Lowry and Frost 1984). Most feeding in the Canadian Beaufort Sea is believed to occur in the water column, invisible from the surface and far enough above the bottom that no mud is disturbed. Water-column feeding is inferred when whales surface and dive repeatedly in the same area with little net horizontal movement, and often with defecation (Würsig et al. 1985a,b).

Although bowheads are not believed to be as dependent on dense patches of prey as are the rorquals, rough calculations suggest that bowheads must concentrate their feeding in areas where zooplankton biomass is at least slightly above average (Brodie 1981; Griffiths and Buchanan 1982; Lowry and Frost 1984). Limited evidence from Canadian waters indicates that bowheads do indeed concentrate in areas where copepods are especially abundant (Griffiths and Buchanan 1982).

Evidence from several other species of baleen whales indicates that whale movements can be closely attuned to prey distribution. For example, when capelin abundance decreased offshore from Newfoundland, humpback whales (Megaptera novaeangliae) apparently moved inshore where capelin were still abundant (Whitehead and Carscadden 1985). When reduced numbers of humpbacks were found in Glacier Bay, Alaska, prey abundance there was much lower than in a nearby area where humpbacks still concentrated (Bryant et al. 1981). In the Antarctic, changing distributions of rorquals are related to the variable distribution of euphausiids (Beklemishev 1960; Mackintosh 1965). Year-to-year variations in distribution, seasonal occurrence, and diet of rorquals in the North Pacific and Bering Sea seem related to variable prey abundance and to oceanographic factors affecting prey (Nemoto 1959; Nasu 1974). Baleen whales often are especially abundant near fronts between water masses, near eddies, or in areas of upwelling (Gaskin 1982). However, it should be noted that most studies that purport to show connections between whale and prey abundance are not entirely conclusive because of the lack of synoptic data. Fronts, eddies and upwelling areas not used by whales are not reported in the literature.

MATERIALS AND METHODS

METEOROLOGY

Velocity and direction of surface winds are the meteorological parameters of greatest interest to the present study. Wind is the mechanism that determines the location of the Mackenzie River plume and drives coastal upwelling. In order to provide quantitative information on the regional surface winds, six-hourly wind observations from Tuktoyaktuk, N.W.T., were obtained from the Atmospheric Environment Service (AES) of Environment Canada. The wind data used in this study were for the months of July, August and September for the years 1980 to 1983, inclusive.

Wind measurements at Tuktoyaktuk are reliable indicators of the wind field over the southeastern Beaufort Sea (Danard and Gray 1984; Fissel and Birch 1984). Comparisons of simultaneous wind measurements for Tuktoyaktuk and offshore drilling platforms revealed statistically significant correlations ($r = 0.83$ to 0.90). Offshore winds had velocity components averaging 20% greater than those at Tuktoyaktuk, with the highest cross-correlations occurring for offshore winds lagging Tuktoyaktuk winds by approximately six hours.

Time-series plots of the wind data were generated by a DEC PDP11 computer programmed to display (1) the six-hourly wind values oriented along the east-west direction, and (2) the wind run (time integral of the east-west wind component). These plots were examined visually to define the varying wind regimes occurring over the period from early July to mid September of each year. The categories used were weak (mean wind velocity <2 m/s), moderate (mean wind velocity 2-4 m/s) and strong (mean wind velocity ≥ 4 m/s). The dominant direction of the wind was determined for the moderate and strong categories of wind events. The individual wind events were subsequently used to define time intervals for comparisons of oceanographic features and bowhead whale distributions.

Sea ice data were extracted from composite ice concentration maps produced by Ice Forecasting Central of AES. These charts were derived from a synthesis of satellite imagery, visual and SLAR observations as recorded aboard AES ice survey aircraft. Maps were produced showing the boundaries where ice concentrations exceeded one-tenth and seven-tenths coverage. The one-tenth level was chosen to define regions where ice concentrations were significant enough to invalidate temperature and sediment levels recorded from contemporary satellite imagery. The seven-tenths level was used to indicate the edge of the main pack ice.

PHYSICAL OCEANOGRAPHY

Oceanographic data collected during the summers of 1980 to 1983, inclusive, were obtained and processed. These data consisted primarily of measurements of temperature and salinity, supplemented by less extensive turbidity measurements. Because most of the oceanographic data were related to satellite imagery, either for ground truthing or to define conditions in the absence of imagery, the range of depths of interest for this study was restricted to the surface layer. Data were collected and examined from the surface to the seasonal pycnocline.

The surface layer above the pycnocline is responsive to changes in the wind, and will show the effects of advection of plume water. Water below the pycnocline is less active and too few data were available to warrant analysis of the deeper layers.

The individual data sets used in this study are tabulated in Table 3. The largest number of data sets was collected by Canadian Marine Drilling Ltd. from its drillships operating in the Beaufort Sea. These data were obtained in two formats: as summary listings of CTD data purchased from Canmar's Environment Operation Group, and as daily sea-temperature observations obtained from the annual reports of the Beaufort Weather Office of AES.

The oceanographic data were analyzed to (1) provide ground truth data for features discovered on satellite images, (2) define conditions during times for which satellite images were not available, and (3) study the variability of oceanographic conditions and response to wind forcing. The value of ground truthing for satellite imagery analysis is discussed elsewhere in this report. In this application, considerable difficulty was experienced in the vicinity of the offshore edge of the major river plume front. Usually the oceanographic data were not obtained simultaneously with the satellite images. Due to the large horizontal gradients in surface water properties, advection of frontal features can result in major differences over times of several hours or less.

The oceanographic data were also used to define surface distributions of water properties in the absence of satellite imagery. Although helpful in discerning large-scale water mass distributions within the study area, the very limited number of concurrent measurement locations (typically 3-4, maximum of 7) precluded the possibility of resolving the spatial distribution of the river plume. This problem was made more difficult by the fact that most of the available observations were collected in water depths >25 m, while the plume is usually found in shallower waters.

TABLE 3

Sources of physical oceanographic data from the southeastern Beaufort Sea used in this study

Site Name/ Location	Water Depth (m)	Duration of Record	Type of Data^{a}	No. of Observations	Data Source^{b}
1980					
Kenalooak	68	1 Aug-31 Aug	CTD	16	Lemon and Kowalski (1982)
	68	1 Aug-9 Sep	T (sfc)	Daily	BWO
Koakoak	47	14 Jul-3 Oct	CTD	38	Lemon and Kowalski (1982)
	47	1 Aug-6 Oct	T (sfc)	Daily	BWO
Kopanoar	58	14 Jul-28 Sep	CTD	40	Lemon and Kowalski (1982)
	58	1 Aug-14 Sep	T (sfc)	Daily	BWO
Orvilruk	60	17 Jul-7 Sep	CTD	25	Lemmon and Kowalski (1982)
	60	1 Aug-16 Sep	T (sfc)	Daily	BWO
Tarsiut	23	11 Jul-24 Jul	CTD	8	Lemon and Kowalski (1982)
Kilannak	27	10 Sep-19 Sep	T (sfc)	Daily	BWO
Off Richards Island	10-26	14 Aug, 26 Aug	CTD	8	Griffiths and Buchanan (1982)
King Point	6-20	20-21 Aug, 6 Sep	CTD	6	Griffiths and Buchanan (1982)
Kugmallit Bay	6	10 Jul, 15 Aug 6 Sep, 21 Sep	CTD	4	Thomas et al. (1981)
1981					
Koakoak	47	26 Jul-15 Sep	CTD	29	DPL
	47	19 Jul-8 Oct	T (sfc)	Daily	BWO
Kopanoar	58	25 Jul-31 Jul	CTD	2	DPL
	58	12 Sep-14 Sep	CTD	3	DPL
North Issungnak	25	27 Jul-13 Sep	CTD	23	DPL
		14 Jul-8 Oct	T (sfc)	Daily	BWO
Kilannak	27	23 Jul-3 Sep	T (sfc)	Daily	BWO
Issungnak	20	26 Jul-25 Sep	CTD	2	Erickson et al. (1983)
	20	24 Jul-30 Aug	CT-chain^{3}	Cont.	Erickson et al. (1983)
Off Richards Island	5-40	31 Jul-6 Sep	CTD	19	Griffiths and Buchanan (1982)
1982					
Kenalooak	68	27 Jul-18 Oct	CTD	41	DPL
		15 Jul-3 Oct	T (sfc)	Daily	BWO
Kiggavik	25	1 Oct-2 Oct	CTD	2	DPL
		21 Jul-3 Oct	T (sfc)	Daily	BWO
Nerlerk	52	4 Jul-27 Aug	CTD	17	DPL
Aiverk	55	5 Oct-18 Oct	CTD	11	DPL
Irkaluk	60	26 Juy-3 Oct	CTD	28	DPL
Orvilruk	60	29 Aug-18 Oct	CTD	27	DPL
1983					
Aiverk	61	3 Aug-24 Sep	CTD	11	DPL
		25 July-24 Sep	T (sfc)	Daily	BWO
Natiak	42	19 July-10 Sep	CTD	23	DPL
		25 July-10 Sep	T (sfc)	Daily	BWO
Havik	35	25-27 July, 17-19 Sep	CTD	4	DPL
		13 Sep-23 Sep	T (sfc)	Daily	BWO
Arluk	58	30 July-16 Sep	CTD	15	DPL
		25 July-21 Sep	T (sfc)	Daily	BWO
Siulik	51	27 Jul-18 Sep	CTD	19	DPL
		27 Jul-19 Sep	T (sfc)	Daily	BWO
Off Richards Island/ Kugmallit Bay	5-20	17 Jul-26 Jul	CTD	47	Nadeau (1984)
	N/A	21-23 Aug	T (sfc) S (sfc)^{3}	24	Borstad (1985)

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[a] S (sfc) - surface salinity
T (sfc) - surface temperatue
CTD - temperature salinity depth profile
CT-chain - continuous temperature salinity record.

[b] DPL indicates data obtained from Dome Petroleum Ltd. (Canmar) for this study.
BWO indicates data obtained from Annual Reports of the Beaufort Sea Weather Office of AES.

A subset of the oceanographic data proved useful in delineating the response of the oceanographic conditions to wind forcing. The most useful data set in this respect was that collected in July and August 1981 near the Issungnak site (Erickson et al. 1983). These data consisted of continuous measurements of temperature and salinity at particular depths at a fixed location. This type of analysis can also be carried out using oceanographic observations from the drillships. However, in many cases the results of such analyses are less useful due to the reduced sampling rate (once each 2-3 days), combined with the fact that the drillships tended to operate in deeper water, farther from the influence of the intense river plume.

SATELLITE IMAGERY

Satellite images, obtained primarily from the AVHRR (Advanced Very High Resolution Radiometer) instrument on the NOAA-6 and -7 polar orbiting satellites, were used to map the spatial and temporal changes in the Beaufort Sea surface water distributions over the 1980-1983 periods of interest. Key objectives were to locate areas with elevated levels of suspended sediments and water temperatures that could be associated with the silty, warm discharge of the Mackenzie River into the southeastern Beaufort Sea. Concentrations of suspended sediment were detected through their reflection of visible (0.4 to 0.7 µm) and near infrared (0.7 to 2 µm) wavelength solar energy. Surface water temperatures, on the other hand, were derived from the fluxes of longer wavelength (>2 µm) thermal infrared radiation. One pair of CZCS images recorded by the NIMBUS-7 satellite is included in the study. The wavelength limits of the individual AVHRR and CZCS bands are indicated in Table 4. In previous applications of this technique, Marko (1975), Harper and Penland (1982), Marko and Oberski (1982), Marko et al. (1983), and Borstad (1985) have documented the extents of river-related plumes and their approximate relationships to forcing factors.

TABLE 4

Wavelength (in micrometers) of the six image-producing bands of three satellites

Band	NOAA-6	NOAA-7	NIMBUS-7
1	0.58-0.68	0.58-0.68	0.433-0.453
2	0.725-1.10	0.725-1.10	0.510-0.530
3	3.55-3.93	3.55-3.93	0.540-0.560
4	10.5-11.5	10.5-11.3	0.660-0.680
5	-	11.5-12.5	0.700-0.800
6	-	-	10.5-12.5

Data Sources

The analyzed images were derived from the digital radiance values (energy/unit area, unit time) detected onboard the satellite in the specified wavelength band, from a given fixed solid angle of the imaging system field of view. For the AVHRR and CZCS instruments, this minimum unit of spatial sampling, designated as a picture element or "pixel", corresponds, at nadir, to an area of approximately 1100 m x 1100 m on the earth's surface. The combination of the satellite's orbital movement and an orthogonal, repetitive scanning movement of the optical observing axis allows the accumulation of near-simultaneous radiance values for all "pixels" in a strip approximately 2500 km wide, centred below the orbit of the satellite.

Satellite imagery data were obtained in several different forms and from different sources as described below.

Computer-Compatible Magnetic Tape. These data were reformatted copies of the original files of digital satellite pixel radiances recorded by receiving ground stations. In some instances, the original 10-bit resolution satellite data were reduced to 8 bits by a subsequent fourfold division. The 10-bit images retained the original digitized sensitivity of the satellite sensor and hence were the preferred data forms for mapping water properties. The truncated 8-bit data products were slightly less useful in discriminating spatial variability but still provided a desirable data source.

Tape data were obtained from three different sources: the Environmental Data and Information Service (EDIS) in Washington, DC; the Prince Albert, Saskatchewan, distribution centre of the Canada Centre of Remote Sensing (PASS); and the Arctic Weather Centre (ARWC) of the Atmosphere Environment Service in Edmonton, Alberta. Only EDIS data were received in the untruncated 10-bit form. Truncated versions of 10-bit 1980 EDIS images were, however, used in the study for reasons of economy, since these images were already in hand from a previous project.

Hardcopy Imagery. Hardcopy paper images are produced by the above-cited agencies from the original digital data using specific "enhancements" or correspondences between the image grey-scale and digital pixel radiance values. This process makes it impossible to recover many details of the original digital image, and, in particular results in lower radiometric sensitivity at the low end of the radiance scale normally associated with seawater observations. As a result, these images are less than ideal for surface-property mapping. Nevertheless, due to the greater cost of tape storage, hardcopy has been and continues to be the primary medium for archiving imagery. As a result, the analysis and interpretation of hardcopy images can provide less precise but often useful information on surface variability during the numerous periods of good surface viewing that are not represented in the digital tape archives. In all instances except one, the few hardcopy images used in this study were produced with the full spatial resolution of the digitally recorded data. The one exception was the 7 August 1982 image (denoted by an asterisk in Table 5) obtained from the University of Alberta collection of subsampled imagery.

Data Processing and Analysis

The image processing and analysis procedures were selected to

1. identify recognizable, definable bodies of surface water in the southeastern Beaufort Sea, and describe their temporal and spatial variability during periods relevant to bowhead whale distribution;
2. investigate the feasibility of mapping mesoscale surface features whose spatial and temporal scales, on the order of 1-10 km and <1 day, are intermediate between (a) the larger, slower phenomena covered in (1), and (b) undetectable smaller-scale turbulent and advective flow features.

Images containing sufficient detail for our purposes were obtained for 20 days during the four-year period of interest (Table 5). These data included 14 digital imagery pairs, consisting of visible and thermal infrared images of the same area. Of these, six had been previously analyzed in slightly different form by Borstad (1985). Selection of suitable imagery required review of the large ARWC and University of Alberta hardcopy imagery collections and the viewing of an additional number of digital tape images that were eventually rejected from further consideration because of intolerable amounts of cloud and/or ice in the study area.

The primary tool for the processing and analysis of both digital and hardcopy images was the Institute of Ocean Sciences' (IOS) Image Processor. A rectification step used recognizable geographic reference points in the images to determine corresponding satellite orbital and imaging parameters. These parameters were then used to remap the original pixel values onto an equi-rectangular projection (lines of latitude and longitude are everywhere parallel with spacing proportional to the corresponding separations on the earth surface at the coordinates of the map centre-point, 70°N, 133°W). Video image displays of individual pixel radiance values and specific false-colour and grey-scale representations were then used to identify the boundaries of cloud-covered and ice-infested regions prior to the analyses of the surface properties in open water areas.

TABLE 5

Satellite imagery used in study

Date	Time	Band	Satellite	Source	Type
5 Aug 1980	17:48	1,4	NOAA-6 AVHRR	EDIS	Tape
7 Aug 1980	03:24	4	NOAA-6 AVHRR	EDIS	Hardcopy
20 Aug 1980	18:44	3,6	NIMBUS-7 CZCS	EDIS	Tape
24 Aug 1980	23:30	2,4	NOAA-6 AVHRR	EDIS	Tape
31 Aug 1980	16:43	1,4	NOAA-6 AVHRR	EDIS	Tape
3 Sep 1980	18:50	1,4	NOAA-6 AVHRR	EDIS	Tape
5 Aug 1981	20:05	1,4	NOAA-7 AVHRR	EDIS	Tape
6 Aug 1981	19:54	1,4	NOAA-7 AVHRR	EDIS	Tape
14 Aug 1981	23:18	1,4	NOAA-7 AVHRR	EDIS	Hardcopy
7 Aug 1982	23:22	1,4	NOAA-7 AVHRR	EDIS	Hardcopy
7 Aug 1982*	21:30	4	NOAA-7 AVHRR	EDIS	Hardcopy
13 Aug 1982	12:27	4	NOAA-7 AVHRR	EDIS	Hardcopy
24 Aug 1982	23:30	1,4	NOAA-7 AVHRR	EDIS	Tape
26 Aug 1982	22:52	1,4	NOAA-7 AVHRR	EDIS	Tape
5 Sep 1982	22:37	1,4	NOAA-7 AVHRR	EDIS	Hardcopy
13 Aug 1982	22:32	1,4	NOAA-7 AVHRR	EDIS	Tape
3 Aug 1983	02:42	2,4	NOAA-7 AVHRR	ARWC	Tape
14 Aug 1983	20:25	1,4	NOAA-7 AVHRR	PASS	Tape
22 Aug 1983	22:10	1,4	NOAA-7 AVHRR	PASS	Tape
26 Aug 1983	23:03	1,4	NOAA-7 AVHRR	PASS	Tape
2 Sep 1983	23:18	1,4	NOAA-7 AVHRR	EDIS	Hardcopy

The comparison of hardcopy image data with digital results required an initial conversion of the hardcopy into video form, followed by digitization by the image processing system. Care was necessary to ensure approximately uniform illumination over the hardcopy surface in order to avoid introducing spurious spatial variability into the image obtained with the system's video camera. The resulting redigitized versions of the original satellite images were rectified and remapped into a common projection using a set of processing programs similar to those applied to the fully digital image data.

Our procedure for extracting surface property data used, whenever possible, the Bands 1 and 4 imagery obtained from the NOAA-6, -7 AVHRR instruments to obtain quantitative indicators of suspended-sediment concentrations and temperature, respectively. The absence, in some cases, of Band 1 imagery necessitated the use of Band 2 data. Band 2 is less sensitive to suspended sediment levels primarily because of the higher absorptivity of water at near-infrared wavelength. This difficulty is discussed below.

Because of differences in sun angle, sea state, atmospheric transparency, and instrument sensitivity, direct comparison of absolute radiance values as recorded at different times and locations would require calibration against in situ measurement data. Unfortunately, such data were rarely available (except for a relatively small set of surface measurements collected by Borstad [1985] in connection with the 22 August 1983 image). As a result, no direct comparisons were made among the absolute pixel radiance values recorded on different images. Instead, procedures were derived to simplify the representation of each image sufficiently to allow the approximate location of identifiable surface water components without recourse to specific, image-independent radiance criteria. Our analyses were directed at detecting temporal changes in the configuration of water masses as identified on the basis of temperature and/or sediment patterns in individual images. Major spatial gradients in pixel radiance were used to define the boundaries of the designated waterbody components such as the "intense" and "diffuse" portions of the thermal and suspended-sediment plumes. This procedure used the computing and graphics capabilities of the IOS image processor to contour the radiance field of each image at intervals of one digital radiance unit. These contoured products and the corresponding fields of digital pixel values were used to locate the steepest gradients in the mapped surface parameters. In almost all cases, the prominent gradients observed in widely separated parts of the plume on any one image tended to be associated with the same critical radiance values. As a result, the prominent gradients associated with the apparent Mackenzie River plume edge tended to have the same radiance values regardless of the choice of enhancements. Thus, selection of the plume boundary on the processed image was an objective process.

Two distinct plume edge boundaries were evident in the processed images. These boundaries were associated with the two steepest gradients in the temperature- and sediment-related radiance parameters. The gradient closest to shore bounded the warmest and siltiest "intense" portion of the plume (characterized by the lowest Band 4 and 6 and highest Band 1-3 radiance values). The second contour was farther offshore and defined a generally smaller but distinct gradient in the temperature- and suspended sediment-related radiance values that bounded a more "diffuse" portion of the plume.

Other boundaries were sometimes apparent. One such boundary was associated with late summer (late August and September) Band 1 and 2 images in which the peak values and spatial gradients in surface water temperatures and suspended sediment concentrations tended to be well below values recorded earlier in summer. This change was accompanied by a general increase in the surface temperature and visible-wavelength reflectivity of waters outside the nominal diffuse plume boundary. These changes occurred because of accumulated solar energy absorption as well as outward diffusion and mixing from the river plume. The additional Band 1 (or 2) boundary was designated as the "trace" boundary. It defined the limits of a detectably elevated suspended-sediment level relative to the clear water background.

A second type of boundary, primarily associated with early season thermal infrared imagery, was used to identify regions containing very cold water. This "cold water" boundary, was useful in establishing the zone where surface water temperature was elevated through the combined effects of river discharge, solar heating, ice melt and atmospheric exchanges. It also provided an indicator of upwelling or other processes that introduce anomalously cold water to the sea surface.

To investigate possible linkages between bowhead whale distributions and surface water properties, we evaluated the observed positions of the whales relative to the boundaries of the four designated water masses (i.e. intense, diffuse, trace and cold water) at these times. Water mass boundaries were plotted on the same one to 3.3 million scale equi-rectangular map projection used to represent the whale sightings, sea ice and oceanographic data gathered in this study. In each case, cloud- and ice-covered areas were masked out before further analysis of the digital imagery. The extent of river induced variability in surface water properties can be estimated by comparing the NOAA Band 1 and 4 radiance values at each water mass boundary with those recorded in adjacent waters or in more offshore waters well removed from plume influences. Such comparisons were facilitated through listing the critical radiance values for each boundary and the local radiance values in other areas of interest.

A very limited examination of sea surface variability on a "mesoscale" (1-10 km and periods of 1 day or less) was carried out to assess the feasibility of using AVHRR imagery to test the hypotheses that the probability of whale presence increases with the extent of such variability. Analysis was confined to the thermal infrared (Band 4) image for 6 August 1981. After suitable masking to exclude land, cloud and ice contributions, a previously developed program (Harwood and Borstad 1985) was used to calculate the differences between the digital radiance level of each pixel and its eight nearest neighbours. The largest difference in values was displayed at the pixel site to provide a measure of the mesoscale variability. The evaluation of possible options for mesoscale analyses was carried out on the basis of the spatial distribution of these maximal differences in near-neighbour radiance values.

Data Analysis Limitations

There are three major limitations in the processed satellite imagery: (1) the processing procedures produced simplified versions of the original data, (2) no ground truthing was available for the images, and (3) the images were collected with a variety of instruments and processed using a variety of procedures.

The convenient definition of distinct water masses was generally found to be relatively unambiguous except in late August and September when there usually was a general reduction in the peak radiance values associated with the gradients of both surface water temperature and turbidity. This seasonal change introduced some uncertainty into the choice of critical radiance values that defined boundaries. The use of the "trace" water category aided in identifying the presence of this problem and gave an indication of the degree to which the "diffuse" plume boundary underestimated the actual area of plume influence.

Instrument or image-related limitations of the data are summarized in Table 6. These limitations may have caused an error of 10 km or more in the positioning of water mass boundaries. These possible position errors were considered in the interpretation of results.

An important limitation to the usefulness of the available imagery is the long time interval between successive observations. The average length of these intervals was about 10 days. In comparison, the time scale believed to be associated with large-scale changes in weather patterns and distributions of water properties is about 2-3 days. Thus, only a fraction of the actual changes that occur in the

TABLE 6

Summary of problems, and their consequences, with the available satellite imagery

Defect	Consequences
1. Use of truncated 8-bit resolution digital images.	Reduced resolution of surface features and consequent difficulties in comparison with images made with untruncated, 10-bit image data.
2. Differences in the radiometric sensitivity of the AVHRR Band 1 and 2, and CZCS Band 3 detectors and the frequent unavailability of Band 1 imagery.	The CZCS Band 3 data exhibit the highest sensitivity to suspended sediment levels and the AVHRR Band 2 data the lowest. Because of their differing sensitivities, quantitative comparisons of sediment-related surface water boundaries are difficult without ground truthed data (which were unavailable for this study). Use of AVHRR Band 2 data (rather than Band 1) greatly reduced the possibility of detecting surface features related to suspended sediment load.
3. Differences in the radiometric sensitivities of the AVHRR Band 4 and CZCS Band 6 images.	The resolution of thermal water surface structure is lower when the CZCS Band 6 data are used. In the absence of ground truth data, comparison of images generated using these two bands is difficult.
4. Fixed, image-specific grey-scales of hardcopy images.	Precludes possibility of displaying additional surface structures through the use of alternative enhancements. The hardcopy images, when redigitized, are equivalent to a truncation of the original data to 3- or 4-bit resolution. This caused greater difficulties when comparing images than with the 8-bit or 10-bit images noted above.

distribution of surface water properties are normally documented in the imagery available for any given season. The extent of this problem can be somewhat reduced in future studies by more effective recovery of all recorded digital imagery data. However, some loss of information is inevitable because of cloud obstruction. Improvement in the documentation of sea surface properties requires the availability of additional sampling mechanisms, such as airborne remote-sensing, measurements from surface vessels, and the installation and recovery of moored instruments.

BOWHEAD WHALE DISTRIBUTIONS

Information about bowhead whale distributions in the eastern Beaufort Sea was compiled from the published and unpublished sources listed in Table 7. Data were available from late July or early August to mid September for the years 1980 to 1983. The data were mapped by the previously described wind event periods. The time frames used for previous compilations of survey results (e.g., Richardson et al. 1985) were generally incompatible with the timing of the wind event periods. Therefore, it was usually necessary to use the original survey data to prepare new maps for the specific wind event periods defined here. In order to account for delays in oceanic response to changes in wind, maps of whale distributions begin and end, when data are sufficient, approximately 36 h later than the actual wind event period. However, it should be noted that there is no information on the response time of the biological system to changes in either wind or the hydrographic regime.

All bowhead sightings during systematic aerial surveys and other aircraft-based studies (intensive behavioural and photogrammetric work) were plotted for each of the wind event periods. Relative numbers of whales in areas where flights were conducted were categorized as no whales, a few whales, or many whales. Tens of whales observed in a group, or in areas of approximately 50 x 50 km or less, were coded as many whales. Individual small groups of <10 whales, or a few scattered sightings, were coded as few whales. The areas encompassed by concentrations of whales were delineated on the maps.

The distribution maps must be interpreted with considerable caution. Survey coverage in any one area ranged from nil or sparse to extremely intense, and survey procedures were variable. Systematic surveys were not available from the entire study area in any period. In early August of 1982-84, there was considerable non-systematic but essentially no systematic coverage. Where and when available, systematic coverage was very helpful in comparing relative numbers of bowheads. When there was substantial coverage of both the systematic and non-systematic types, major concentrations detected by one approach were generally detected by the other

TABLE 7

Systematic and non-systematic aerial surveys of bowhead whales in the Canadian Beaufort Sea, late July to early September of 1980 to 1983. Survey effort is summarized in terms of d, days of surveying; f, number of offshore flights; h, hours of surveying; km, kilometres of straight-line transects (from Richardson et al. 1985)

	1980	1981	1982	1983
Systematic surveys	- **Renaud & Davis (1981)** - 6 Aug-4 Sep - 7 d/6258 km - 3 surveys off Tuk Pen (133° to 129°W)	- **Davis et al. (1982)** - 18 July-14 Sep - 28 d/37,745 km[a] - 4 surveys, AK border to Amund Gulf (138°-141° to 117°-126°)	- **Harwood & Ford (1983)** - 18 Aug-13 Sep - 9 d/7442 km - 2 surveys, AK border to C. Dalhousie (140°-141° to 129°-130°W)	- **McLaren & Davis (1985)** - 19 Aug-11 Sep - 9 d/7045 km - 2 surveys, AK border to C. Dalhousie (141° to 129°W)
Behavior & disturbance	- **Richardson (1982)** - 3-31 August - 16 f/101 h - Mostly N of Mack Delta & Tuk Pen	- **Richardson (1982)** - 27 July-8 Sep - 27 d/32 f/117 h - Mostly N of Mack Delta & Yukon	- **Richardson (1983)** - 1-31 August - 19 d/27 f/122 h - Widespread off Delta & Yukon	- **Richardson (1984)** - 1 Aug-1 Sep - 18 d/28 f/114 h - Mostly N of Mack Delta & Yukon
Alaskan surveys extending into Canada[d]	- **Ljungblad (1981)**[b] - 28 July-24 Oct - 8 f/8 d - Mostly off Yukon; some off Tuk	- **Ljungblad et al. (1982)**[b] - 15 Aug-20 Sep - 10 f/10 d - Mostly off Yukon	- **Ljungblad et al. (1983)**[b] - 2 Aug-15 Oct - 16 f/16 d - Mostly off W Yukon	- **Ljungblad et al. (1984a,b, unpubl.)**[b] - 2 Aug-5 Oct - 29 f/23 d - Mostly off W Yukon
Photogram-metric & other studies	- **Hobbs & Goebel (1982)** - 21 July-12 Sep - 13 f/13 d[c] - Mostly off Tuk Pen & C. Bathurst - **Norton Fraker & Fraker (1981)** - 24 July-9 Aug - 3 f/3 d - N of Delta near Issungnak	- part of Davis et al. (1982); see above	- **Davis et al. (1983)** - 12 Aug-5 Sep - 15 d/72+ h/>8781 km - AK border to C. Parry (141°-125°)	- **Cubbage et al. (1984)** - 7 Aug-6 Sep - 24 f - AK border to Amund Gulf (141°-122°)

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[a] Includes coverage in Amundsen Gulf as well as Beaufort Sea _per se_.
[b] Flights that extended east of 141°W are considered here.
[c] Excludes flights also mapped by Ljungblad (1981).

as well. However, when coverage was sparse, moderate concentrations of whales were sometimes missed or, more commonly, greatly underrepresented by one type of coverage.

Both systematic and non-systematic surveys had limitations. Because systematic surveyors usually did not circle whales, non-systematic coverage commonly detected groups where systematic coverage detected only one or two whales or even no whales. On the other hand, the concentration of non-systematic coverage in areas where whales were expected caused considerable complications in estimating relative numbers in different areas. Ideally, this could be allowed for by converting to 'sightings per unit effort'. However, this was not practical here. Effort was not always quantifiable, and it was necessary to combine results from studies with widely varying field procedures.

In summary, caution is necessary in interpreting the maps even for areas and times when systematic surveys were done. Apparent differences in bowhead abundance between areas and years should be considered real only when the difference was large and there was considerable survey coverage.

RESULTS

EFFECTS OF WIND ON THE HYDROGRAPHY OF THE SOUTHEASTERN BEAUFORT SEA

Time Series Comparisons

Large, time dependent variations in water properties (temperature and salinity) of the surface layer occur over the SE Beaufort shelf. These changes result from the mixing and advection of Mackenzie River water within the region. An example of the large temporal variability is provided by continuous temperature and salinity measurements obtained near the Issungnak site (18 m water depth) in the summer of 1981 (Fig. 6). Easterly winds result in decreasing salinities and increasing temperatures, due to the offshore and westward displacement of water influenced by the Mackenzie River. Under westerly winds, the opposite change is produced as the river waters are driven inshore and to the east, being replaced by the cold, saline Arctic Ocean water.

Not all of the variation in the temperature and salinity of the surface layer is explained by changes in surface winds. Seasonal variation is also present, with maximum temperatures and minimum salinities occurring in late July-early August, followed by a sharp reduction in temperature and increase in salinity in late August-early September. This seasonal cycle is related to the maximum accumulation of river water in late July and reduced river discharges and increased dispersion as the open water area expands through August and September. Also apparent in the temperature and salinity data of Figure 6 is short-term variability, likely resulting from internal waves, internal oscillations and baroclinic instabilities. These oceanographic features are generally enhanced in the vicinity of the large vertical and horizontal gradients found near the edge of the river plume, as observed during periods when temperatures are high and salinities are low (Fig. 6).

Routine daily measurements of sea surface temperatures collected at drillships were used to examine the temporal variability of the surface layer at other locations for the years 1980 to 1983 (Figs. 7 to 10). In all years, variations of sea temperature over periods of a few days can generally be related to the prevailing wind regime. In the area north of Richards Island and Kugmallit Bay, westerly and northwesterly winds are associated with reduced temperatures, while increasing temperatures usually coincide with or follow winds having an easterly component. This pattern of response extends to a considerable distance offshore (e.g., at the Kenalooak site, in 1980 and 1982, located 120 km north of Richards Island). The amplitude of the response appears to vary more with the distance from river outlets (Shallow Bay and Kugmallit Bay) than with distance from shore. For

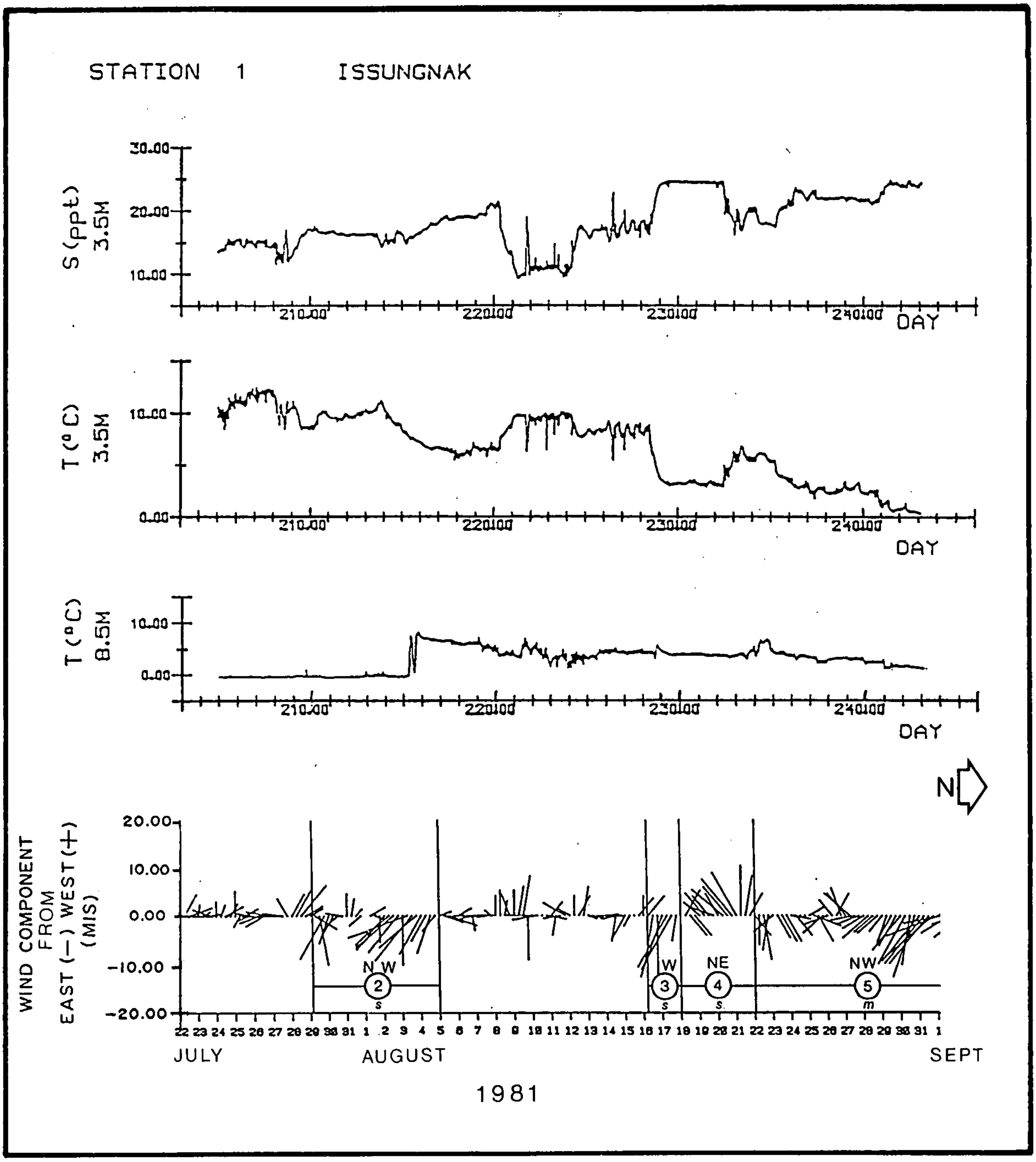

Figure 6. Continuous measurements of temperature and salinity obtained near the Issungnak site (18 m water depth) in 1981. The importance of the wind in causing changes is illustrated through the display of measured winds at Tuktoyaktuk. The sticks represent the speed and direction toward which the wind was blowing, relative to geographical north as indicated by the North reference arrow. The times of four "wind events" (event numbers 2-5) are shown, along with the average direction <u>from</u> which the wind was blowing during the event. m = moderate wind event; s = strong wind event.

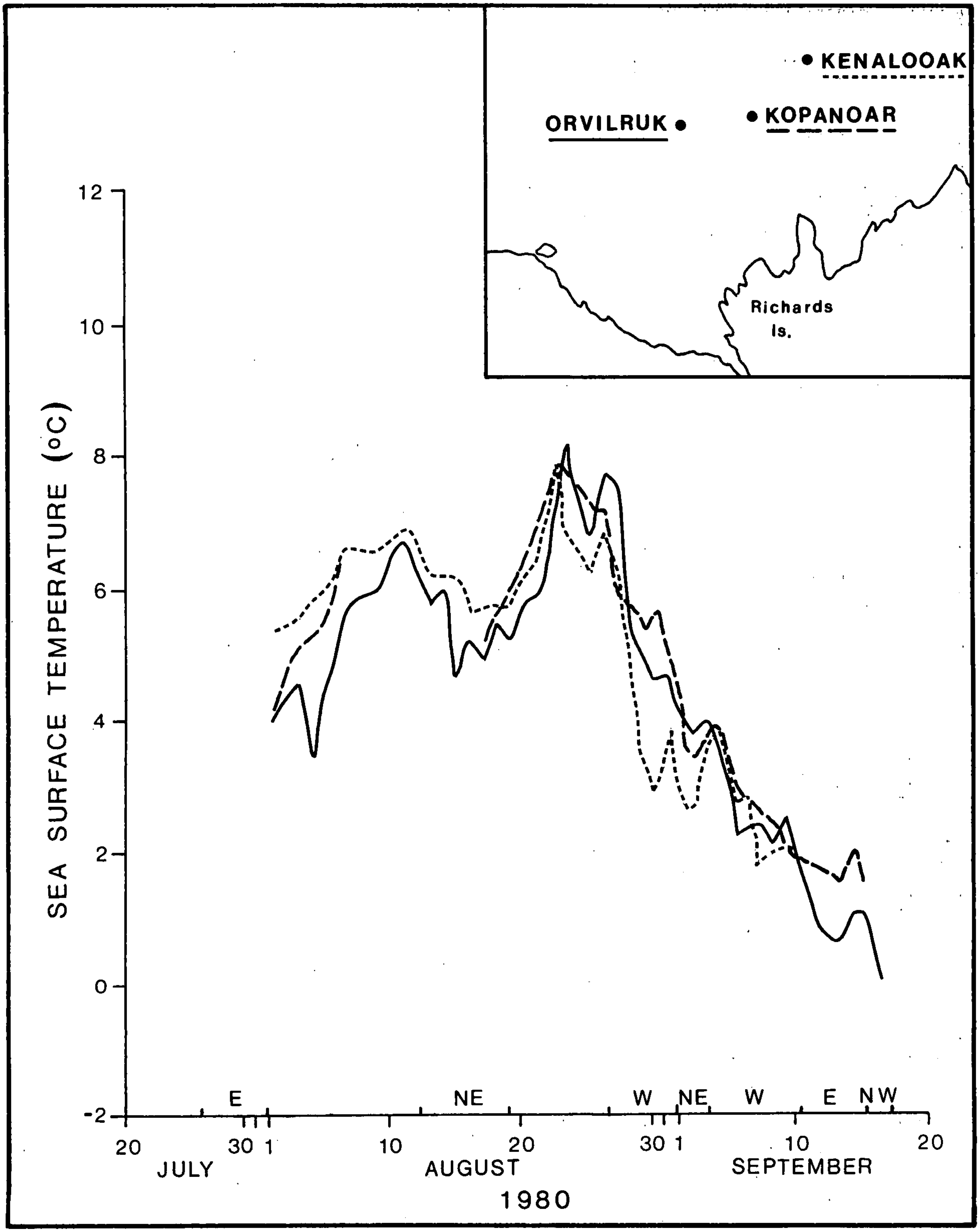

Figure 7. Daily measurements of sea surface temperatures obtained from drillships in 1980. Directions from which the wind was blowing during major wind events are indicated along the time axis.

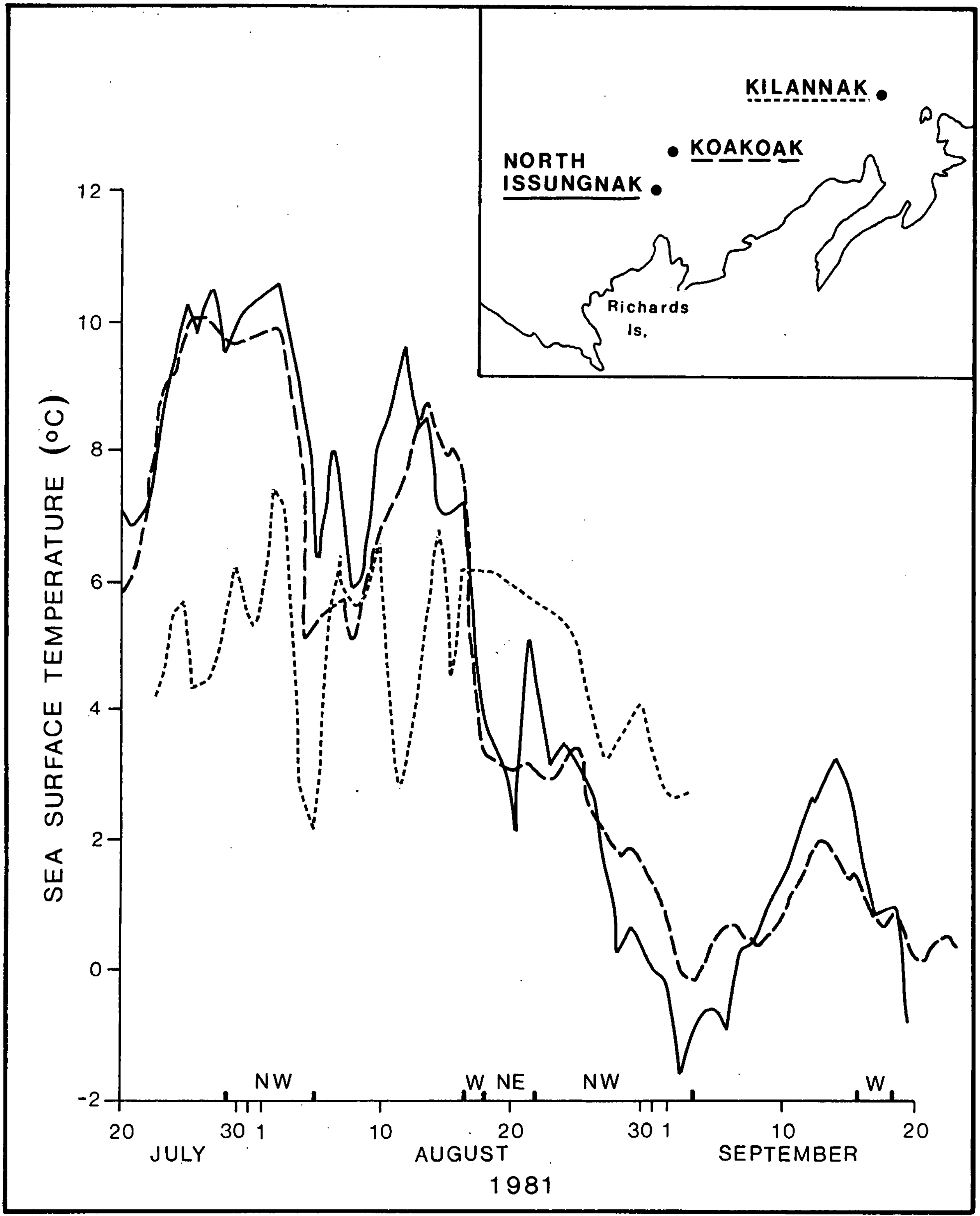

Figure 8. Daily measurements of sea surface temperatures obtained from drillships in 1981. Major wind events are indicated along the time axis.

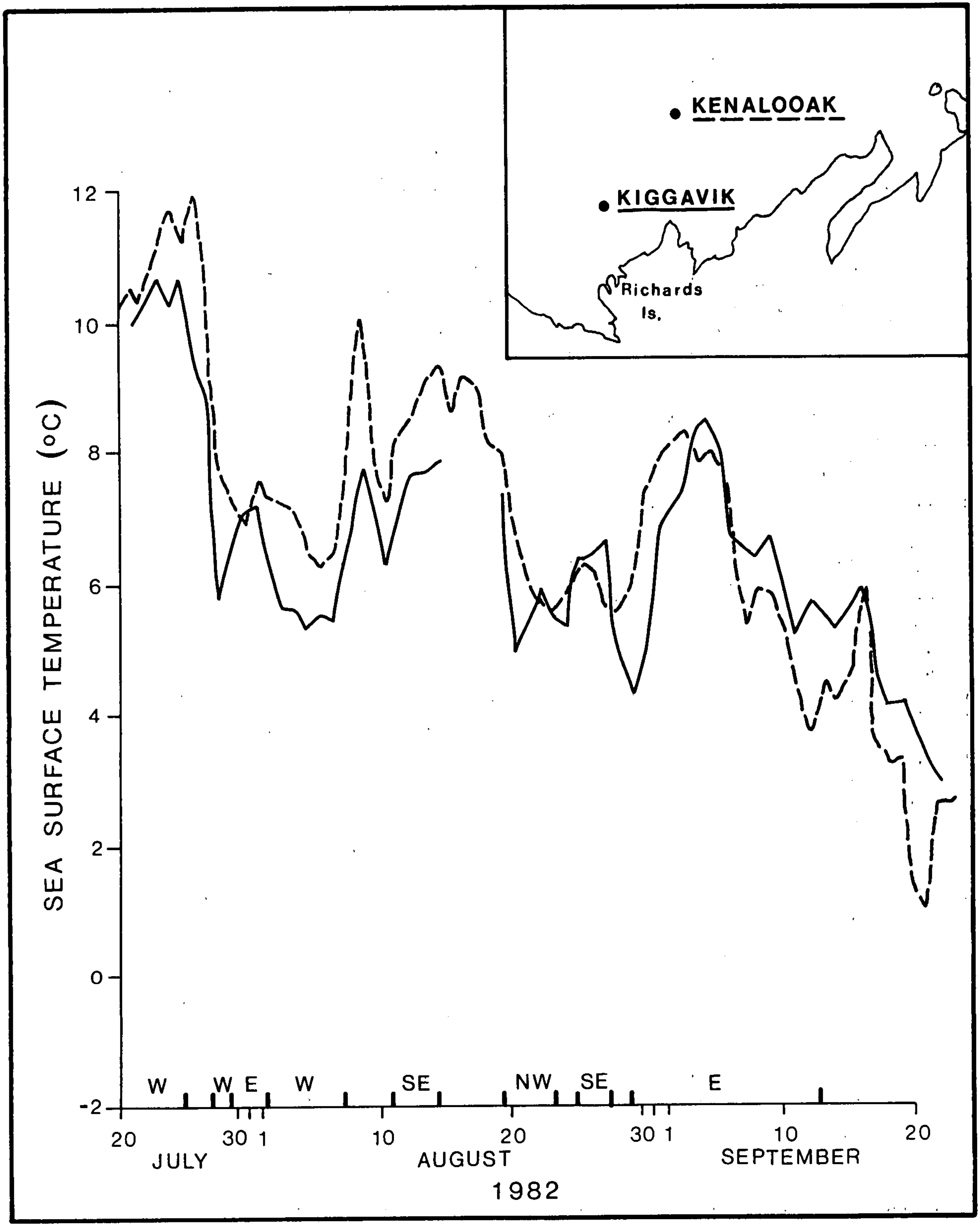

Figure 9. Daily measurements of sea surface temperatures obtained from drillships in 1982. Major wind events are indicated along the time axis.

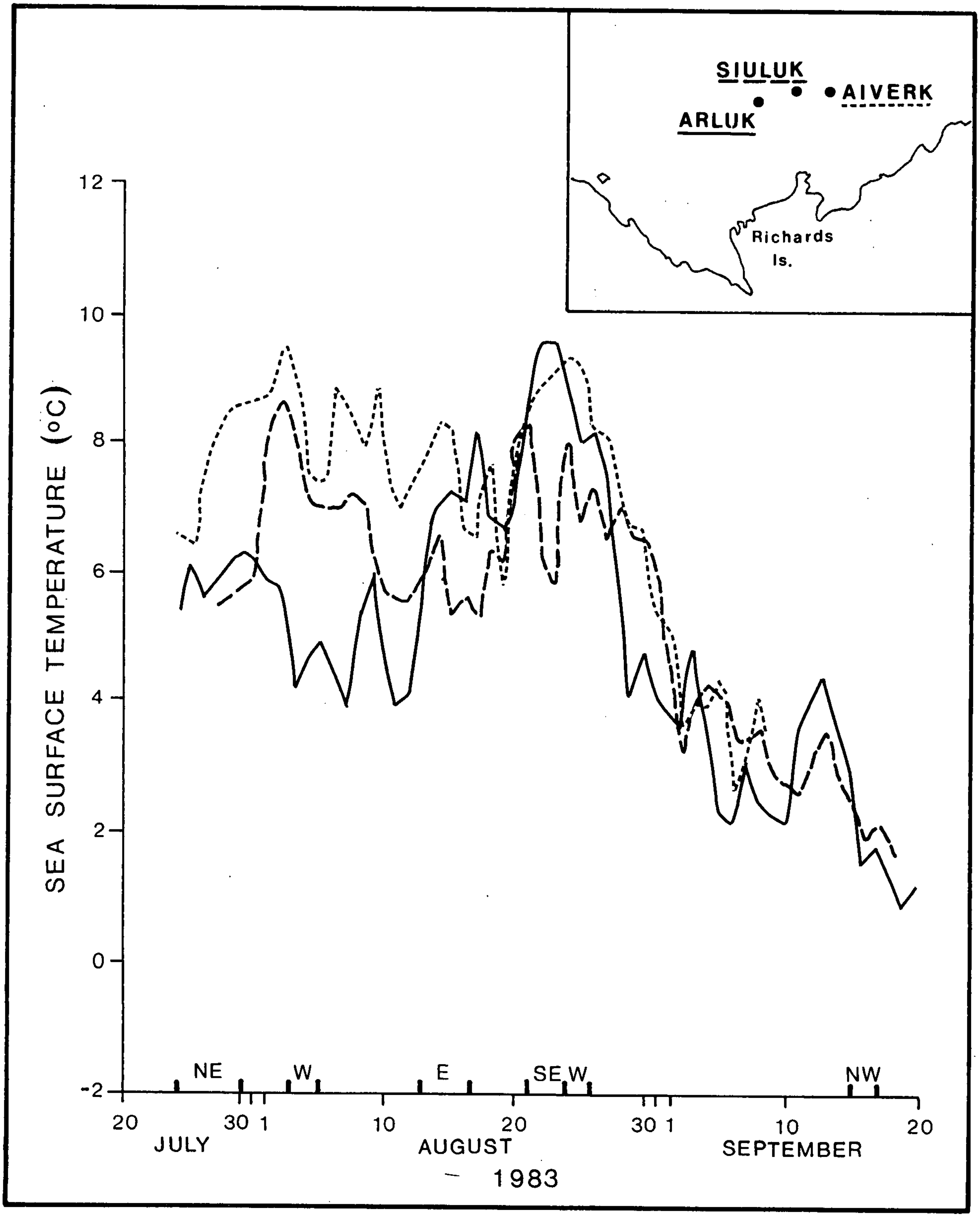

Figure 10. Daily measurements of sea surface temperatures obtained from drillships in 1983. Major wind events are indicated along the time axis.

example, the response at the Kiggavik site (located 50 km from shore) was generally smaller than experienced much farther from shore at the Kenalooak site in 1982 (Fig. 9). The largest response appeared to occur north of Kugmallit Bay and the eastern half of Richards Island.

The above description of the response of sea temperatures to wind forcing in the area north of Richards Island is highly generalized. Deviations from the general pattern occurred in several instances in 1980, 1982 and 1983.

At locations farther west, the wind-induced changes are smaller. Thermal changes at these locations may reflect a greater likelihood that melting sea ice will reduce the sea temperature. This effect was particularly important in the 1983 results (Fig. 10) where the temperatures at the westernmost site, Arluk, were consistently reduced in the first half of August, due to incursions of sea ice from the northwest.

North of the Tuktoyaktuk Peninsula, the wind-induced changes in sea temperatures diminish with increasing distance from shore and lateral distance from the Kugmallit Bay river source (see, for example, the data obtained at Kilannak in 1981). Moreover, within the inshore zone (depths <20 m), the response to winds is opposite to that in the offshore and more westerly regions. Here, westerly winds result in increased temperatures (decreased salinity) due to the eastward advection and concentration of the plume along the coast. Under easterly winds, the temperatures decrease and salinities increase as the plume is displaced offshore and westward, resulting in the presence of cold, saline waters associated with coastal upwelling.

Surface Oceanography by Wind Event Periods

The spatial distribution of the Mackenzie River plume, and its response to surface winds, was further examined through the preparation of maps of surface oceanographic features (temperature, salinity and turbidity) for the region. The sequence of redistribution of the river plume was then compared with the sequence of surface wind patterns.

Wind Events: 1980-1983. Wind event periods were determined using measurements from Tuktoyaktuk, during the summers of 1980-1983. The characteristics of the surface wind during each period of relatively consistent wind are listed in Tables 8 and 9 and summarized in Figure 11. Over the 4-yr period, a total of 33 wind 'events' (vector mean speed exceeding 3 m/s) occurred in the July-mid September period. The wind events were evenly divided between those with a component from the west (16) and those with a component from the east (16). A single wind event (second event of 1982, Fig. 11), was dominated by northerly winds. Individual wind events were

TABLE 8

Detailed description of wind events and intervening periods from early July to mid September 1980 to 1983

Year	Event No.		Start Period Date/h	End Period Date/h	No. Days	Wind Run (km/period)[a]		Mean Velocity		Maximum Velocity			Accumulated Wind Run (km)[a]		Mean Velocity (m/s)[a]	
						E/W	N/S	m/s	Deg. from	m/s	Deg. from	Date/h	E/W	N/S	E/W	N/S
1980	1	E-Moderate	Jul 01/00	Jul 22/12	21.5	-6604	-3842	4.11	60	9.7	90	Jul 04/12	-6604	-3842	-3.56	-2.07
		W-Weak	Jul 22/12	Jul 25/18	3.25	-170	-402	1.55	23	5.3	100	Jul 24/00	-6774	-4244	-0.61	-1.43
	2	W-Strong	Jul 25/18	Jul 27/00	1.25	612	-529	7.49	311	13.3	320	Jul 26/00	-6162	-4773	5.67	-4.9
	3	E-Moderate	Jul 27/00	Aug 01/06	5.25	-1743	-533	4.02	73	8.6	30	Jul 28/06	-7905	-5306	-3.84	-1.18
		NE-Weak	Aug 01/06	Aug 12/06	11	-699	-696	1.04	45	6.7	160	Aug 06/12	-8604	-6002	-0.74	-0.73
	4	NE-Strong	Aug 12/06	Aug 19/12	7.25	-2597	-2055	5.29	52	12.8	40	Aug 17/18	-11201	-8057	-4.15	-3.28
		SE-Weak	Aug 19/12	Aug 26/18	7.25	-462	159	0.78	109	7.8	320	Aug 24/18	-11663	-7898	-0.74	0.25
	5	W-Moderate	Aug 26/18	Sep 01/06	5.5	1683	90	3.55	267	12.2	300	Aug 30/06	-9980	-7808	3.54	0.19
	6	NE-Strong	Sep 01/06	Sep 03/06	2	-652	-898	6.42	36	8.3	60	Sep 01/18	-10632	-8706	-3.77	-5.2
	7	W-Moderate	Sep 03/06	Sep 10/12	7.25	2090	356	3.38	260	8.3	270	Sep 04/12	-8542	-8350	3.34	0.57
	8	E-Moderate	Sep 10/12	Sep 15/18	5.25	-1548	568	3.64	110	8.3	100	Sep 13/12	-10090	-7782	-3.41	1.25
	9	NW-Strong	Sep 15/18	Sep 18/12	2.75	1479	-980	7.47	304	13.3	310	Sep 16/12	-8611	-8762	6.22	-4.12
		Total			79.5	-8611	-8762						-8611	-8762		
		Mean						1.79	45						-1.25	-1.28
1981		NW-Weak	Jul 01/00	Jul 15/06	15.25	469	-782	0.69	329	10.8	260	Jul 14/12	469	-782	0.36	-0.59
	1	SE-Strong	Jul 15/06	Jul 19/18	4.5	-1761	565	4.76	108	10.3	100	Jul 17/18	-1292	-217	-4.53	1.45
		E-Weak	Jul 19/18	Jul 29/06	9.5	-887	-285	1.14	72	9.2	280	Jul 20/00	-2180	-502	-1.08	-0.35
	2	NW-Strong	Jul 29/06	Aug 05/00	6.75	2456	-1604	5.03	303	13.3	340	Aug 03/06	276	-2106	4.21	-2.75
		SE-Weak	Aug 05/00	Aug 16/06	11.25	-704	336	0.8	116	8.3	100	Aug 09/12	-428	-1770	-0.72	0.35
	3	W-Strong	Aug 16/06	Aug 18/00	1.75	1240	-354	8.53	286	13.3	290	Aug 17/00	812	-2124	8.2	-2.34
	4	NE-Strong	Aug 18/00	Aug 22/00	4	-1419	-582	4.44	68	10.3	240	Aug 21/00	-607	-2706	-4.11	-1.68
	5	NW-Moderate	Aug 22/00	Sep 03/00	12	3818	-2943	4.65	308	13.3	290	Aug 30/00	3211	-5649	3.68	-2.84
		E-Weak	Sep 03/00	Sep 15/18	12.75	-1421	10	1.29	90	7.2	120	Sep 07/12	1790	-5639	-1.29	0.01
	6	W-Strong	Sep 15/18	Sep 18/06	2.5	1470	-375	7.02	284	12.2	300	Sep 17/00	3260	-6014	6.81	-1.74
		Total			80.25	3260	-6014						3260	-6014		
		Mean						0.99	332						0.47	-0.87
1982		Weak	Jul 01/00	Jul 09/06	9.25	-108	-1725	2.16	4	7.78	300	Jul 06/18	-108	-1725	-0.14	-2.16
	1	E-Strong	Jul 09/06	Jul 16/00	6.75	-3134	410	5.42	97	8.61	70	Jul 10/18	-3242	-1315	-5.37	0.7
	2	N-Moderate	Jul 16/00	Jul 19/12	3.5	-202	-984	3.32	12	8.33	30	Jul 17/18	-3444	-2299	-0.67	-3.25
	3	W-Moderate	Jul 19/12	Jul 24/12	5	1504	432	3.62	254	9.17	270	Jul 20/06	-1940	-1867	3.48	1
		Weak	Jul 24/12	Jul 26/12	2	-151	-256	1.72	31	9.17	350	Jul 25/00	-2091	-2123	-0.87	-1.48
	4	W-Strong	Jul 26/12	Jul 29/06	2.75	1252	-216	5.34	280	12.22	320	Jul 27/18	-840	-2339	5.27	-0.91
	5	E-Moderate	Jul 29/06	Aug 01/00	2.75	-826	91	3.5	96	7.78	120	Jul 30/18	-1666	-2248	-3.48	0.38
	6	W-Strong	Aug 01/00	Aug 06/18	5.75	2190	-574	4.56	285	9.17	300	Aug 02/00	524	-2822	4.41	-1.16
		Weak	Aug 06/18	Aug 10/12	3.75	280	37	0.87	263	7.22	280	Aug 09/18	804	-2786	0.86	0.11
	7	SE-Moderate	Aug 10/12	Aug 14/06	3.75	-1085	840	4.24	128	9.17	170	Aug 13/18	-281	-1946	-3.35	2.59
		Weak	Aug 14/06	Aug 19/06	5	583	-65	1.36	276	8.33	330	Aug 18/00	302	-2010	1.35	-0.15
	8	NW-Strong	Aug 19/06	Aug 23/06	4	1931	-1094	6.42	300	13.33	300	Aug 21/06	2233	-3104	5.59	-3.17
		Weak	Aug 23/06	Aug 24/18	1.5	-101	-205	1.76	26	3.61	350	Aug 23/12	2132	-3309	-0.78	-1.58
	9	SE-Moderate	Aug 24/18	Aug 27/12	2.75	-814	640	4.36	128	5.28	120	Aug 25/06	1317	-2669	-3.43	2.69
		Weak	Aug 27/12	Aug 29/00	1.5	303	27	2.35	265	4.17	220	Aug 28/06	1621	-2642	2.35	0.21
	10	E-Moderate	Aug 29/00	Sep 13/00	15	-4306	955	3.4	103	8.33	100	Sep 09/12	-2685	-1688	-3.32	0.74
		Weak	Aug 13/00	Sep 16/12	3.5	-139	438	1.52	162	8.33	310	Sep 14/12	-2824	-1250	-0.46	1.45
	11	W-Strong	Sep 16/12	Sep 17/18	1.25	998	215	9.45	258	14.44	290	Sep 17/06	-1826	-1035	9.24	1.99
		Total			79.75	-1826	-1035						-1826	-1035		
		Mean						0.3	60						-0.27	-0.15
1983	1	E-Moderate	Jul 01/00	Jul 11/18	11.75	-3415	-59	3.36	89	10.28	80	Jul 02/18	-3415	-59	-3.36	-0.06
		NW-Weak	Jul 11/18	Jul 19/00	7.25	1090	-672	2.04	302	7.22	280	Jul 16/12	-2325	-731	1.74	-1.07
		Weak	Jul 19/00	Jul 25/00	6	-1322	-18	2.55	89	5.56	70	Jul 24/06	-3647	-748	-2.55	-0.03
	2	NE-Moderate	Jul 25/00	Jul 29/18	4.75	-1163	-679	3.28	60	8.33	40	Jul 27/00	-4810	-1427	-2.83	-1.65
		Weak	Jul 29/18	Aug 02/12	3.75	-845	-301	2.77	70	8.33	80	Aug 01/00	-5656	-1728	-2.61	-0.93
	3	W-Strong	Aug 02/12	Aug 05/00	2.5	1408	-275	6.64	281	12.78	290	Aug 03/12	-4248	-2003	6.52	-1.27
		Weak	Aug 05/00	Aug 13/06	8.25	115	-352	0.52	342	7.78	30	Aug 09/12	-4132	-2355	0.16	-0.49
	4	E-Strong	Aug 13/06	Aug 17/00	3.75	-1645	-193	5.11	83	8.33	100	Aug 15/00	-5777	-2548	-5.08	-0.6
		Weak	Aug 17/00	Aug 21/06	4.25	45	374	1.03	187	7.22	340	Aug 19/18	-5737	-2174	0.11	1.02
	5	SE-Moderate	Aug 21/06	Aug 23/18	2.5	-797	517	4.38	123	7.22	130	Aug 23/12	-6529	-1657	-3.67	2.39
	6	W-Moderate	Aug 23/18	Aug 26/00	2.25	620	-216	3.38	289	5.56	280	Aug 25/12	-5909	-1873	3.19	-1.11
		Weak	Aug 26/00	Sep 15/06	20.25	674	-231	0.41	289	11.39	210	Sep 05/06	-5236	-2104	0.39	-0.13
	7	NW-Strong	Sep 15/06	Sep 17/00	1.75	764	-772	7.18	315	12.78	330	Sep 15/18	-4472	-2875	5.05	-5.1
		Total			79	-4472	-2875						-4472	-2875		
		Mean						0.78	57						-0.66	-0.42

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[a] Components to the east and north are treated as negative; components to the west and south are treated as positive.

TABLE 9

Wind conditions during and between wind event periods from late July to early September 1980 to 1983 and salinities off Richards Island

Year	Date	Event No.	No. Days	Wind Run (km/period)[a]		Vector Wind[b]		Salinity °/oo ± s.d.[c]		
				E/W	N/S	Degrees	km/d	at 1 m	at 4 m	No. Samples
1980	22 Jul-25 Jul	-	3.25	-170	-402	23	134	25.1 ± 2.0	25.8 ± 2.3	4
1980	25 Jul-27 Jul	80-2	1.25	612	-529	311	647	23.2 ± 2.0	24.2 ± 0.9	2
1980	27 Jul-1 Aug	80-3	5.25	-1743	-533	73	347	27.3 ± 3.6	27.5 ± 3.4	4
1980	1 Aug-12 Aug	-	11	-699	-696	45	90	26.5 ± 2.8	26.7 ± 2.5	8/7[d]
1980	12 Aug-19 Aug	80-4	7.25	-2597	-2005	52	453	26.0 ± 2.5	27.2 ± 2.8	8
1980	19 Aug-26 Aug	-	7.25	-452	159	109	66	24.0 ± 4.6	26.5 ± 2.3	4
1980	26 Aug-1 Sep	80-5	5.5	1683	90	267	306	23.2 ± 2.5	24.0 ± 1.9	5/4
1980	1 Sep-3 Sep	80-5	2	-652	-898	36	555	23.6 ± 1.6	24.0 ± 0.9	2
1980	3 Sep-10 Sep	80-7	7.25	2090	356	260	292	19.6 ± 0.1	19.8 ± 0.6	2
1981	19 Jul-29 Jul	-	9.5	-887	-285	72	98	12.1 ± 3.0	13.2 ± 2.9	3
1981	29 Jul-5 Aug	81-2	6.75	2456	-1604	303	435	15.9 ± 2.5	16.2 ± 2.4	5
1981	5 Aug-16 Aug	-	11.25	-704	336	116	69	14.1 ± 3.3	17.5 ± 5.2	8
1981	16 Aug-18 Aug	81-3	1.75	1240	-354	286	737	24.8 ± 0.4	25.1 ± 0.5	2
1981	18 Aug-22 Aug	81-4	4	-1419	-582	68	383	22.6 ± 3.4	22.7 ± 3.6	4
1981	22 Aug-3 Sep	81-5	12	3818	-2943	308	402	24.1 ± 1.6	25.1 ± 2.9	15/14
1981	3 Sep-15 Sep	-	12.75	-1421	10	90	111	20.6 ± 3.0	23.7 ± 1.2	12/14
1982	26 Jul-29 Jul	82-4	2.75	1252	-216	280	462	27.2 ± 1.8	28.0 ± 2.0	6
1982	29 Jul-1 Aug	82-5	2.75	-826	91	96	302	26.9 ± 0.6	27.1 ± 0.5	2/3
1982	1 Aug-6 Aug	82-6	5.75	2190	-574	285	394	25.7 ± 1.2	25.9 ± 1.2	4
1982	6 Aug-10 Aug	-	3.75	280	37	263	75	24.2 ± 0.1	24.9 ± 0.1	3
1982	10 Aug-14 Aug	82-7	3.75	-1085	840	128	366	23.1 ± 1.8	23.8 ± 0.7	3
1982	14 Aug-19 Aug	-	5	583	-65	276	117	23.6 ± 2.1	23.8 ± 1.8	4
1982	19 Aug-23 Aug	82-8	4	1931	-1094	300	555	25.2 ± 0.2	25.2 ± 0.2	4
1982	23 Aug-24 Aug	-	1.5	-101	-205	26	152	25.2 ± -	25.3 ± -	1
1982	24 Aug-27 Aug	82-9	2.75	-814	640	128	377	25.7 ± 0.7	25.7 ± 0.8	4
1982	27 Aug-29 Aug	-	1.5	303	27	265	203	24.7 ± 0.4	25.5 ± 0.2	2
1982	29 Aug-13 Sep	82-10	15	-4306	955	103	294	22.2 ± 2.7	24.4 ± 1.9	13
1983	25 Jul-29 Jul	83-2	4.75	-1163	-679	60	284	11.7 ± 0.7	12.3 ± 0.8	3
1983	29 Jul-2 Aug	-	3.75	-845	-301	70	239	13.6 ± 1.1	14.4 ± 1.6	4
1983	2 Aug-5 Aug	83-3	2.5	1408	-275	281	574	11.8 ± -	12.1 ± -	1
1983	5 Aug-13 Aug	-	8.25	115	-352	342	45	16.9 ± 1.8	19.0 ± 0.9	2
1983	13 Aug-17 Aug	83-4	3.75	-1645	-193	83	442	15.7 ± 3.5	16.9 ± 4.2	2
1983	17 Aug-21 Aug	-	4.25	45	374	187	89	13.5 ± 0.3	15.3 ± 2.5	3
1983	21 Aug-23 Aug	83-5	2.5	-797	517	123	380	16.8 ± -	19.2 ± -	1
1983	23 Aug-26 Aug	83-6	2.25	620	-216	289	292	19.1 ± 0.6	19.6 ± 0.1	2
1983	26 Aug-15 Sep	-	20.25	674	-231	289	35	16.8 ± 0.5	17.0 ± 1.0	15

[a] Components to the east and north are treated as negative; components to the west and south are treated as positive.

[b] Direction from which the wind was blowing.

[c] Measured by drillships in an area bounded by 70°05'N, 70°42'N, 133°55'W and 136°30'W.

[d] No. samples at 1 m / no. at 4 m (if numbers are different).

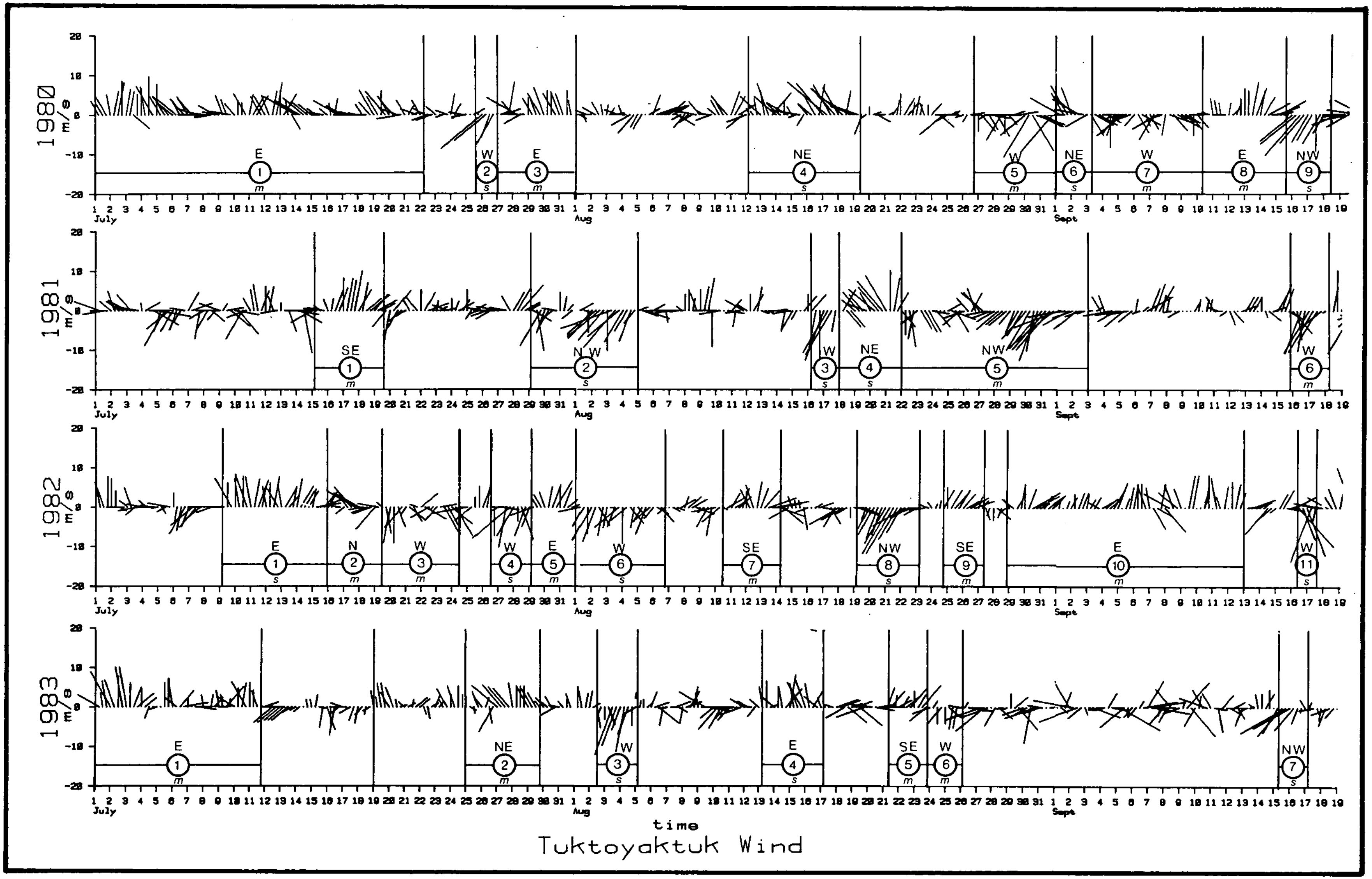


Figure 11. The 6-hourly wind vectors as measured at Tuktoyaktuk from 1 July to 19 September 1980-1983. The wind vectors are presented as sticks indicating the speed and direction toward which the wind was blowing, relative to geographical north as indicated by the large arrow labelled as N. The occurrence of individual wind events, as discussed in the text, is shown along the time axes, along with the average direction <u>from</u> which the wind was blowing. m = moderate wind event; s = strong wind event.

typically 3-7 days in duration. However, some events were limited to 1-2.5 days duration (4 of 5 of these short events were intense westerly or northwesterly winds), while others extended over periods of 8 to 21 days (three in total, two were easterly and one was westerly).

The summer wind patterns varied among years. In July and August 1980, winds from the east and northeast occurred more frequently than usual while westerly and northwesterly winds were uncommon (Figs. 12 and 13). July and August 1981 were characterized by northwesterly winds and infrequent occurrences of easterly winds. Wind patterns in 1982 were similar to those in 1981, although southeasterly winds were more common and northerly winds less common, particularly in August. The winds in July 1983 were more easterly than usual. However, in August of 1983 winds had a more uniform directional distribution, resulting in a comparatively small wind run (1750 km northerly) as compared to the larger values for 1980 (3100 km northeasterly), 1981 (5800 km northwesterly) and 1982 (3300 km westerly).

Surface Oceanographic Features. Surface oceanographic distributions were mapped primarily using the visible and near infrared bands of NOAA TIROS satellite imagery (see Methods). The largest horizontal gradients provided a reliable indicator of the outer boundary of the Mackenzie River plume proper and its associated low salinities and high turbidities. This feature, designated as the 'intense' plume, is contiguous with the discharge channels of the river delta. A second area, denoted as the diffuse plume, was also mapped by delineating a secondary set of steep gradients that separated surface waters mixed with Mackenzie River water from the colder and more saline Arctic Ocean water. The diffuse plume is generally less homogeneous than the intense plume. Eddy- and gyre-like features are often contained within and along the inner boundary of the diffuse plume.

Maps of surface temperature and salinity distributions were also prepared using all available conventional surface-based oceanographic observations (see Materials and Methods). This information was annotated onto the maps representing satellite imagery. For the frequent occasions when satellite observations were unavailable due to cloud cover, temperature and salinity maps were derived solely from oceanographic observations. On these maps, the paucity of measurement sites generally precluded any definitive determinations of the locations of the intense and diffuse plumes. Measurements available from within the intense plume were limited to only a few days during the four summers. The drillships, which provided the bulk of the available data, were always in either the diffuse plume or Arctic Ocean water. Because of the spatial complexity of the diffuse plume and the limited number

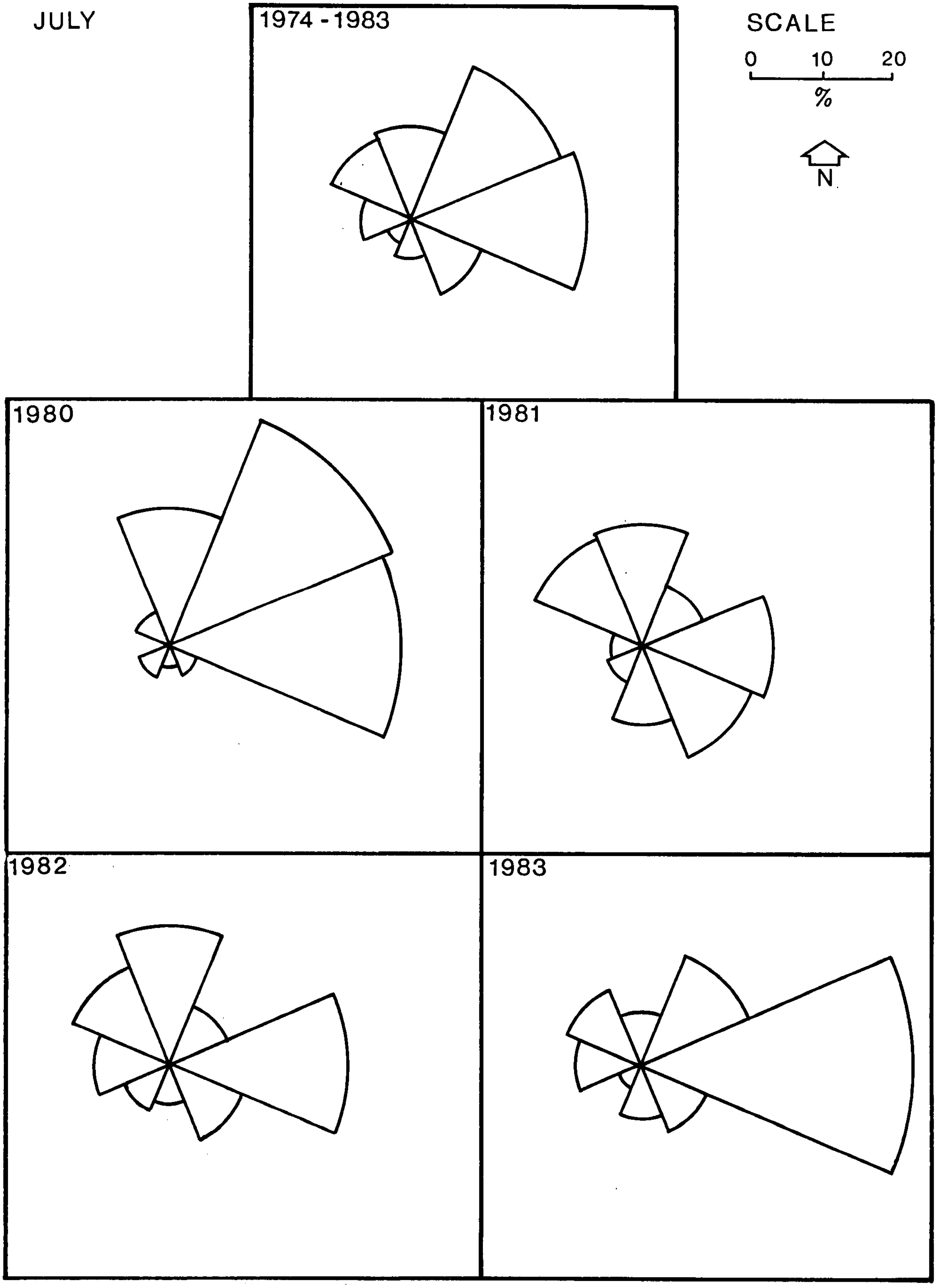


Figure 12. Wind roses from July measurements at Tuktoyaktuk, N.W.T. Plotted as in Figure 4.

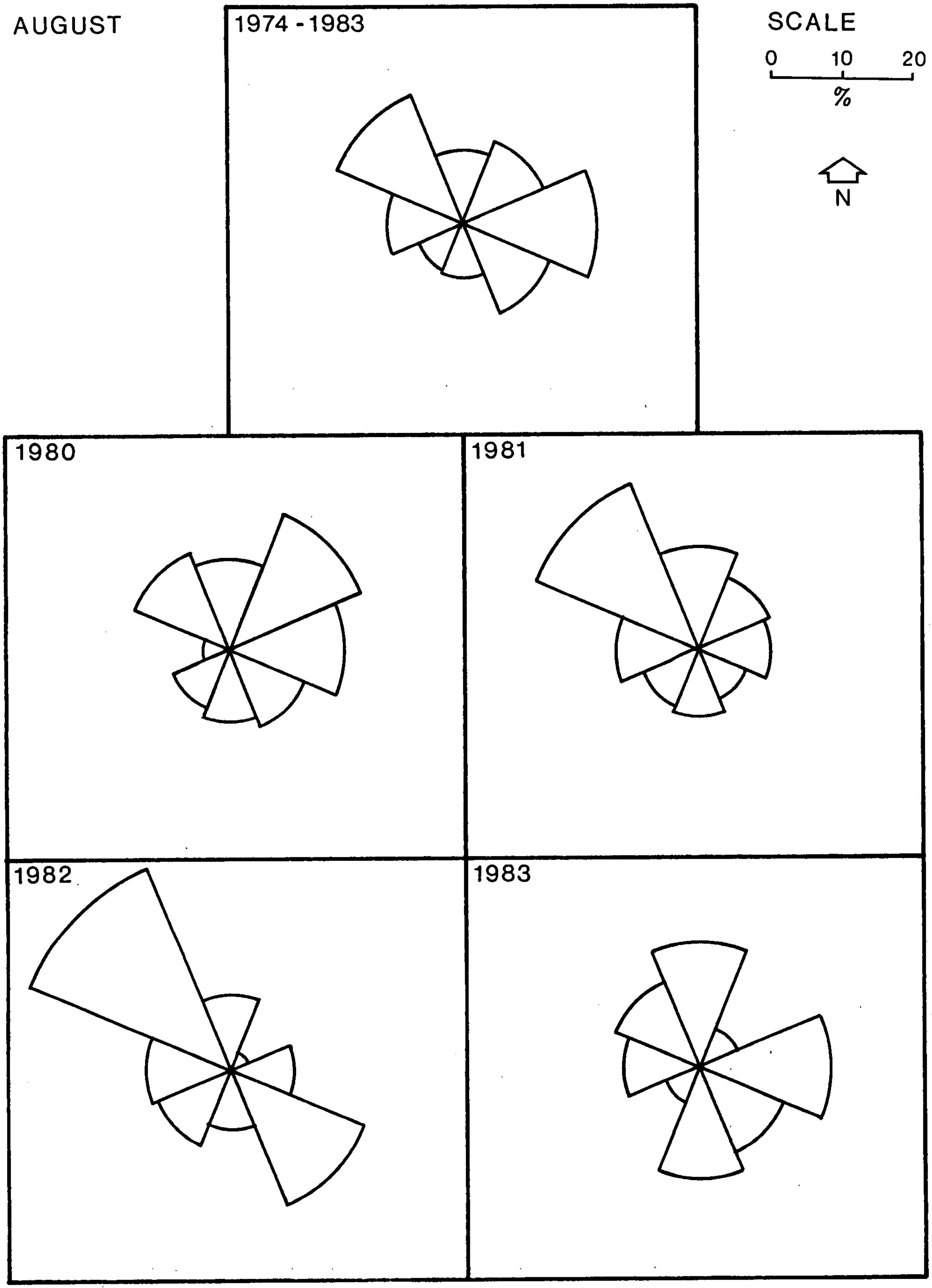


Figure 13. Wind roses for August measurements at Tuktoyaktuk, N.W.T.

of observation sites (2 to 6), estimates of the diffuse plume boundary were judged to be highly uncertain. Due to the inherent uncertainty, maps derived solely from oceanographic observations are presented sparingly in this study.

Maps of the intense and diffuse plumes are presented in Figures 14 to 17. Each map is annotated with a summary of daily wind conditions on the observation date and preceding days. A brief commentary discussing the changes in plume locations in relation to wind forcing is presented below for each summer of observations.

1980: Figures 14a to 14l. In early August (Fig. 14a,b), the intense plume occurred as two separate entities protruding north and westwards from the source outlets in Mackenzie and Kugmallit bays. The diffuse plume streamed farther to the northwest, extending up to 160 km off the coastline at a time (5 August) of weak and variable winds, following the dominant easterly wind event of late July. The location of the diffuse plume shown on the map for 7 August (Fig. 14c) is inconsistent with the 5 August location, possibly as a result of using a low resolution hardcopy image. Digital imagery was used to produce the map of 5 August. The limited data on 14 August (Fig. 14d) suggest that the plume distribution of 5 August was unchanged in areas to the north and northwest of Kugmallit Bay. Following a period of strong northeasterly winds, the 20 August image derived from the thermal band (Fig. 14e) suggests that the area of the diffuse plume may have expanded north and east of Richards Island. The high temperatures and low salinities measured along the Yukon coast were indicative of a considerable westward extension to the plume. Interestingly, the size of the diffuse plume as derived from the visible satellite band was significantly smaller for both the 20 August and 24 August maps than the size depicted on thermal images (compare Figs. 14e,g with Figs. 14f,h). Based on oceanographic observations, the thermal band appears to be a more representative measure of river water influence for this period. A major eastward advection of the river plume areas occurred by 31 August (Fig. 14i,j), apparently due to the westerly wind experienced in late August. By 3 September (Fig. 14k,l), the plumes had moved westward and offshore, at least in the regions adjoining Mackenzie Bay and the Yukon coast. The observation period coincided with the end of a brief but intense northeasterly wind event.

1981: Figures 15a to 15g. At the beginning of August (Fig. 15a), mixing of river water was evident as reduced salinities and increased temperatures extending to the north of 70°N, offshore of Richards Island and Kugmallit Bay. By 5-6 August (Figs. 15b,c,d,e), cold, saline Arctic Ocean water moved into this area, as the plume water was redistributed eastward, under the influence of strong northwesterly winds. By 11-12 August (Fig. 15f), after weak to moderate easterly

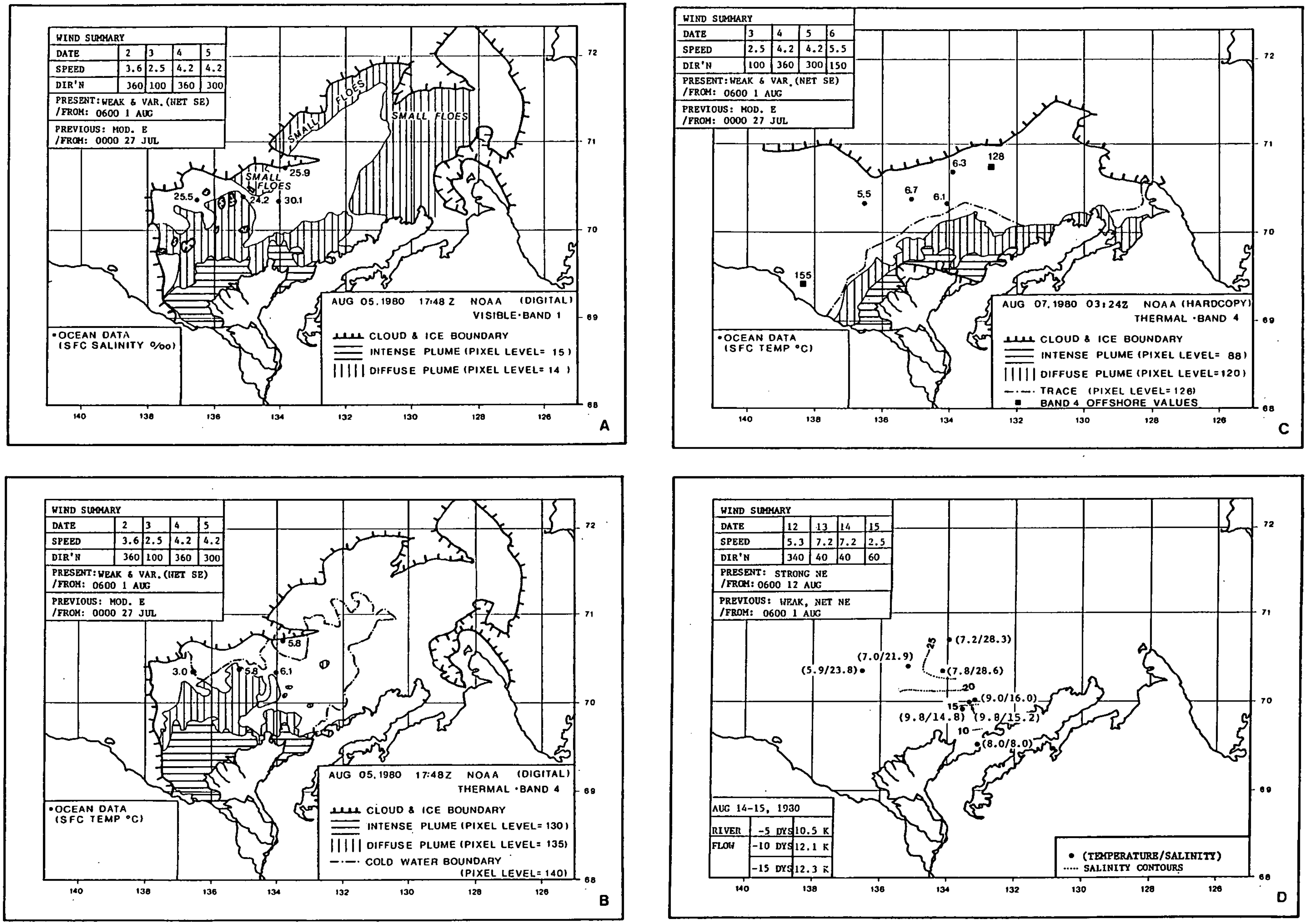
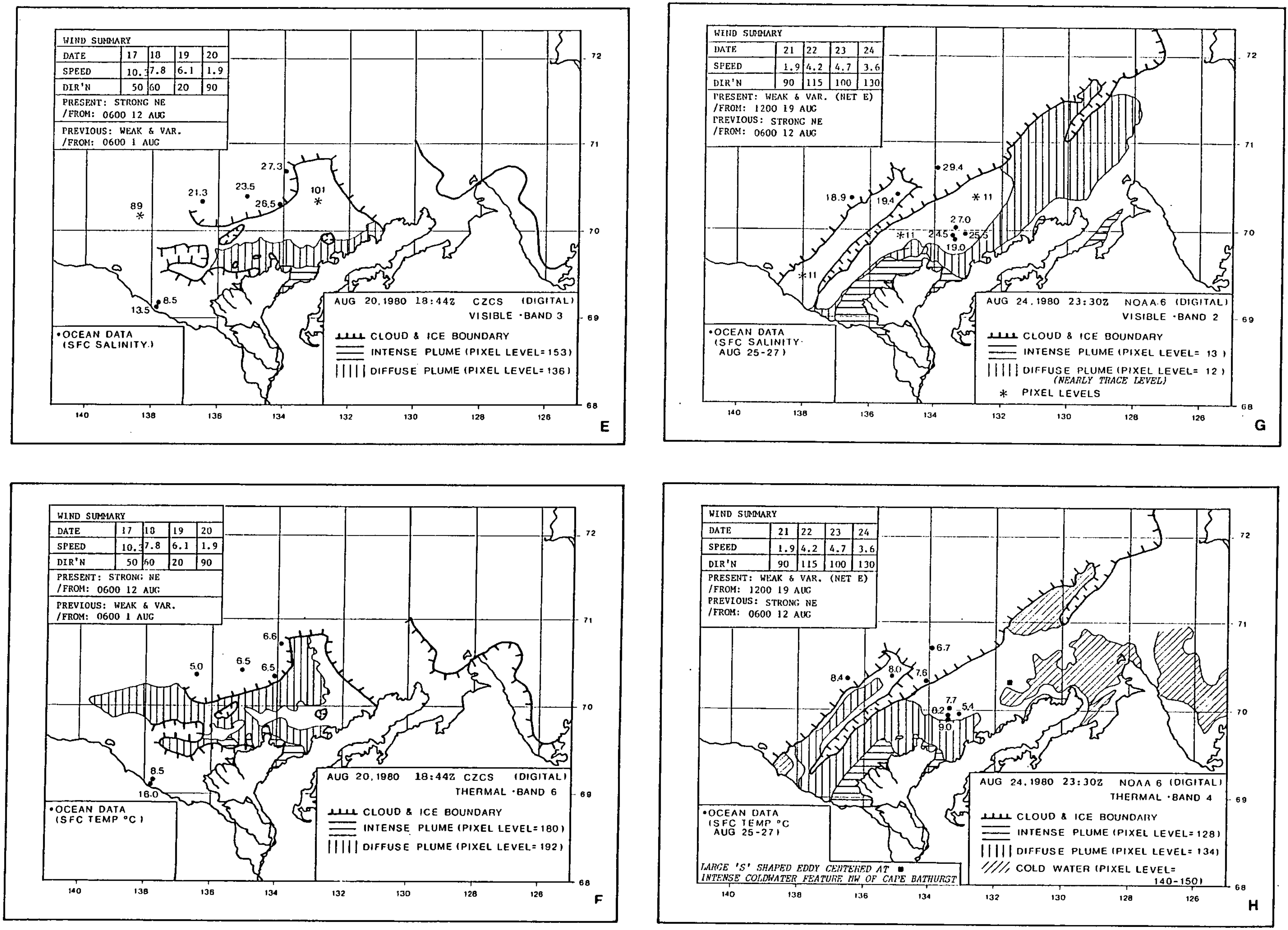


Figure 14. A sequence of maps showing distribution of surface oceanographic properties in 1980, derived from satellite data and ship-based measurements. Only the surface oceanographic data are mapped for wind event periods with no satellite data. Representative wind speeds for the day are in m/s; wind directions are those <u>from</u> which the wind blew.



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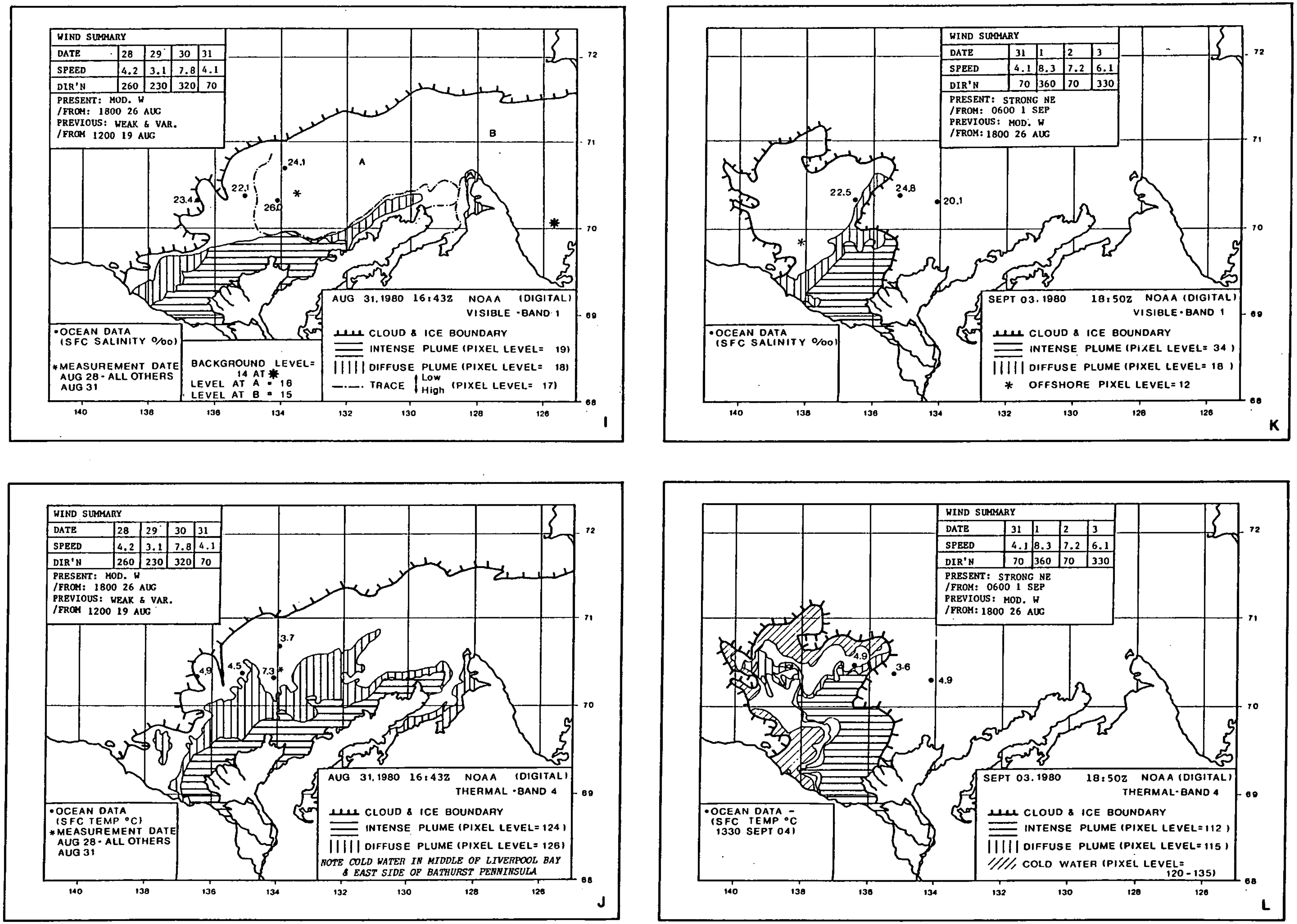

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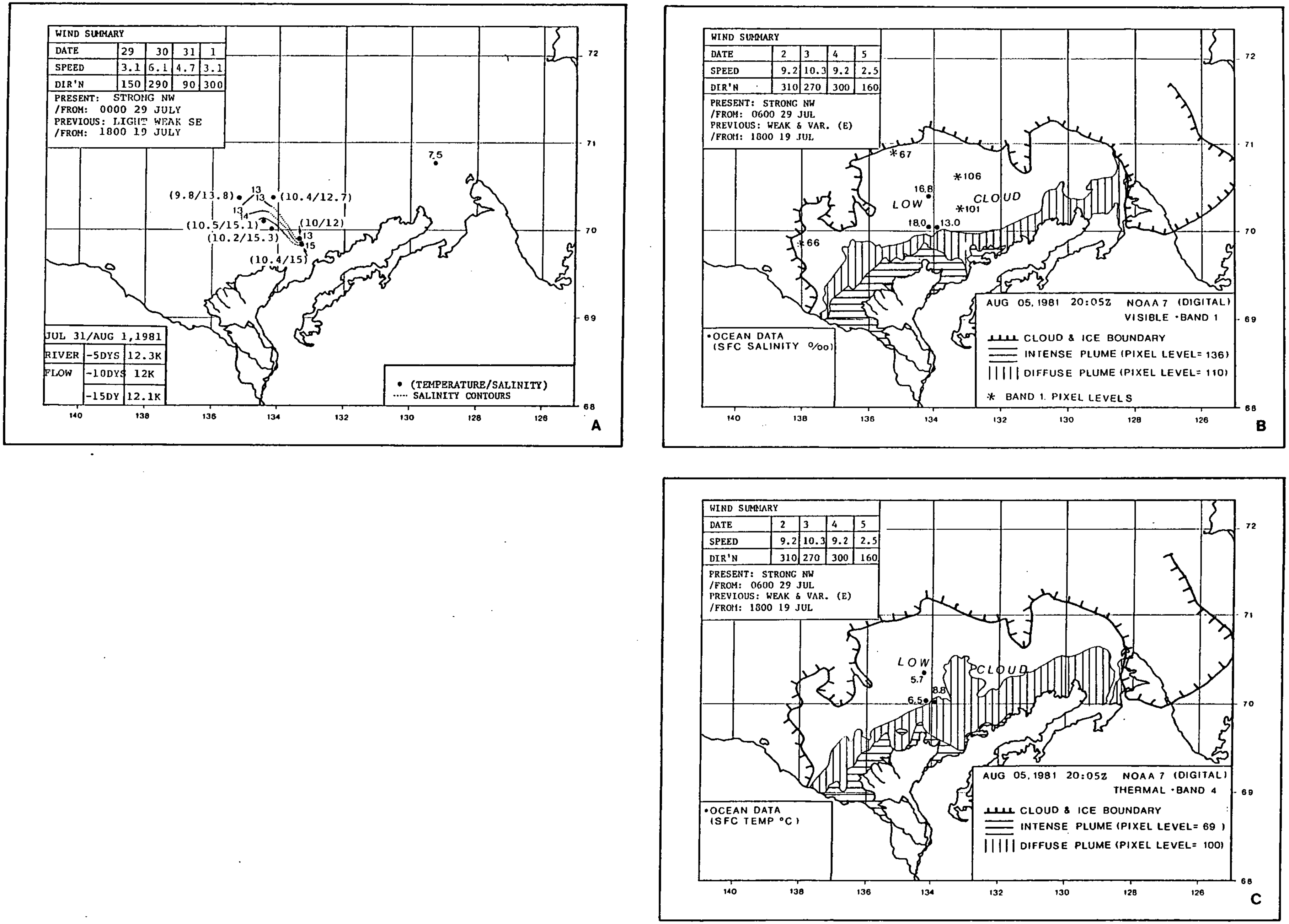


Figure 15. A sequence of maps showing distribution of surface oceanographic properties in 1981, derived from satellite data and ship-based measurements. Only the surface oceanographic data are mapped for wind event periods with no satellite data. Representative wind speeds for the day are in m/s; wind directions are those <u>from</u> which the wind blew.

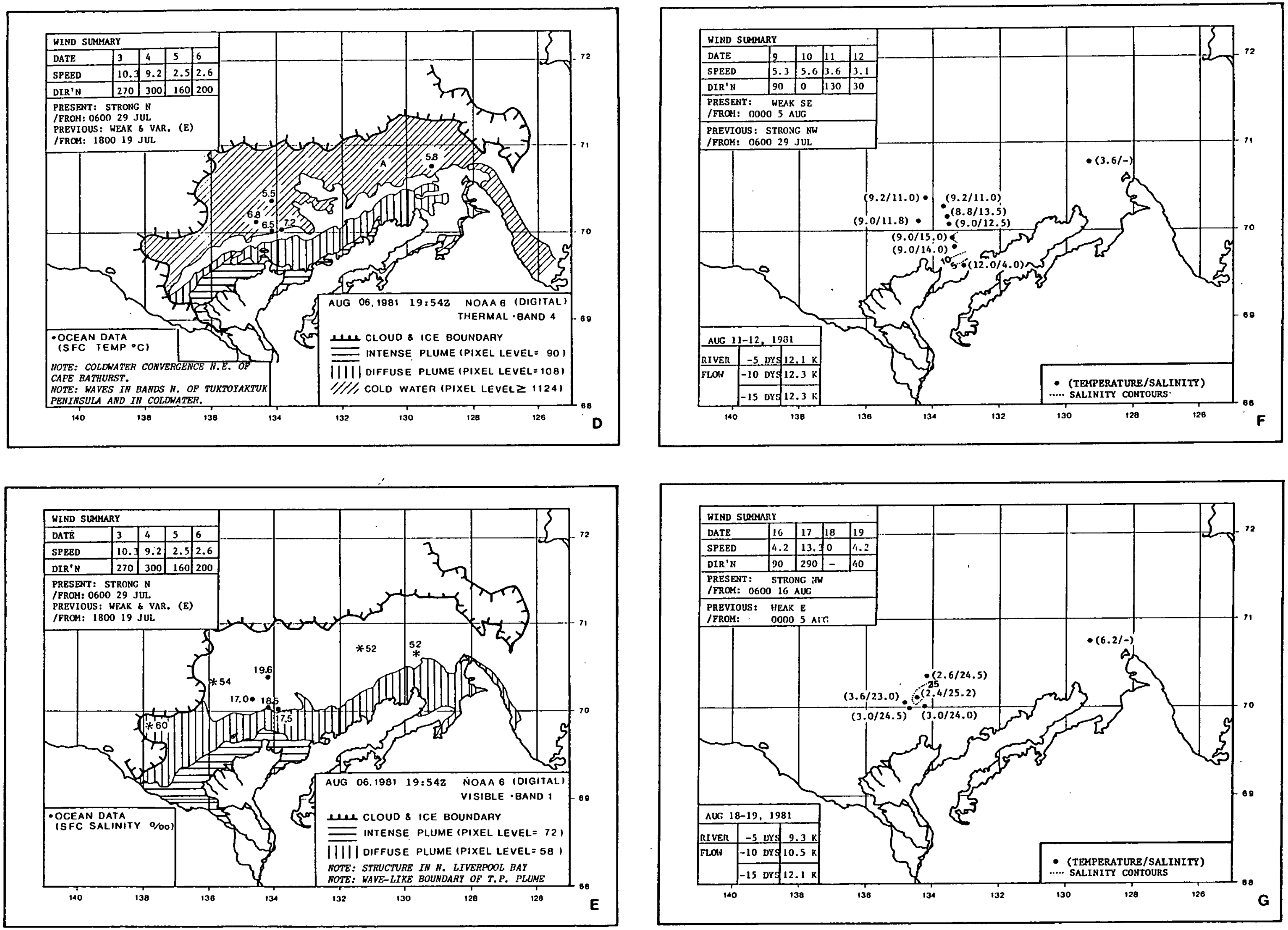


Figure 15. Cont'd.

winds (8-11 August) preceded by variable winds, the area north of 70°N again had surface water properties characteristic of the diffuse plume. Following a two day period (16-17 August) of very strong northwesterly winds, temperatures experienced a major decrease (by up to 6.0°C), while salinities increased by as much as 12 °/oo (Fig. 15g).

1982: Figures 16a to 16f. The first available map for 1982 (7 August, Fig. 16a), shows that the plume was distributed along the coast, from Mackenzie Bay, east through Liverpool Bay and into Franklin Bay. Such a pattern is consistent with the strong westerly winds of 1-6 August. The southeasterly wind event, commencing on 10 August, appears to have displaced the plume away from the Tuktoyaktuk Peninsula, as observed on 13 August (Fig. 16b). From 19-25 August, strong northwesterly winds blew, but the effects are almost completely obscured by cloud on the 24 August maps (Fig. 16c,d). On 26 August (Fig. 16e,f), the plume distribution was generally consistent with the aftermath of northwesterly winds, even though southeasterly winds had been blowing for over a day at the time of observation.

1983: Figures 17a to 17i. The first maps for 1983, derived solely from surface observations (25-26 July, Fig. 17a; 28-29 July, Fig. 17b), reveal the diffuse plume water extending well north of 70°N, from Mackenzie Bay to Kugmallit Bay. Colder, more saline arctic water was observed north of the eastern side of Kugmallit Bay and off the Tuktoyaktuk Peninsula. This pattern was fully consistent with the generally easterly wind conditions observed in the latter half of July 1983. A brief period of strong westerly winds occurred from 2-4 August, but unfortunately, the 3 August image (Fig. 17c) is largely obscured by cloud. The variable winds of 5-12 August were followed by easterly winds on 13-14 August. On 14 August, the plume was distributed north and westwards of its source regions, with a narrow coastal band of the intense plume extending beyond Herschel Island. On 22 August (Fig. 17f,g), the distribution of the plume remained unchanged. This appears to have been consistent with the variable wind conditions of 15-22 August followed by the southeasterly wind event of 21-22 August. The plume appeared to have shifted eastward by 26 August (Fig. 17h,i) in Mackenzie Bay and off the Yukon coast, apparently under the influence of the westerly winds of 24-25 August.

Summary. Comparisons of plume locations with the sequence of wind patterns demonstrates the importance of surface wind in determining the plume distribution. Other factors can modify and perturb the wind-driven advection of the plume. Such factors include (1) the initial distribution of the plume at the onset of a wind event, (2) the river discharge level of the previous several days, (3) plume frontal instabilities and other smaller scale oceanographic processes, and (4) ocean

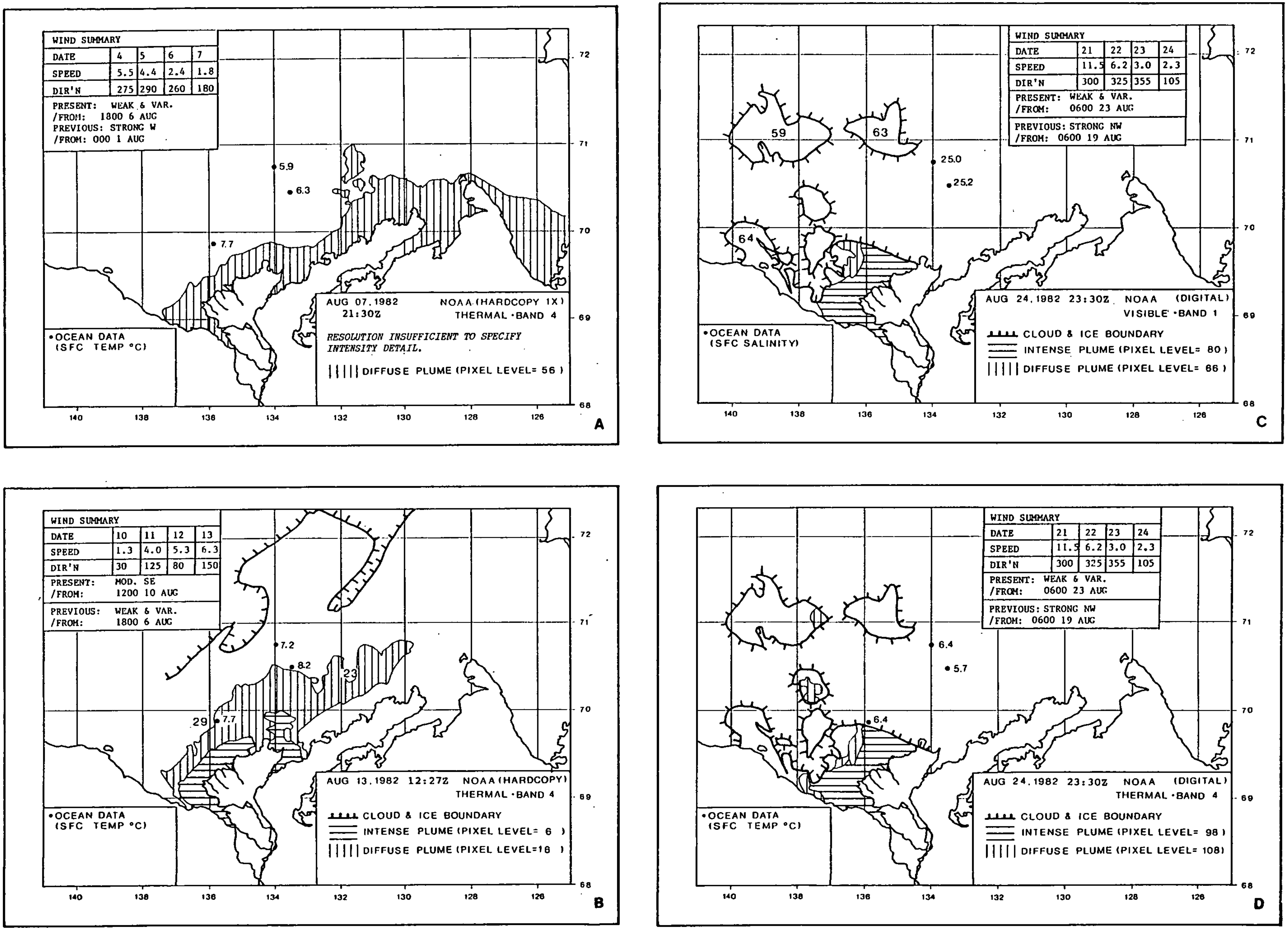
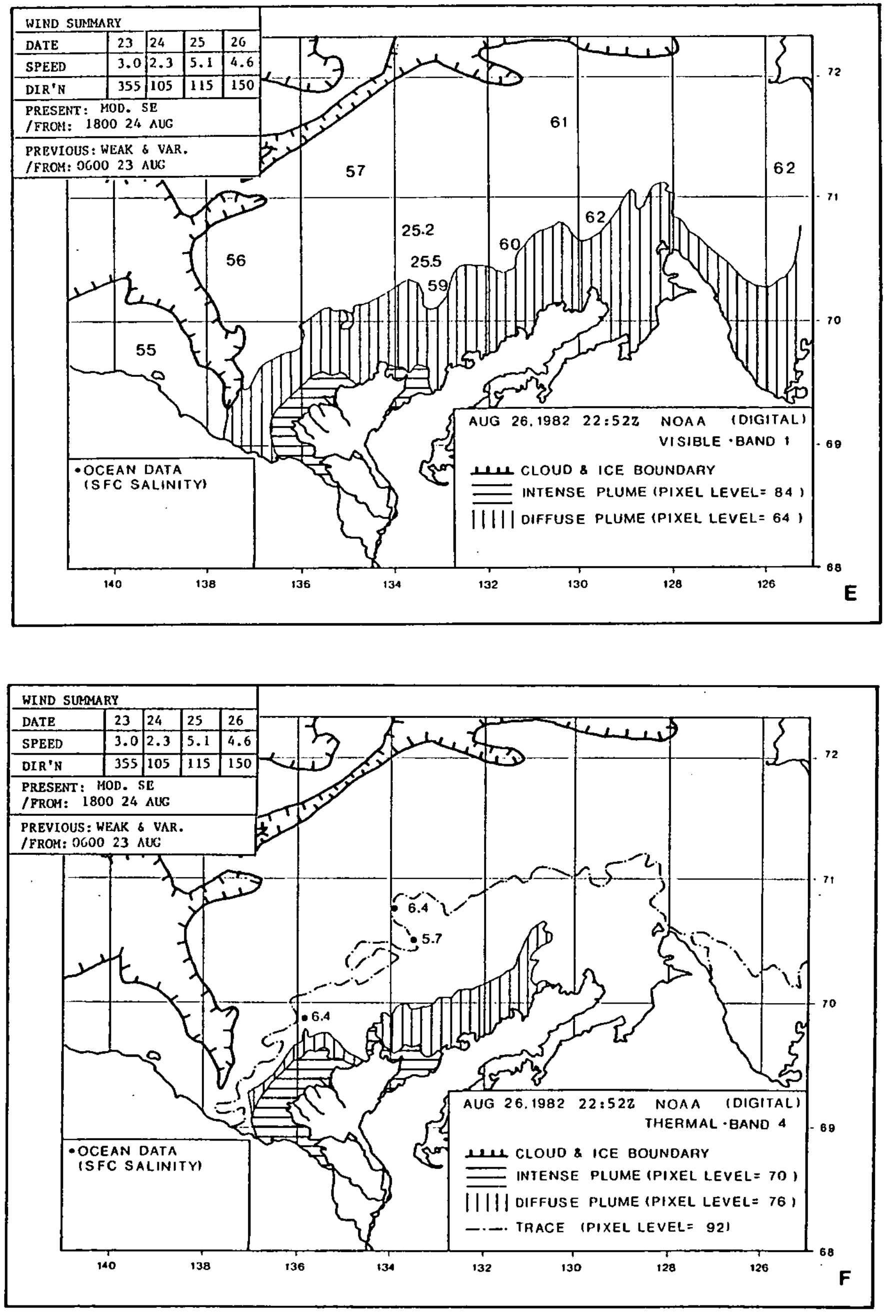


Figure 16. A sequence of maps showing distribution of surface oceanographic properties in 1982, derived from satellite data and ship-based measurements. Only the surface oceanographic data are mapped for wind event periods with no satellite data. Representative wind speeds for the day are in m/s; wind directions are those from which the wind blew.



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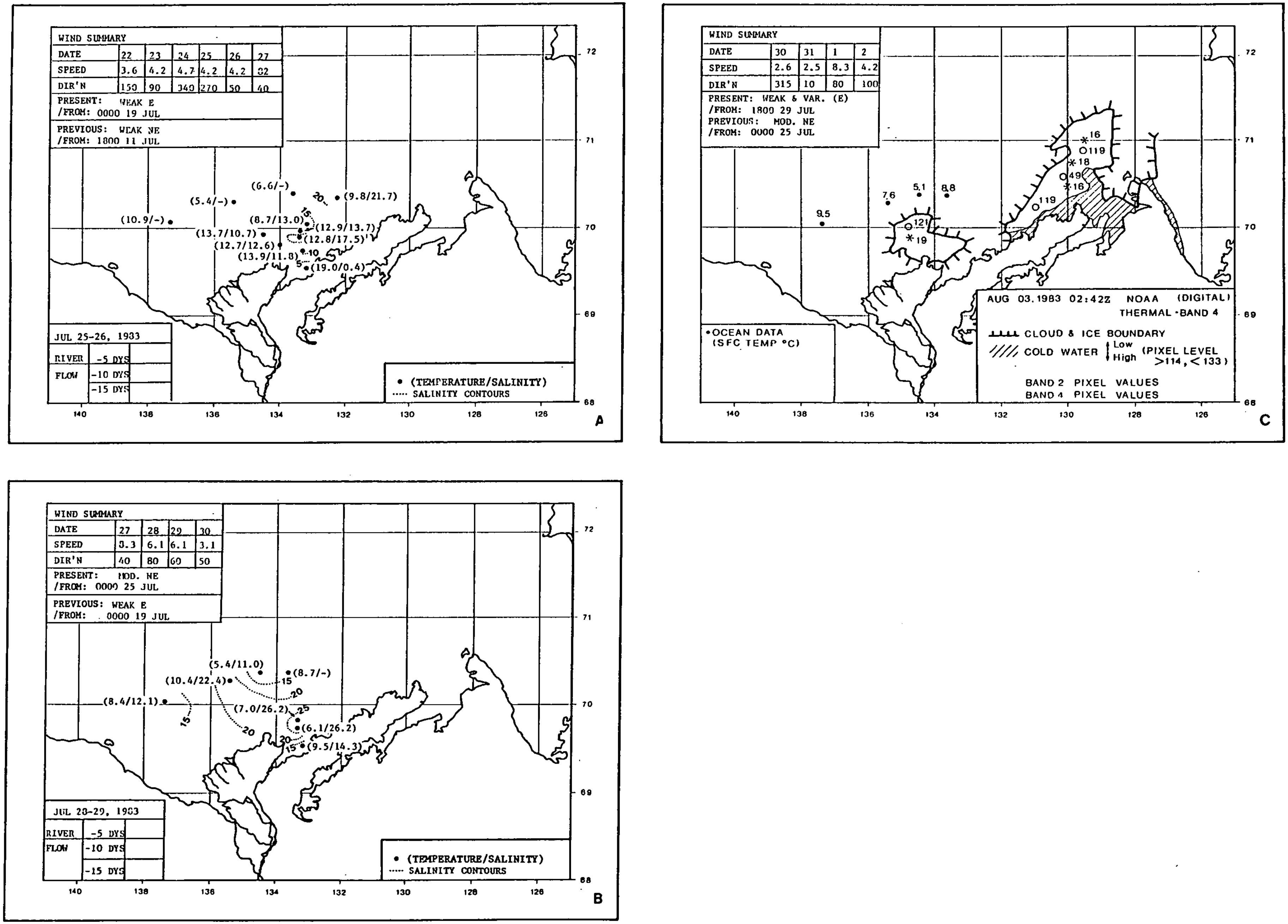
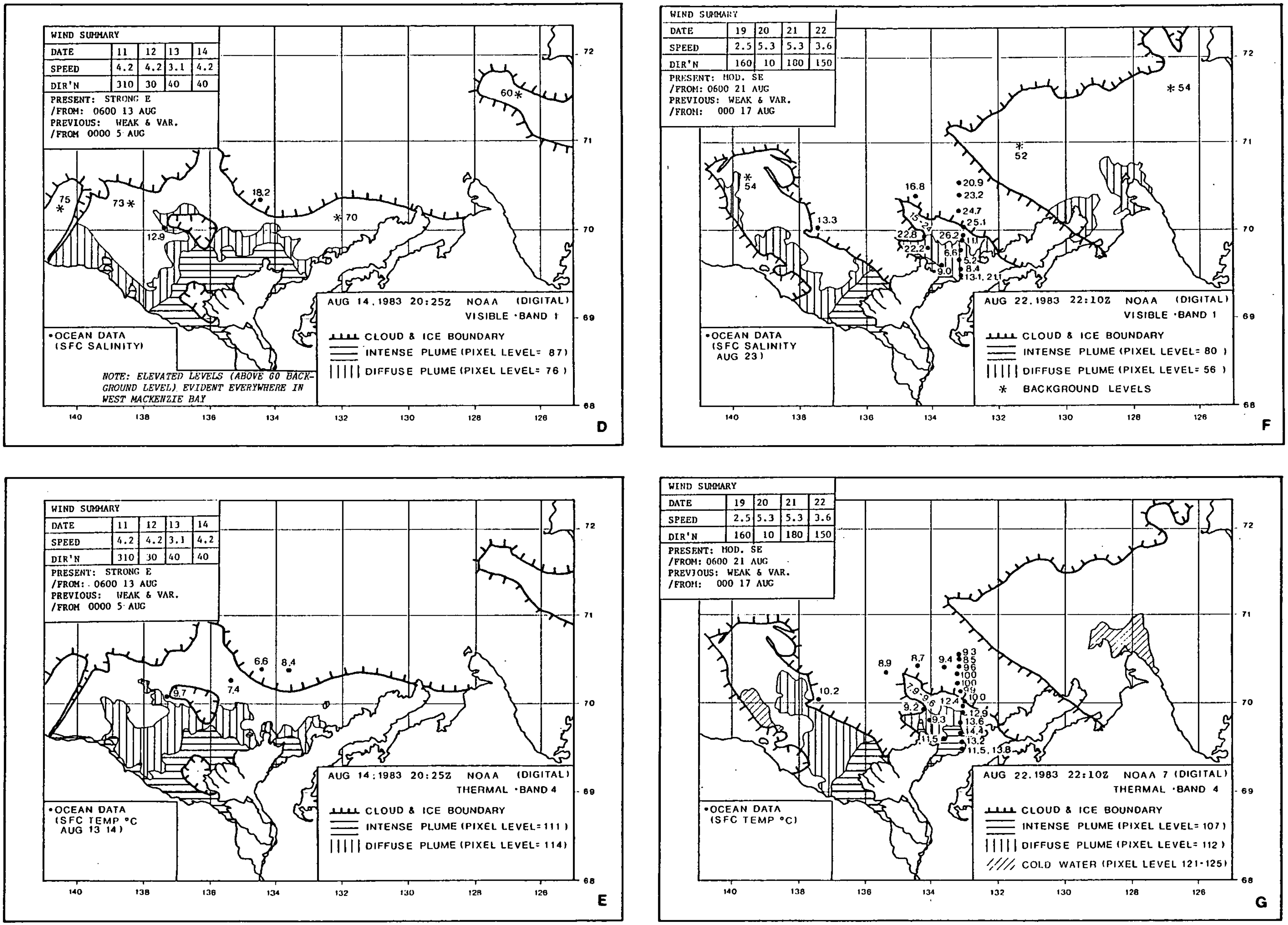


Figure 17. A sequence of maps showing distribution of surface oceanographic properties in 1983, derived from satellite data and ship-based measurements. Only the surface oceanographic data are mapped for wind event periods with no satellite data. Representative wind speeds for the day are in m/s; wind directions are those <u>from</u> which the wind blew.



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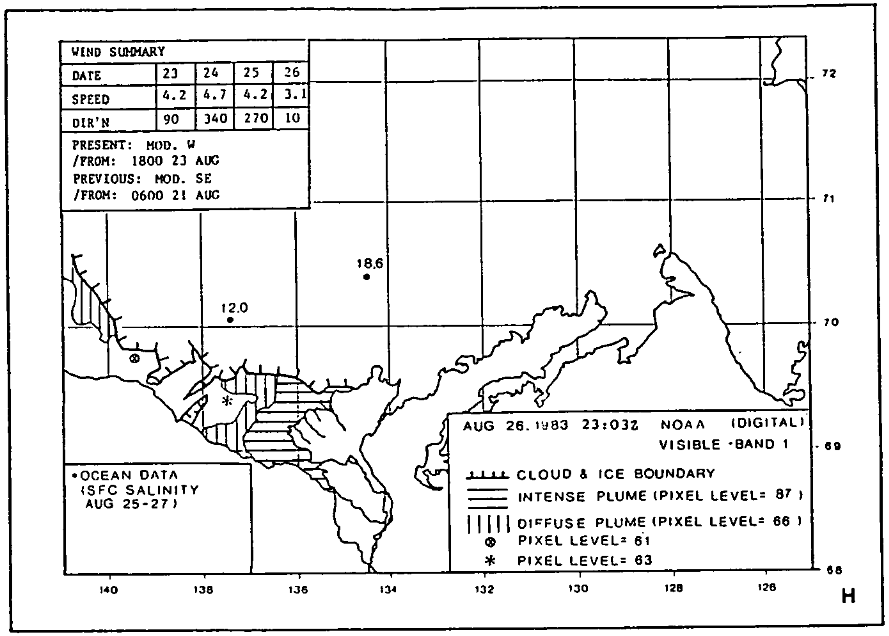

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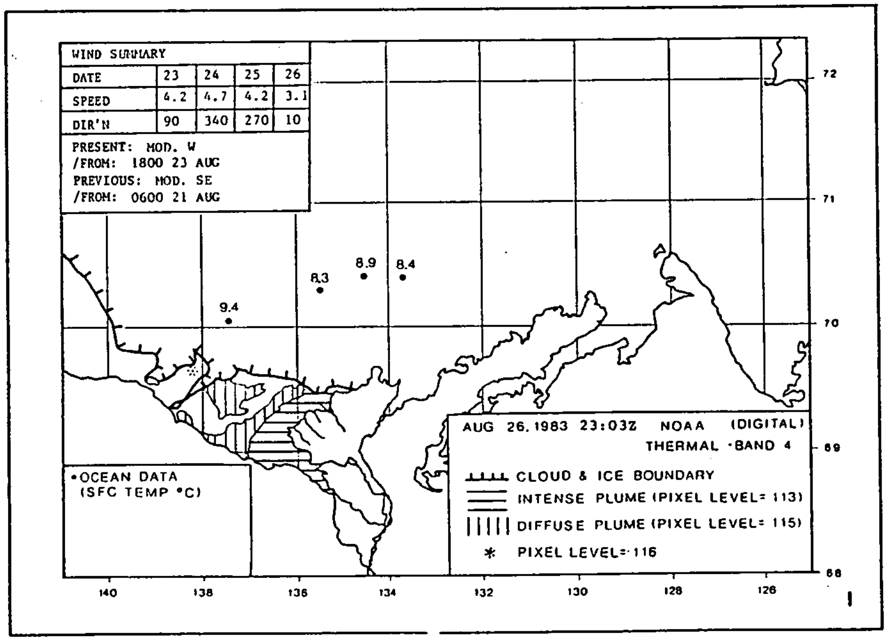

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Figure 17. Cont'd.

currents that were not driven directly by the local wind [these are thought to be small off the Tuktoyaktuk Peninsula, but there is indirect evidence that non-wind driven advection may be more important off the Yukon coast and in Franklin Bay (Fissel 1981; Fissel and Birch 1984)].

Based on the present study, we can estimate the plume distribution for various general wind regimes (Fig. 18). For both easterly and westerly winds, the intense plume is consistently found to extend farthest from shore off Shallow and Kugmallit bays, with a narrower connecting band found along the coast of Richards Island. Under easterly winds, the intense plume extends north of Richards Island, up to 75 km offshore of Shallow Bay, and west to Herschel Island in a narrow (approx. 10 km) coastal band. During and after westerly winds, the intense plume is more limited in its westward and offshore excursions, but it can occur along the full length of the Tuktoyaktuk Peninsula, in a coastal band extending up to 30 km from shore.

The differences between the locations of the diffuse plume under easterly and westerly wind conditions are also of interest (Fig. 18a and b). Under westerly winds, the diffuse plume remains within 50-75 km of shore off Mackenzie Bay and western Richards Island, broadening on some occasions to widths of up to 100 km farther to the east. Generally, however, the offshore limits of the diffuse plume remain within the 20-40 m depth contours. Following prolonged westerly winds, the diffuse plume can extend beyond Cape Bathurst into Franklin Bay. During and following easterly winds, the diffuse plume can extend much farther offshore and to the west. Diffuse plume water was observed to extend up to 150-200 km from the coast off Mackenzie Bay and Richards Island. In this area, the plume is often found on the outer half of the shelf and, on occasion, extends beyond the continental slope. To the west, the diffuse plume can usually be followed well beyond the Herschel Canyon. Under prolonged easterly winds and suitable sea ice conditions the diffuse plume can extend as far west as the Alaskan border. The results demonstrate that the diffuse plume can occur as (1) a broad band along the Yukon coast, or (2) as an offshore plume oriented toward the northwest, with Arctic Ocean water remaining along the coast.

EFFECTS OF WIND ON THE DISTRIBUTION OF SEA ICE

Although certain simple relationships (e.g., Zubov 1943) have been proposed to describe the relationship between sea ice movements and surface wind speed and direction, it is, in practice, extremely difficult to predict the configuration of the offshore pack ice solely on the basis of the preceding wind record. Nevertheless, because of the general weakness of the long-term current structures in the area, some important changes in the position of the Beaufort Sea ice pack are

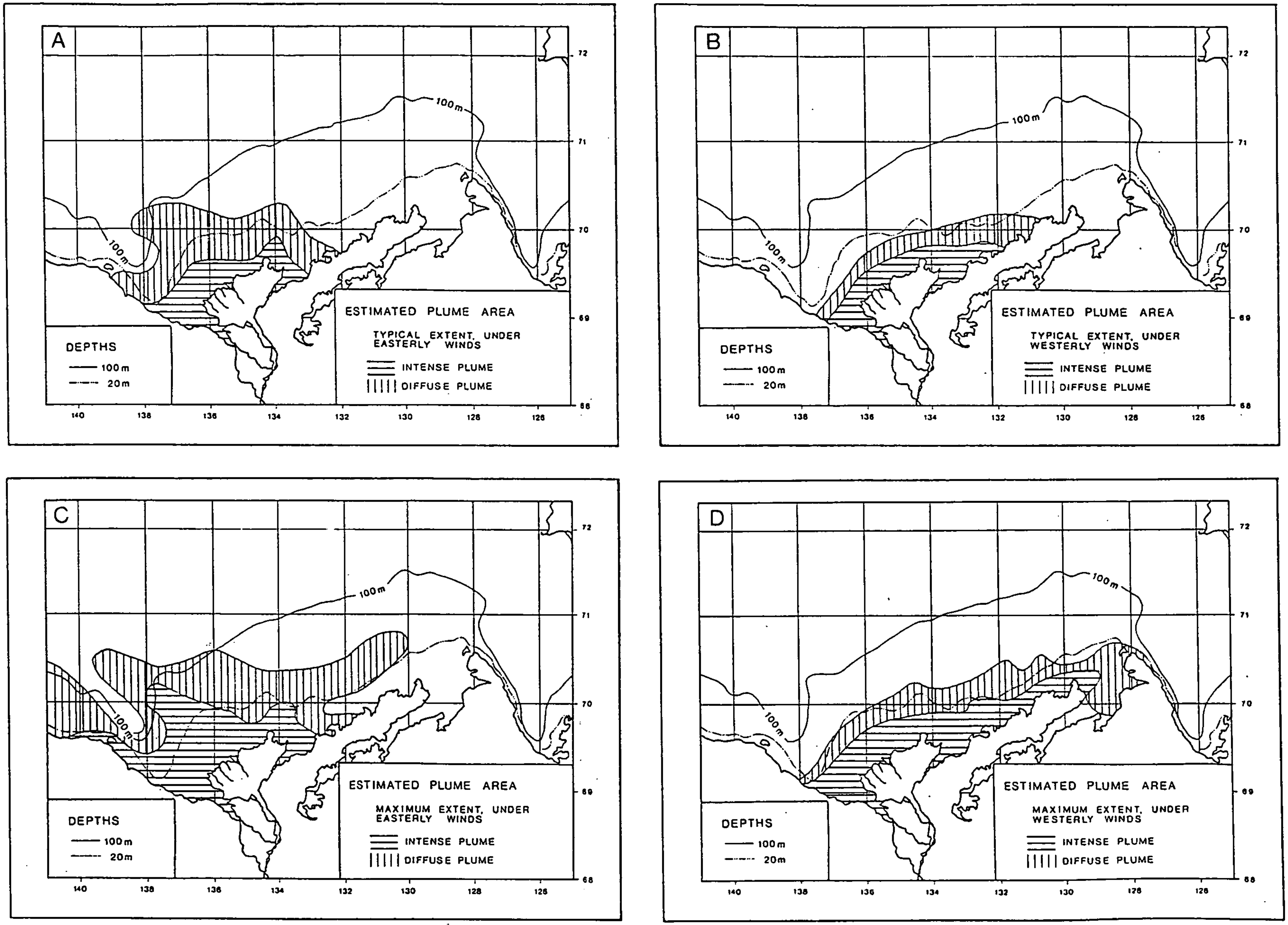


Figure 18. The extent of the Mackenzie River plume, as shown in the 1980 to 1983 satellite imagery data, under the dominant west-northwesterly and southeast-northeasterly wind conditions. Figures 18A and 18B are estimated typical conditions, while Figures 18C and 18D illustrate the estimated maximum extent of the plume.

explicable in terms of the observed winds, particularly when the wind fields have been relatively constant for a period of a few days or longer. Such conditions of relative stability usually occur when winds are from the southeast, northeast or northwest. The nearshore current regime produced by these winds has been described by MacNeill and Garrett (1975; see Fig. 2).

Anticipation and interpretation of changes in the location of the polar pack ice edge are confounded by the transitory nature of the wind regime, the presence of transient currents, the response time of movements of water and of the ice field to changes in wind conditions, and areal differences in the nature of the stratification of the water column. As a result, the following summaries of the 1980-1983 ice boundary progressions rely primarily on the well-established linkage between onshore and offshore ice motion with west-northwest and southeast-northeast winds, respectively. We have ignored finer-scale changes that could be associated with variable wind conditions or with other factors such as systematic differences between the winds at Tuktoyaktuk and those acting on the ice cover.

For **1980** the data of Figures 19a-f indicate a relatively weak response of the ice boundaries to the strong northeasterly winds of 12-19 August. Maximum movements noted during the 7-21 August interval were primarily associated with an approximately 20 n.mi. retreat of the >7/10 ice edge in areas west of 134°W. In fact, the more diffuse <1/10 ice edge actually advanced toward the Tuktoyaktuk Peninsula during this period. The onset of northwest winds around 24 August led to a general shoreward shift of the ice cover (Fig. 19f) despite the re-establishment of northeast winds on 1 September.

In **1981** the moderate to strong winds of 1-6 August and a similar overall monthly trend kept substantial concentrations of ice in western and northern Mackenzie Bay throughout August (Figs. 20a-h). A pronounced period of strong northwest winds that began on 27 August moved some of this ice into the eastern portion of the bay and north of Richards Island in early September and produced a general shoreward shift in the location of offshore pack ice (Fig. 20g).

In **1982** the initial period of strong westerly winds that began on 1 August and ended on 6 August resulted in the continued presence of significant ice concentrations in the western portion of the study region (primarily west of 138°W) throughout early and mid August (Figs. 21a-f). A subsequent interval (19-23 August) of strong northwest winds brought much of this ice into Mackenzie Bay and particularly into the areas north and east of Herschel Island and adjacent to the Yukon Coast west of 138°W (Fig. 21e). The following long spell of weak and moderate easterly winds that ended on 8 September caused some retreat and thinning in this ice (Fig. 21f).

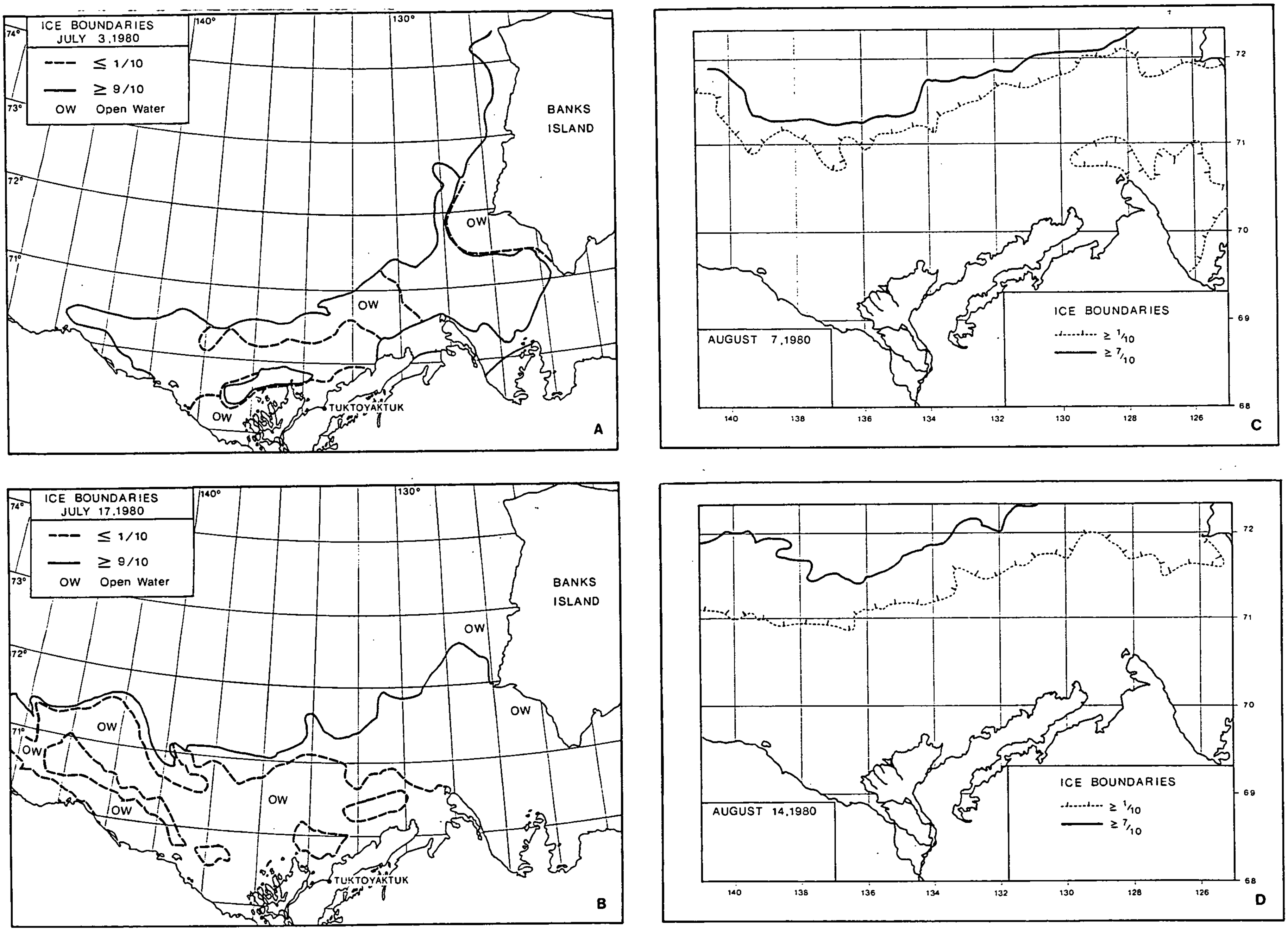


Figure 19. A sequence of maps showing ice conditions in the southeastern Beaufort Sea in 1980. The maps were derived from the ice charts prepared by the Atmospheric Environment Service of Environment Canada. Areas of heavy concentrations are enclosed by the 7/10 ice concentration contour (9/10 in July), while the 1/10 contour represents the extent of moderate ice concentrations.

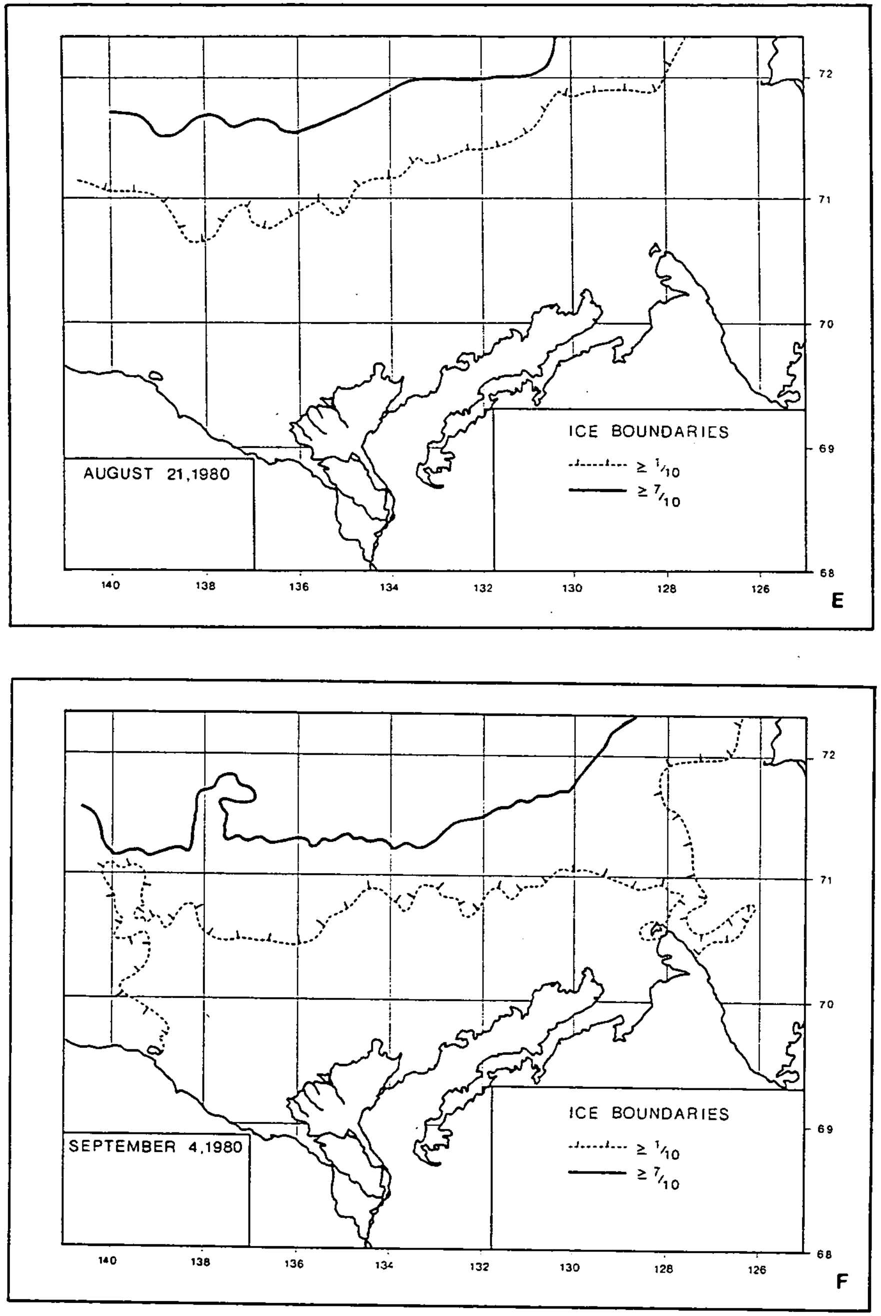


Figure 19. Cont'd.

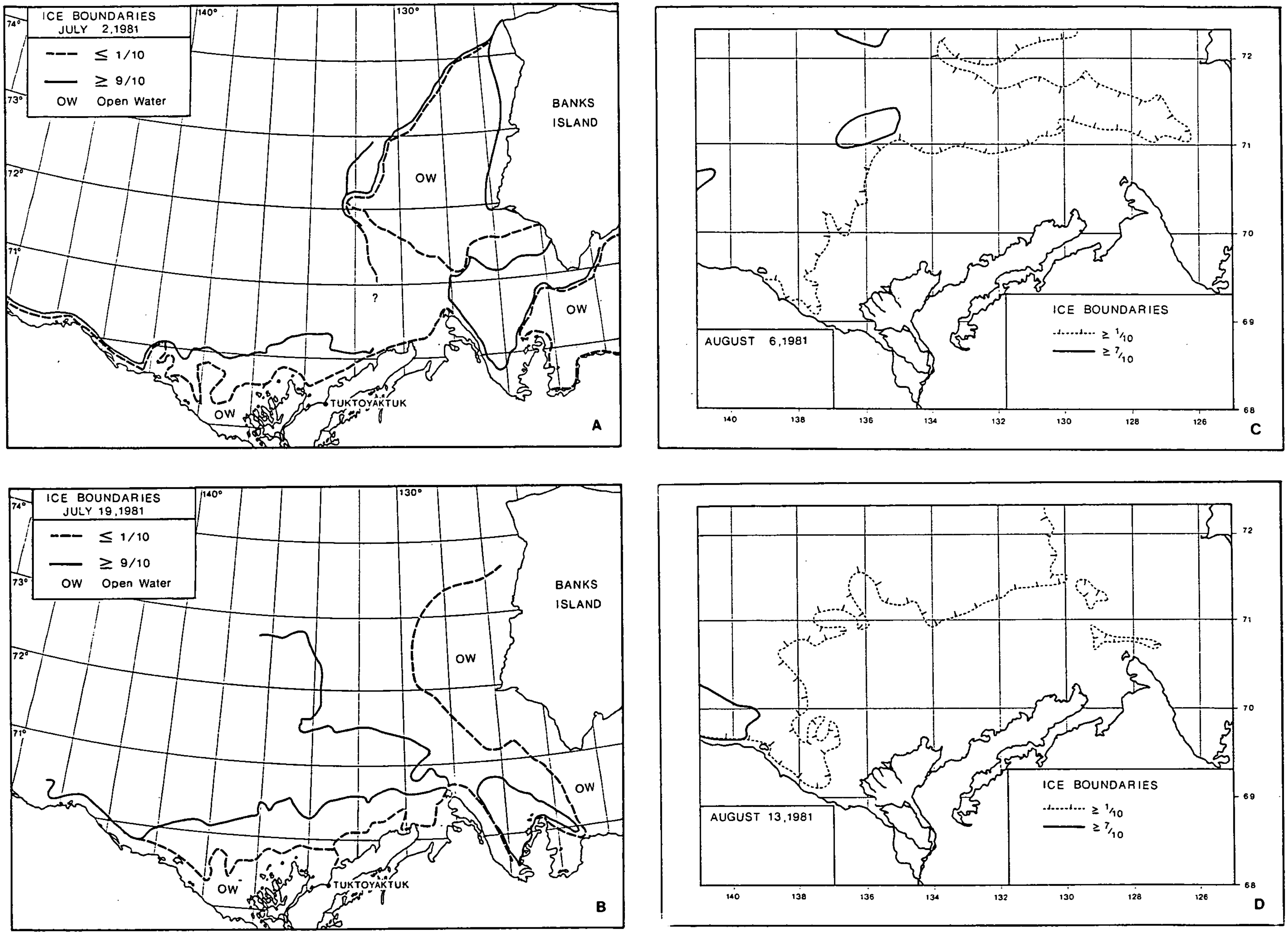
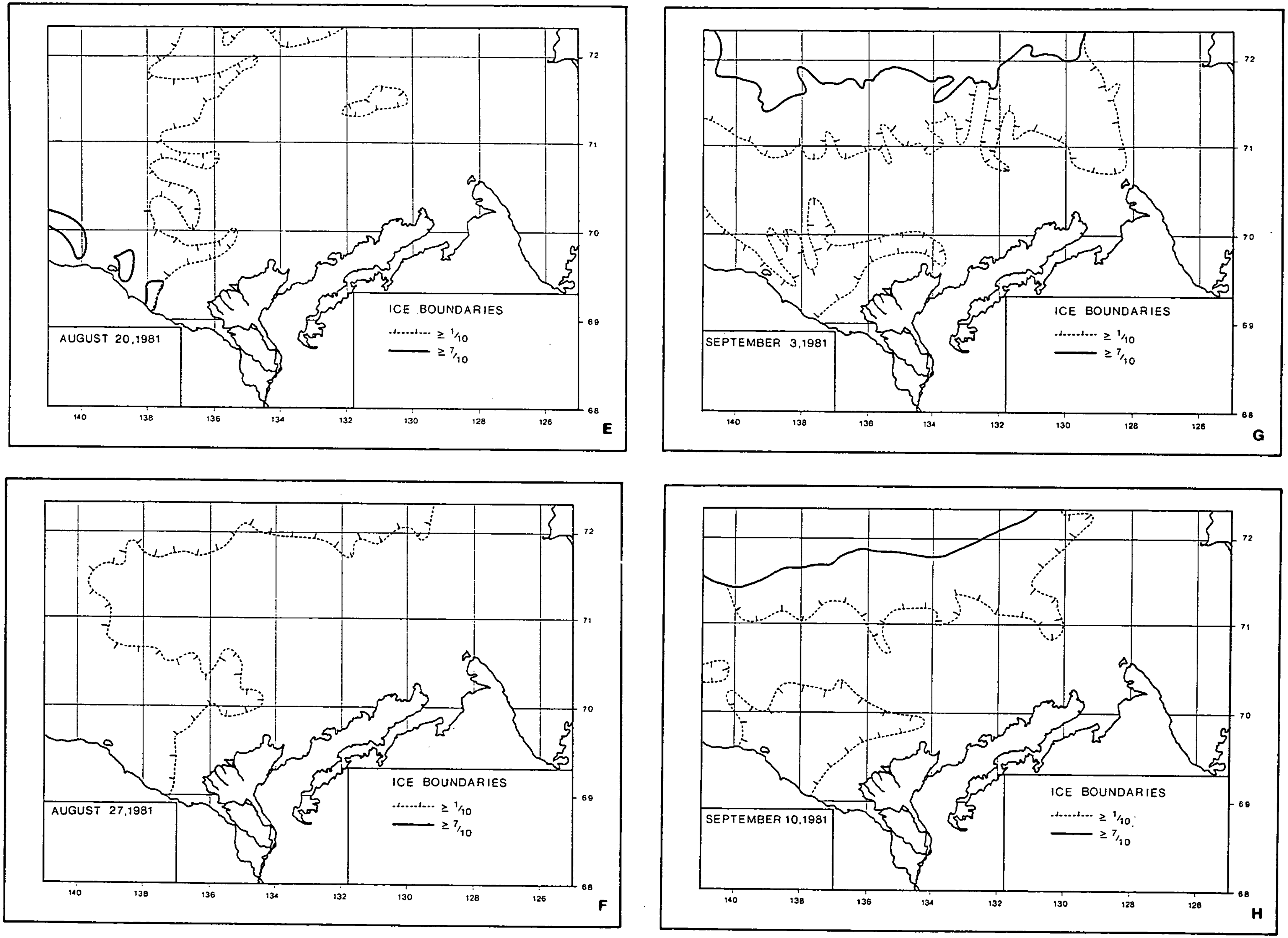


Figure 20. A sequence of maps showing ice conditions in the southeastern Beaufort Sea in 1981. The maps were derived from the ice charts prepared by the Atmospheric Environment Service of Environment Canada. Areas of heavy concentrations are enclosed by the 7/10 ice concentration contour (9/10 in July), while the 1/10 contour represents the extent of moderate ice concentrations.



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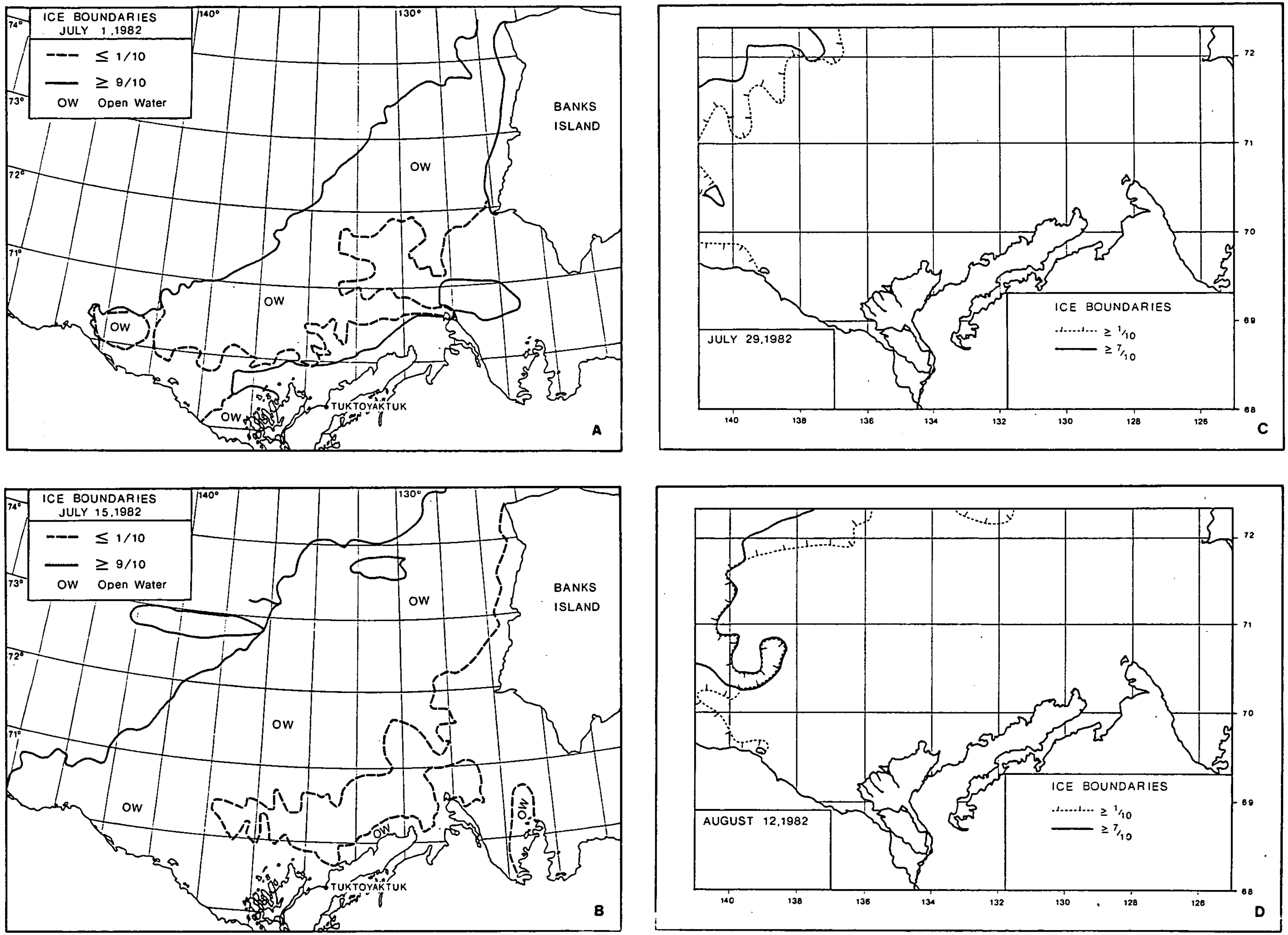

Figure 21. A sequence of maps showing ice conditions in the southeastern Beaufort Sea in 1982. The maps were derived from the ice charts prepared by the Atmospheric Environment Service of Environment Canada. Areas of heavy concentrations are enclosed by the 7/10 ice concentration contour (9/10 in July), while the 1/10 contour represents the extent of moderate ice concentrations.

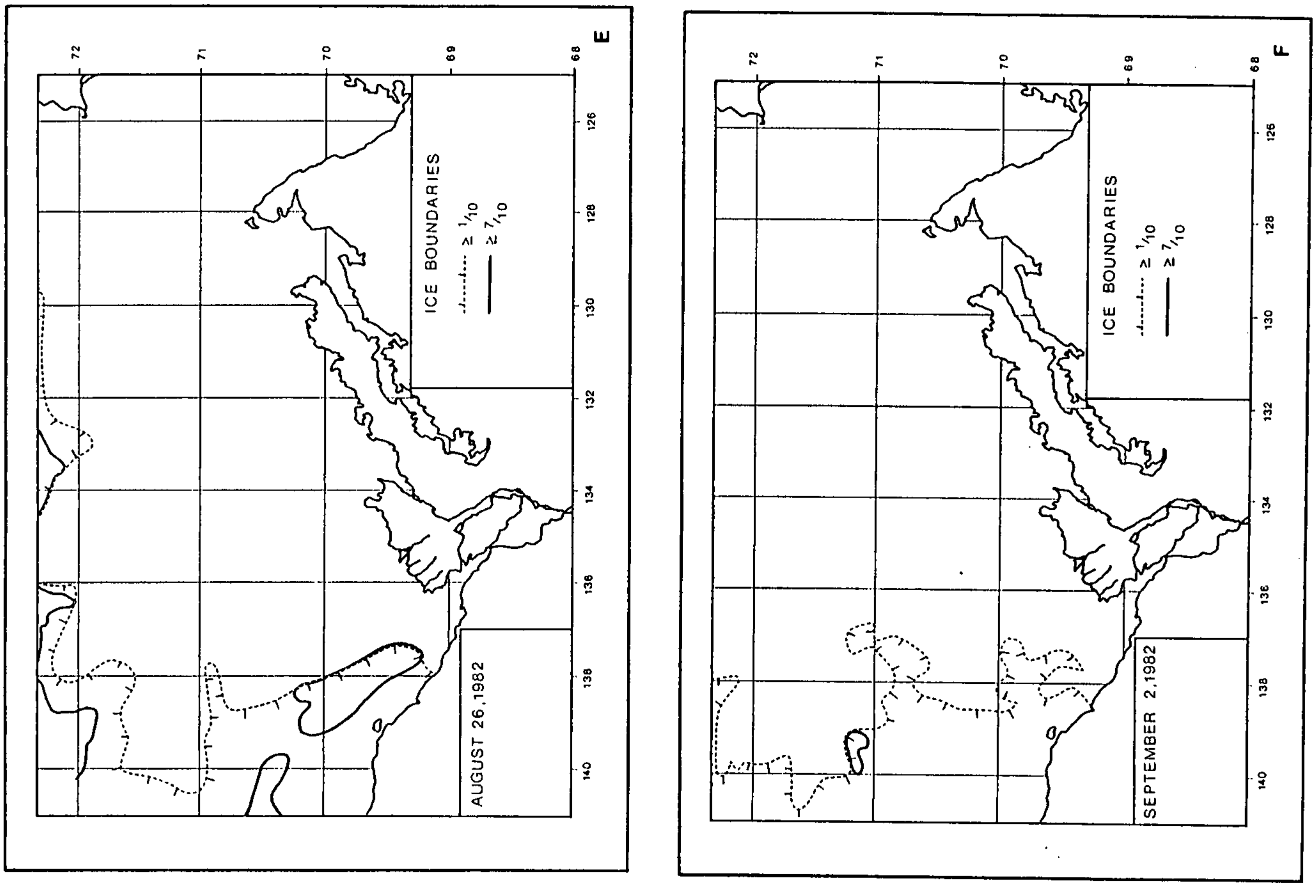

Figure 21. Cont'd.

In early August **1983** the pack ice edge was located well to the south of its 1982 position (compare Figs. 22a-g with 21a-f). In 1983, the ice edge was found farther to the south than at any other time during our study period and was about 36 km farther south than the next most southerly ice edge position (compare Fig. 19a and 22a). The strong westerly winds of 2-5 August cannot fully account for this circumstance. The absence of a distinct directional wind trend over the remainder of August left the ice boundary relatively unchanged except for some melt-induced thinning. The detachment of small patches of ice from the main offshore pack and their movement toward Herschel and Richards Islands (Fig. 22g) were probably induced by the moderate and strong northwesterly winds of 29 and 30 August.

In August and September, ice conditions in the study area tend to be most severe in western Mackenzie Bay and particularly in regions surrounding Herschel Island. The presence of this ice is only partially explicable in terms of the prevailing wind regime. The highly dynamic nature of the observed ice fields, evident in the form of eddies and streamers, suggests that the poorly understood current regime off the Yukon coast, and in particular in the Herschel Canyon region, may have an important influence. It is unlikely that quantitative understanding of the regional ice edge can be achieved without clarification of the oceanography of this area.

EFFECTS OF EARLY SEASON ICE CONDITIONS ON TEMPERATURE AND SALINITY

The importance of the large-scale distribution of sea ice on the range of temperatures and salinities observed during the open water season has been demonstrated for very severe ice years such as 1974 (Herlinveaux and de Lange Boom 1975). In that year, the pack ice edge remained close to shore until late August. This caused the Mackenzie River discharge to be confined to a small portion of the southeastern Beaufort Sea, resulting in abnormally low salinities and, to a much lesser degree, increased temperatures. The 1980-1983 data on ice and oceanographic conditions (Figs. 7-10, 19-22) compiled for the present study demonstrate that the sea ice conditions of early July are an important factor in establishing the range of salinities that can be expected well into the month of August.

The discharge of warm fresh water from the Mackenzie River is largest from mid May to late June. However, the presence of first year sea ice throughout June concentrates the river water in the areas adjoining Shallow and Kugmallit bays. With the breakup of the first year ice at the end of June, the river water disperses and mixes over a much larger area, limited ultimately by the location of the edge of the thick Arctic Ocean pack ice (Marko et al. 1983). In entering the area beyond the margin of the landfast ice (usually

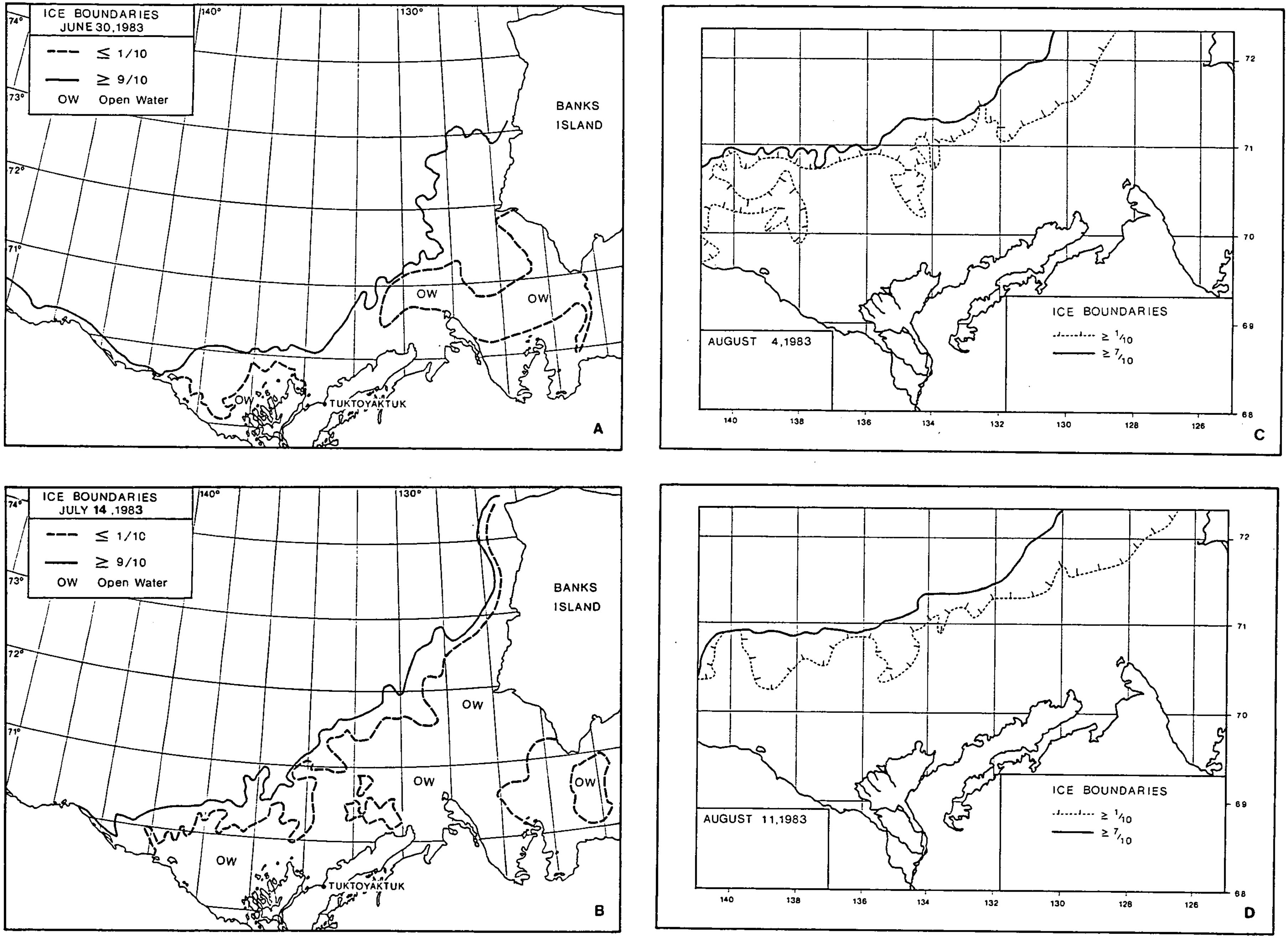

Figure 22. A sequence of maps showing ice conditions in the southeastern Beaufort Sea in 1983. The maps were derived from the ice charts prepared by the Atmospheric Environment Service of Environment Canada. Areas of heavy concentrations are enclosed by the 7/10 ice concentration contour (9/10 in July), while the 1/10 contour represents the extent of moderate ice concentrations.

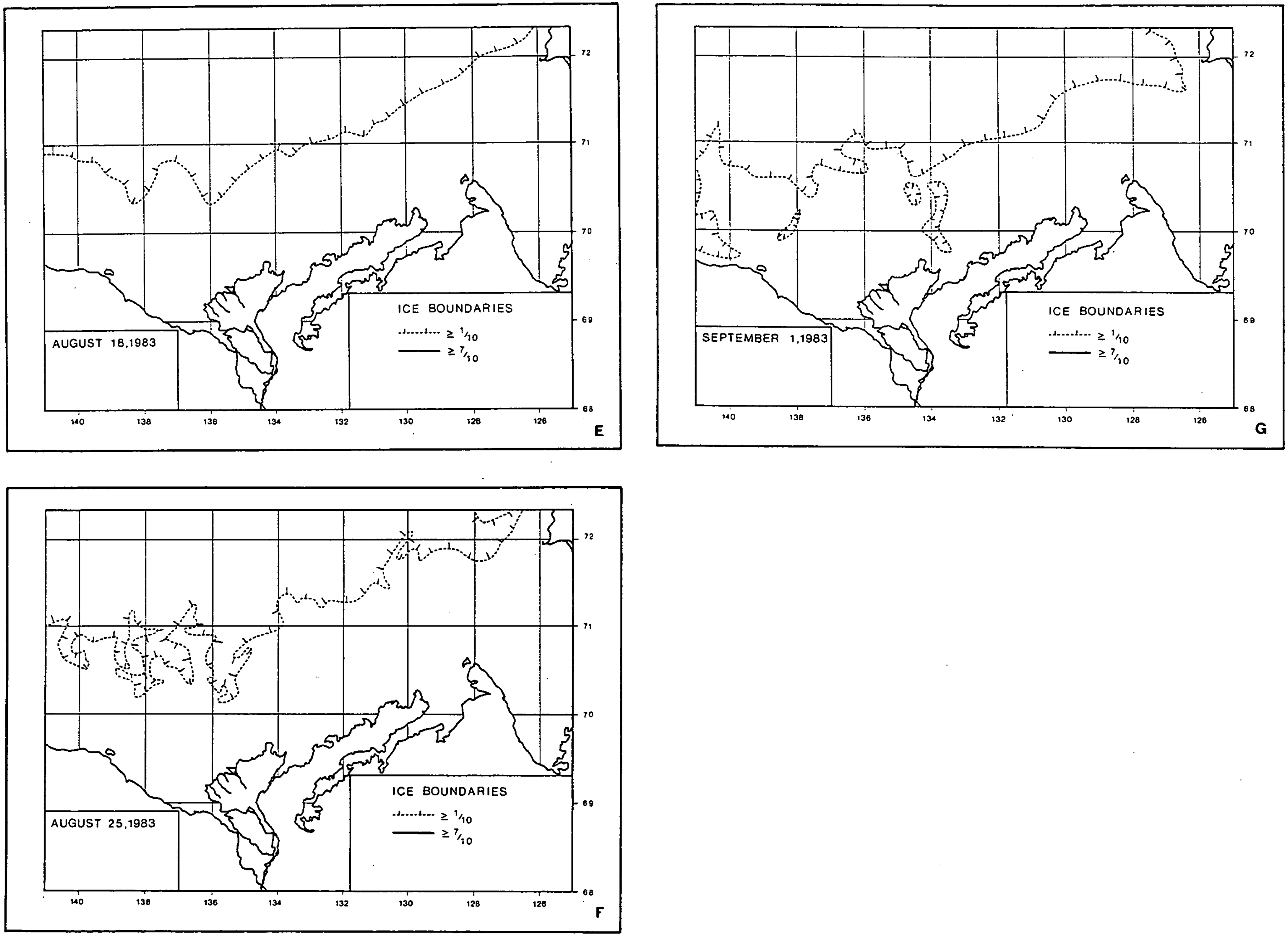

Figure 22. Cont'd.

limited to water depths of 20 m or less), the river water mixes with cold, saline Arctic Ocean water. This mixing results in a dilution of the river water's low salinity and high temperature characteristics. The effect of this mixing with the offshore waters is somewhat different for temperature than salinity, particularly when the area of open water bounded by the pack ice is comparatively small. When this area is small, the heat content of the river water will be lost to melting ice, compensating at least partially for the reduced losses due to less dispersion in the more confined area. However, the enhanced ice melt under these circumstances results in a reduction of salinity. Thus, the relationship of oceanographic conditions to the size of the area bounded by the polar pack ice would be expected to be stronger for salinity than temperature.

Of the four years (1980-1983) being considered for the present study, the ice conditions in early July (Figs. 19-22) can be divided into two groups: (1) in 1980 and 1982, when the pack ice edge was far from shore, there was a large area of open water and broken ice fields, and (2) in 1981 and 1983, when the pack ice edge was comparatively close to the coast, the area of open water and reduced ice concentrations was small.

The salinities observed in the area north of Richards Island, beyond the intense plume, during late July and early August correspond to the ice conditions for each year. In 1980 and 1982, the measured range of surface salinities was large (23-27 in 1980; 26-28 in 1982; Table 9). In 1981 and 1983, when the polar pack ice was close to shore, the observed salinity values were markedly reduced (12-16 in 1981; 11-14 in 1983). However, as expected, differences in the range of observed temperatures (Figs. 7-10) do not appear to be simply related to early ice conditions.

BOWHEAD WHALE DISTRIBUTIONS, 1980-1983

Bowhead whale distributions in August and September for each of the four years, 1980-1983, were mapped for each of the above-described wind event periods. Because of the lag between the start of a wind event and the appearance of its hydrographic effects, the maps depict information collected from 1-2 days after the onset of a wind event period to 1-2 days after its end.

1980

Four major wind event periods occurred from early August to mid September 1980. During the early part of August (Fig. 23a) most bowheads seen were in the industrial zone north of Richards Island. Small numbers were observed off the central Tuktoyaktuk Peninsula. However, there was no survey coverage of areas west of the industrial zone. In mid August, many

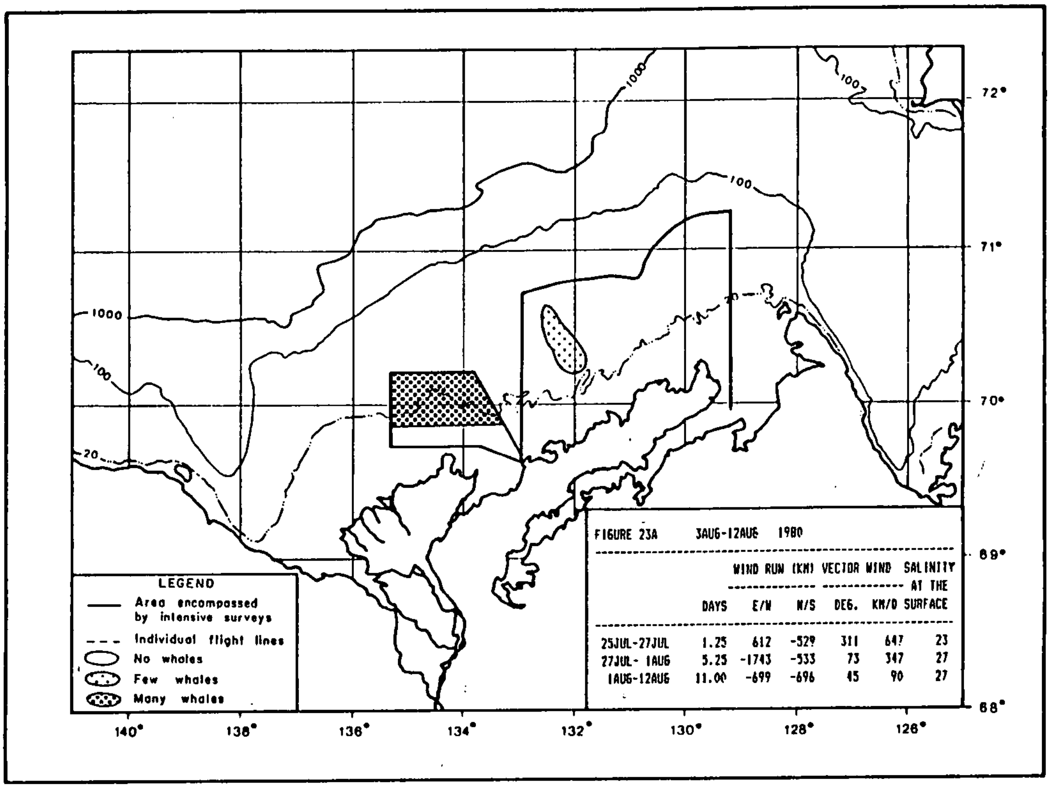

FIGURE 23A 3AUG-12AUG 1980

		WIND RUN (KM)		VECTOR WIND		SALINITY AT THE
	DAYS	E/W	N/S	DEG.	KM/D	SURFACE
25JUL-27JUL	1.25	612	-529	311	647	23
27JUL- 1AUG	5.25	-1743	-533	73	347	27
1AUG-12AUG	11.00	-699	-696	45	90	27

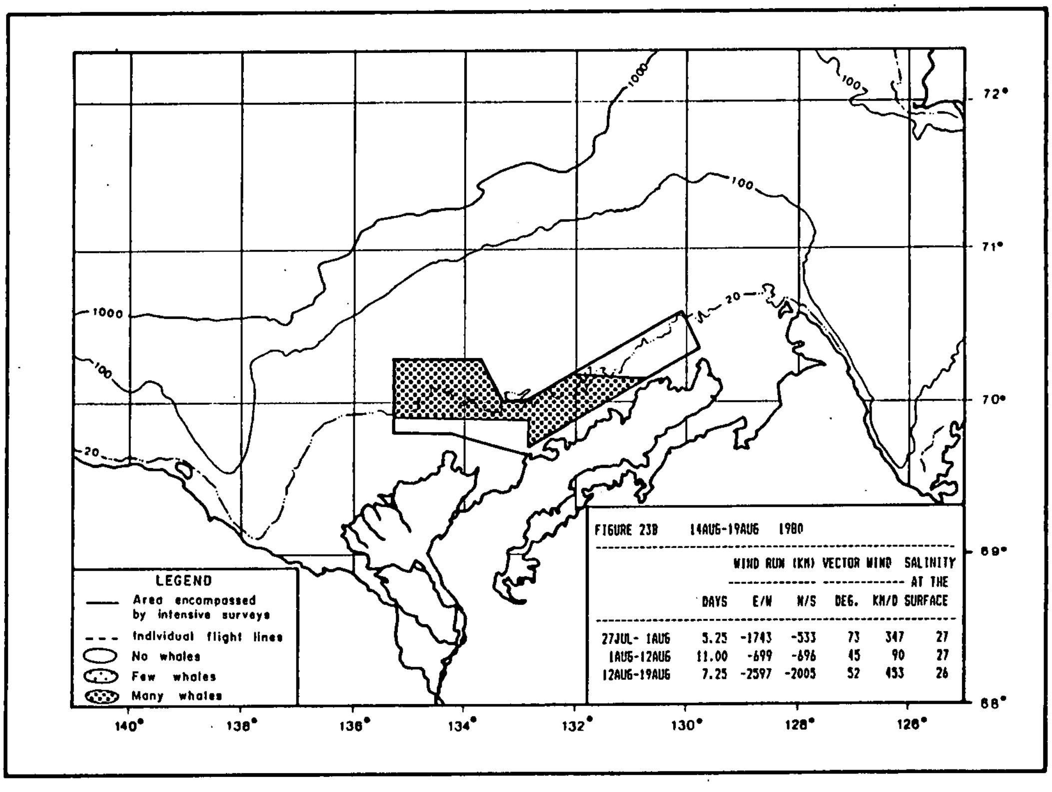

FIGURE 23B 14AUG-19AUG 1980

		WIND RUN (KM)		VECTOR WIND		SALINITY AT THE
	DAYS	E/W	N/S	DEG.	KM/D	SURFACE
27JUL- 1AUG	5.25	-1743	-533	73	347	27
1AUG-12AUG	11.00	-699	-696	45	90	27
12AUG-19AUG	7.25	-2597	-2005	52	453	26

Figure 23. Distribution of bowhead whales in the southeastern Beaufort Sea from late July to mid September of 1980. Distributions were mapped by wind event periods, but started and ended 24-36 h after the wind event period. Areas encompassed by surveys and intensive behavioral and photogrammetric work are indicated by solid lines. Individual flight lines in areas where little work was conducted are indicated by dashed lines. Data on the total east/west and north/south wind runs, the vector wind (to), and mean salinity in the area north of Richards Island are presented as in Table 9 for the indicated and two preceding wind event periods.

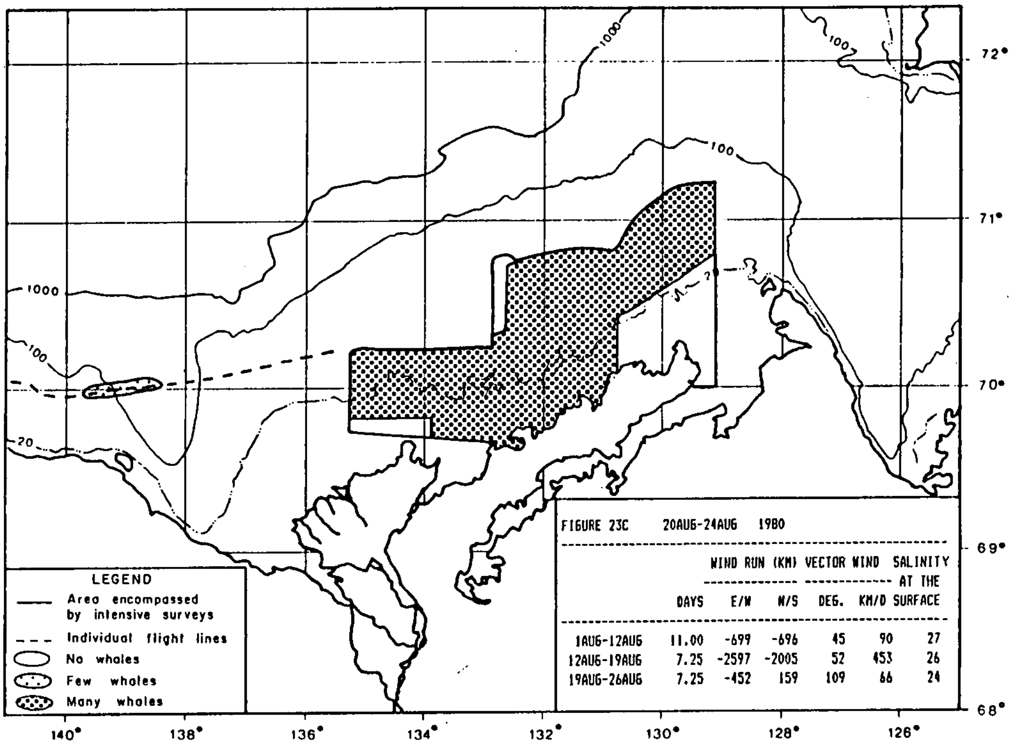

FIGURE 23C 20AUG-24AUG 1980

	WIND RUN (KM)			VECTOR WIND		SALINITY AT THE
	DAYS	E/W	N/S	DEG.	KM/D	SURFACE
1AUG-12AUG	11.00	-699	-696	45	90	27
12AUG-19AUG	7.25	-2597	-2005	52	453	26
19AUG-26AUG	7.25	-452	159	109	66	24

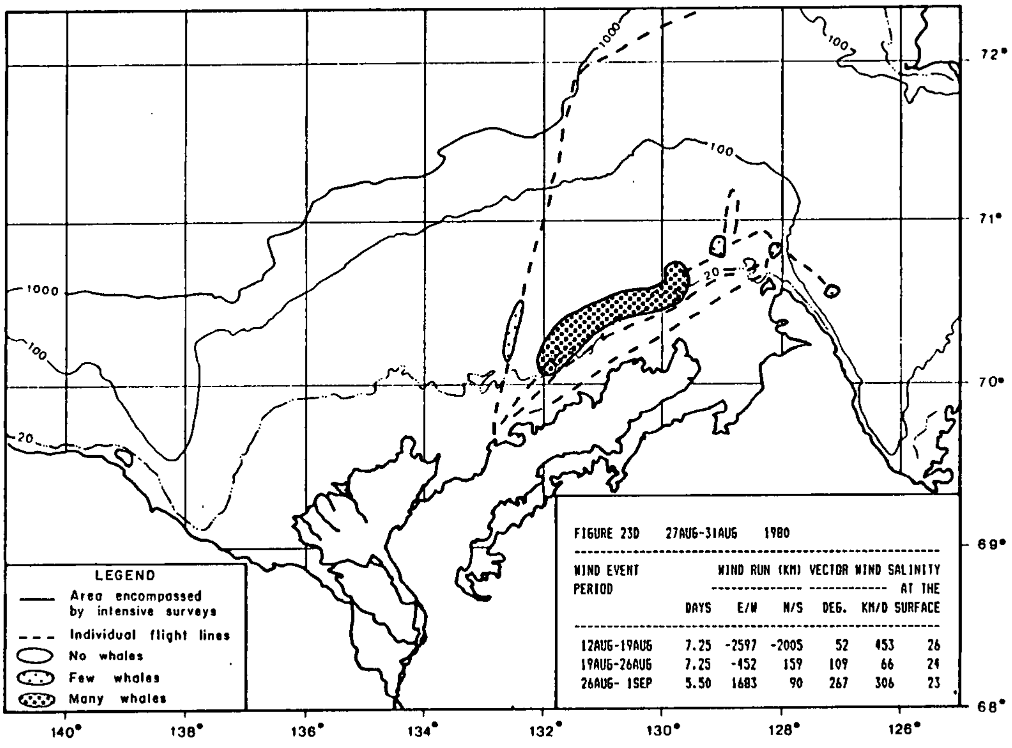

FIGURE 23D 27AUG-31AUG 1980

WIND EVENT PERIOD	WIND RUN (KM)			VECTOR WIND		SALINITY AT THE
	DAYS	E/W	N/S	DEG.	KM/D	SURFACE
12AUG-19AUG	7.25	-2597	-2005	52	453	26
19AUG-26AUG	7.25	-452	159	109	66	24
26AUG- 1SEP	5.50	1683	90	267	306	23

Figure 23. Cont'd.

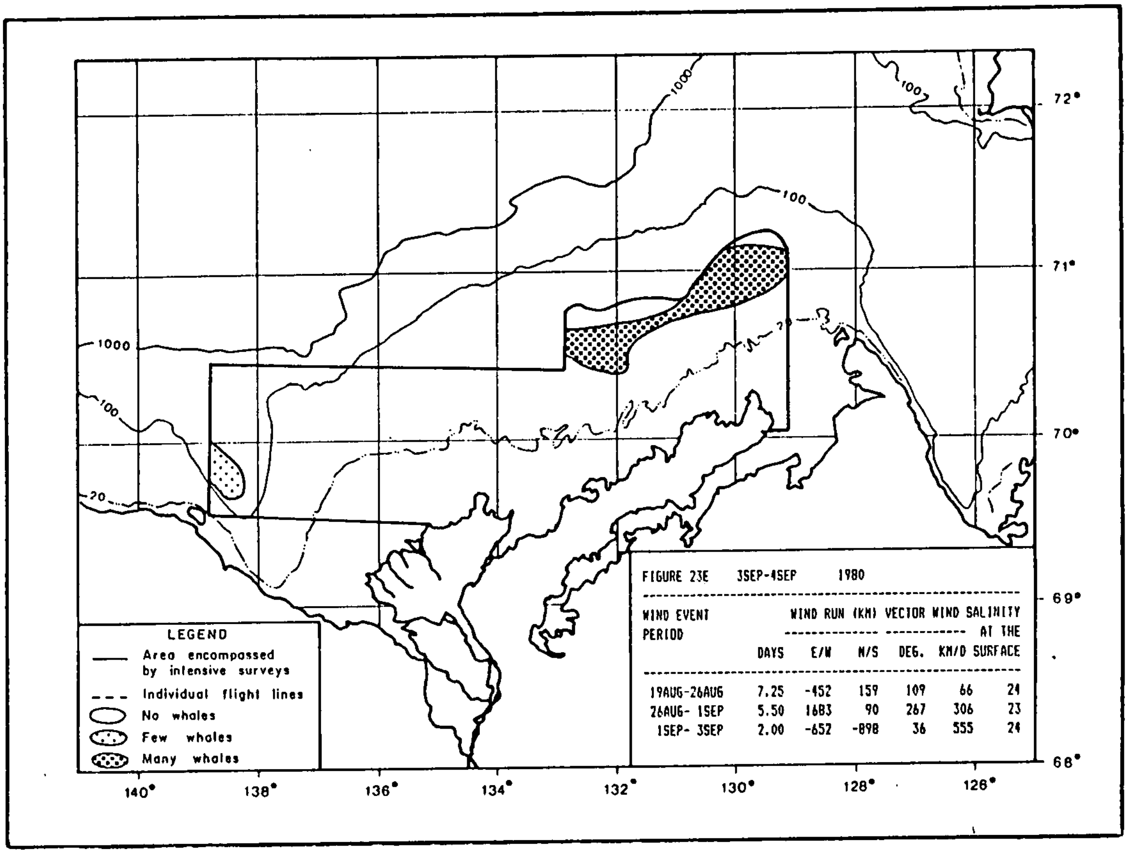

FIGURE 23E 3SEP-4SEP 1980

WIND EVENT PERIOD	WIND RUN (KM)			VECTOR WIND		SALINITY AT THE SURFACE
	DAYS	E/W	N/S	DEG.	KM/D	
19AUG-26AUG	7.25	-452	159	109	66	24
26AUG- 1SEP	5.50	1683	90	267	306	23
1SEP- 3SEP	2.00	-652	-898	36	555	24

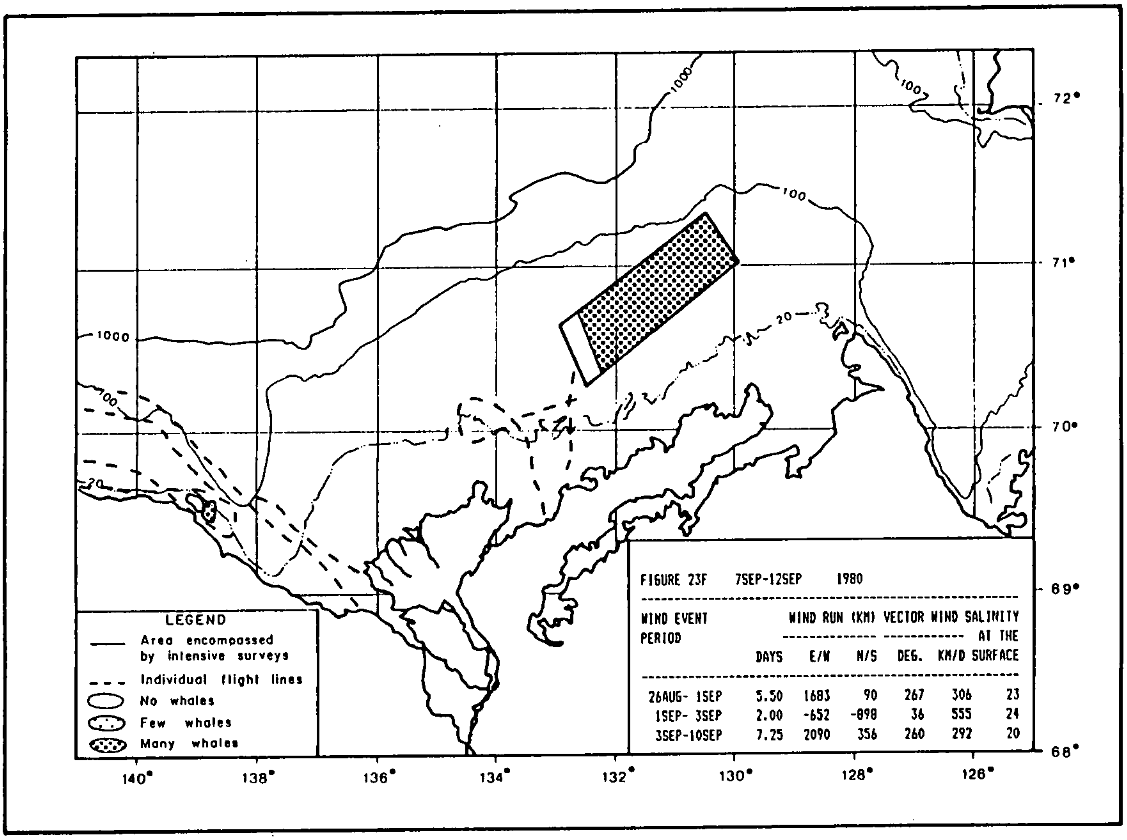

FIGURE 23F 7SEP-12SEP 1980

WIND EVENT PERIOD	WIND RUN (KM)			VECTOR WIND		SALINITY AT THE SURFACE
	DAYS	E/W	N/S	DEG.	KM/D	
26AUG- 1SEP	5.50	1683	90	267	306	23
1SEP- 3SEP	2.00	-652	-898	36	555	24
3SEP-10SEP	7.25	2090	356	260	292	20

Figure 23. Cont'd.

whales were present in the industrial zone and there were large numbers off the Tuktoyaktuk Peninsula (Fig. 23b). These areas were also heavily frequented by bowheads during the 19-26 August wind event period (Fig. 23c). During this period, very large numbers were seen off the Tuktoyaktuk Peninsula, from shallow water out as far as the 50 m depth contour, where coverage ended. Small numbers were also present north of Herschel Island. In late August (Fig. 23d), many bowheads were observed off the Tuktoyaktuk Peninsula and a few were seen near Cape Bathurst, although there was little or no intensive coverage of any of the study area. In early September (Fig. 23e), whales were not observed in shallow waters off the Tuktoyaktuk Peninsula or in the industrial zone, but considerable numbers were present between the 20 and 50 m depth contours off the Tuktoyaktuk Peninsula (again no coverage beyond 50 m in this period). A few bowheads were also seen off Herschel Island at that time. This general distribution was also noted in the second week of September (Fig. 23f), although some bowheads seen off the Tuktoyaktuk Peninsula were in waters greater than 50 m in depth.

1981

Four major wind event periods occurred from late July to mid September 1981. In late July and early August, most bowheads seen were near the ice edge at or beyond the shelf break (100 m depth contour) far north of the Mackenzie Delta (Fig. 24a). Small numbers were observed in several other parts of the surveyed area. During the 5-16 August period (Fig. 24b), most bowheads seen were in the Herschel Canyon area and in the industrial zone, but considerable numbers were also present near the shelf break northwest of Cape Bathurst. There was little coverage during the 16-18 August period (Fig. 24c) and the 18-22 August period (Fig. 24d). The coverage that was obtained showed bowheads to be present north of Richards Island, north of Herschel Island, in the Herschel Canyon area, and east of Cape Bathurst.

Extensive coverage of most of the study area was obtained during the wind event periods in late August and early September. During the 22 August-3 September period (Fig. 24e), bowheads were commonly seen at or beyond the shelf break from Herschel Island to Cape Bathurst. Many were also seen in the industrial zone north of Richards Island. During the 3-15 September period (Fig. 24f), bowheads were commonly observed near Herschel Island, north of the Tuktoyaktuk Peninsula and off Cape Bathurst. This last area had not been surveyed during the previous wind event period.

1982

Five wind event periods occurred from early August to mid September 1982. During the first week of August (Fig. 25a), bowheads were numerous in the Herschel Canyon area, and small

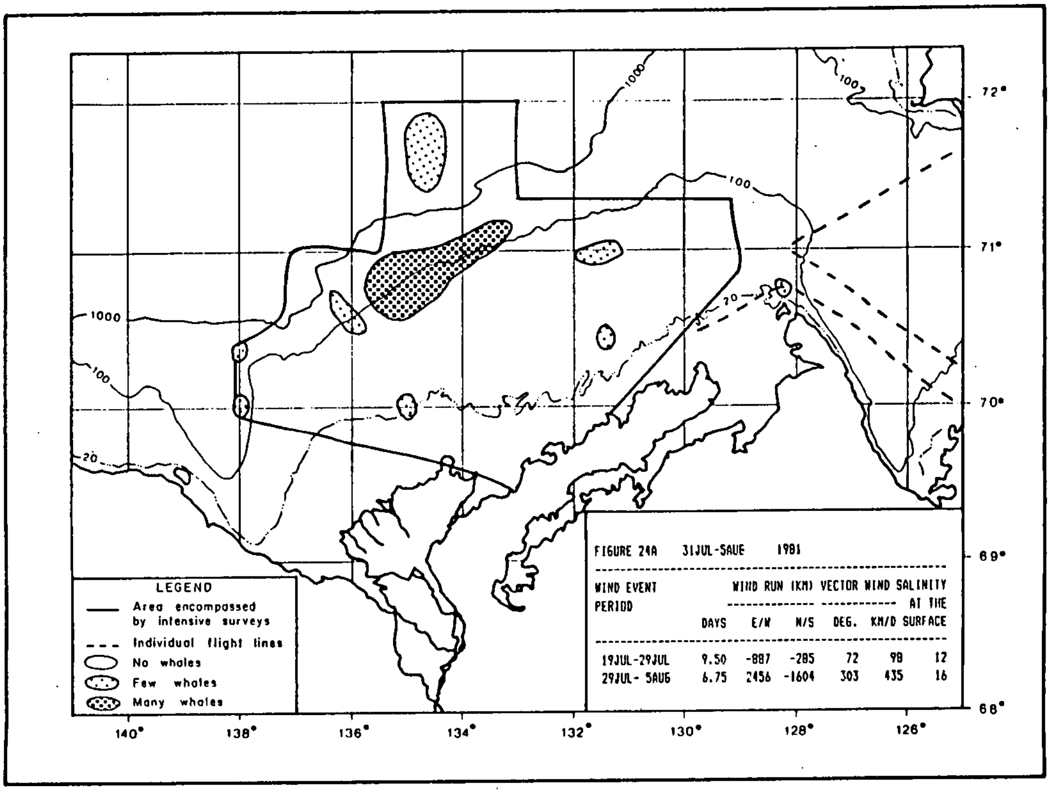

FIGURE 24A 31JUL-5AUG 1981

WIND EVENT PERIOD	WIND RUN (KM) DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
19JUL-29JUL	9.50	-887	-285	72	98	12
29JUL- 5AUG	6.75	2456	-1604	303	435	16

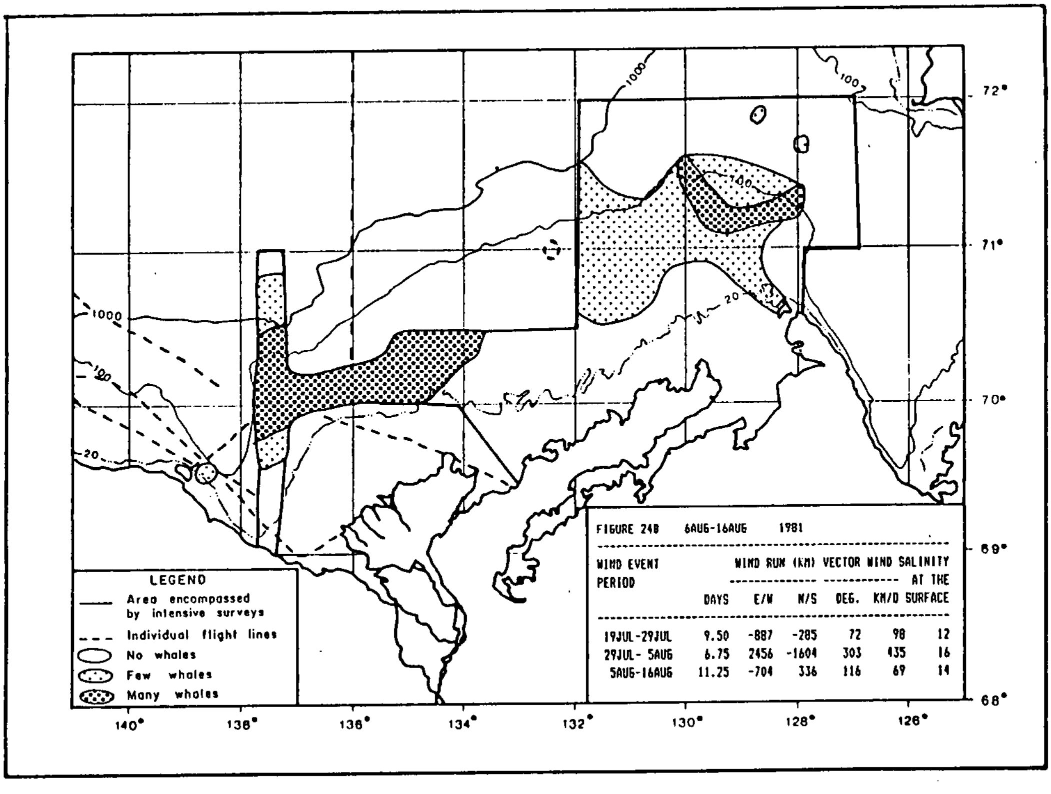

FIGURE 24B 6AUG-16AUG 1981

WIND EVENT PERIOD	WIND RUN (KM) DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
19JUL-29JUL	9.50	-887	-285	72	98	12
29JUL- 5AUG	6.75	2456	-1604	303	435	16
5AUG-16AUG	11.25	-704	336	116	69	14

Figure 24. Distribution of bowhead whales in the southeastern Beaufort Sea from late July to mid September of 1981. Distributions were mapped by wind event periods, but started and ended 24-36 h after the wind event period. Areas encompassed by surveys and intensive behavioral and photogrammetric work are indicated by solid lines. Individual flight lines in areas where little work was conducted are indicated by dashed lines. Data on the total east/west and north/south wind runs, the vector wind (to), and mean salinity in the area north of Richards Island are presented as in Table 9 for the indicated and two preceding wind event periods.

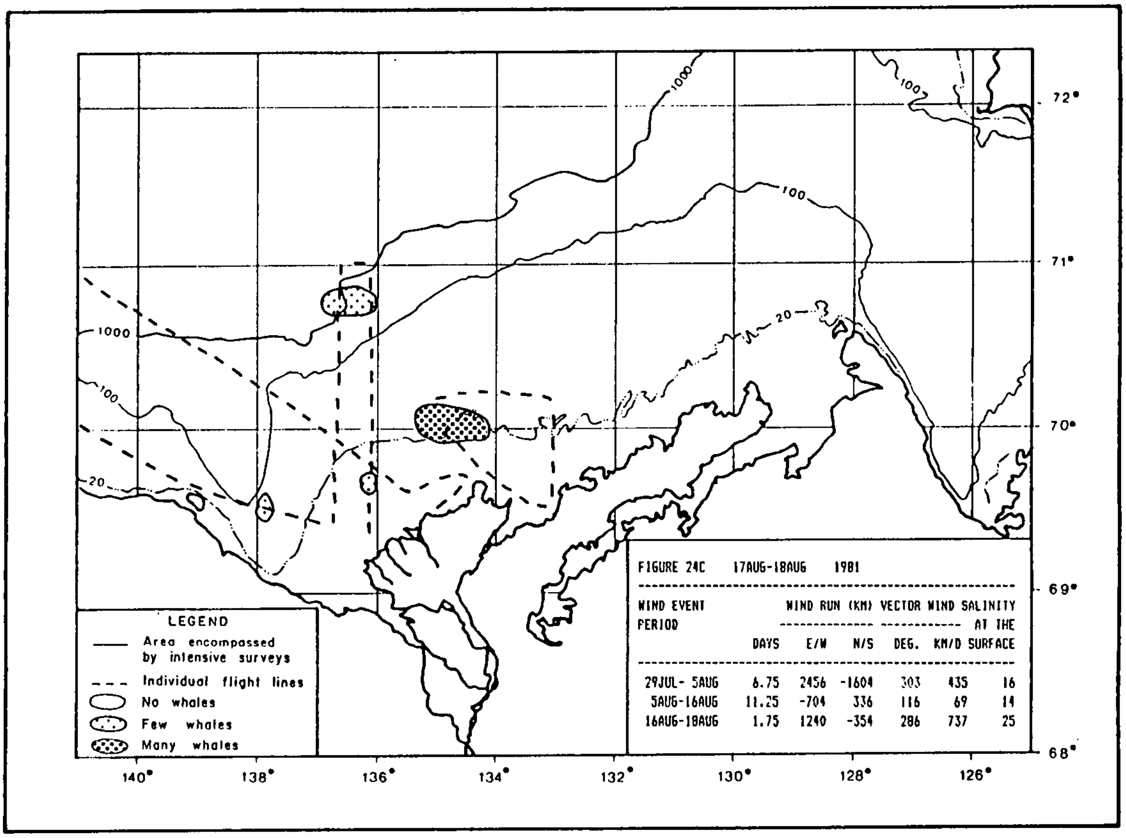

FIGURE 24C 17AUG-18AUG 1981

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
29JUL- 5AUG	6.75	2456	-1604	303	435	16
5AUG-16AUG	11.25	-704	336	116	69	14
16AUG-18AUG	1.75	1240	-354	286	737	25

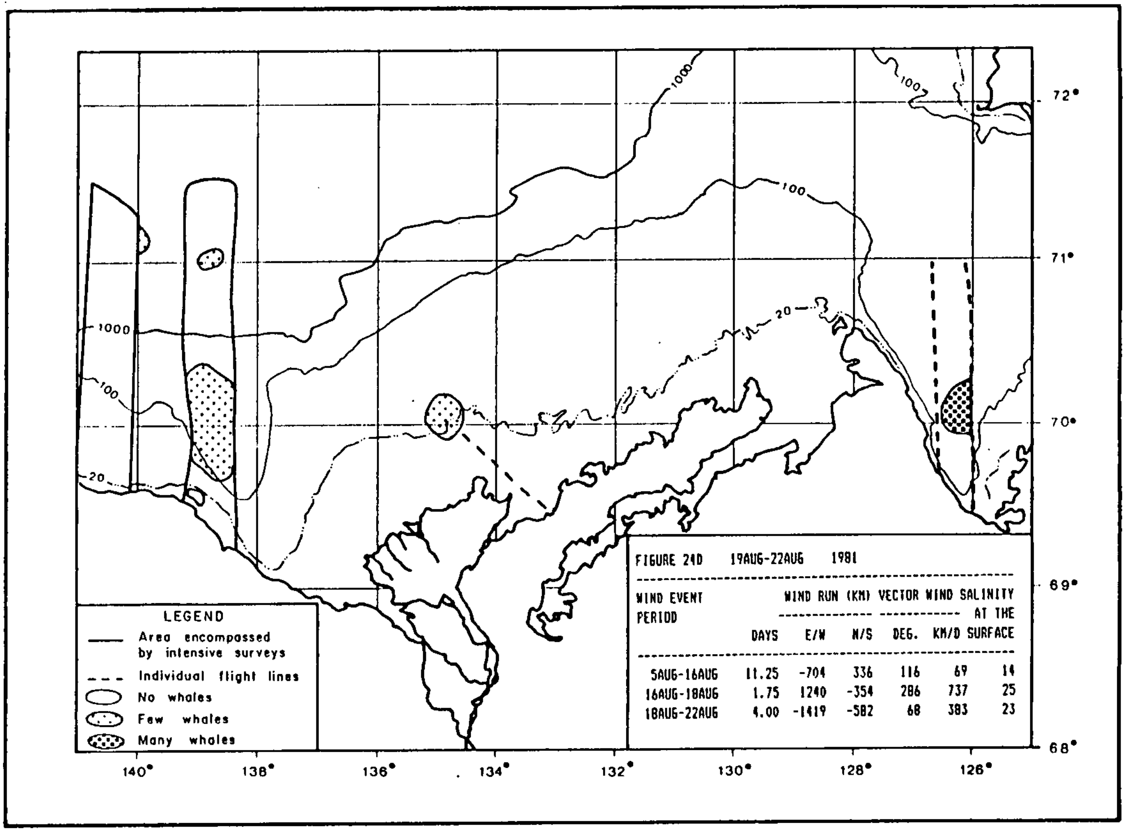

FIGURE 24D 19AUG-22AUG 1981

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
5AUG-16AUG	11.25	-704	336	116	69	14
16AUG-18AUG	1.75	1240	-354	286	737	25
18AUG-22AUG	4.00	-1419	-582	68	383	23

Figure 24. Cont'd.

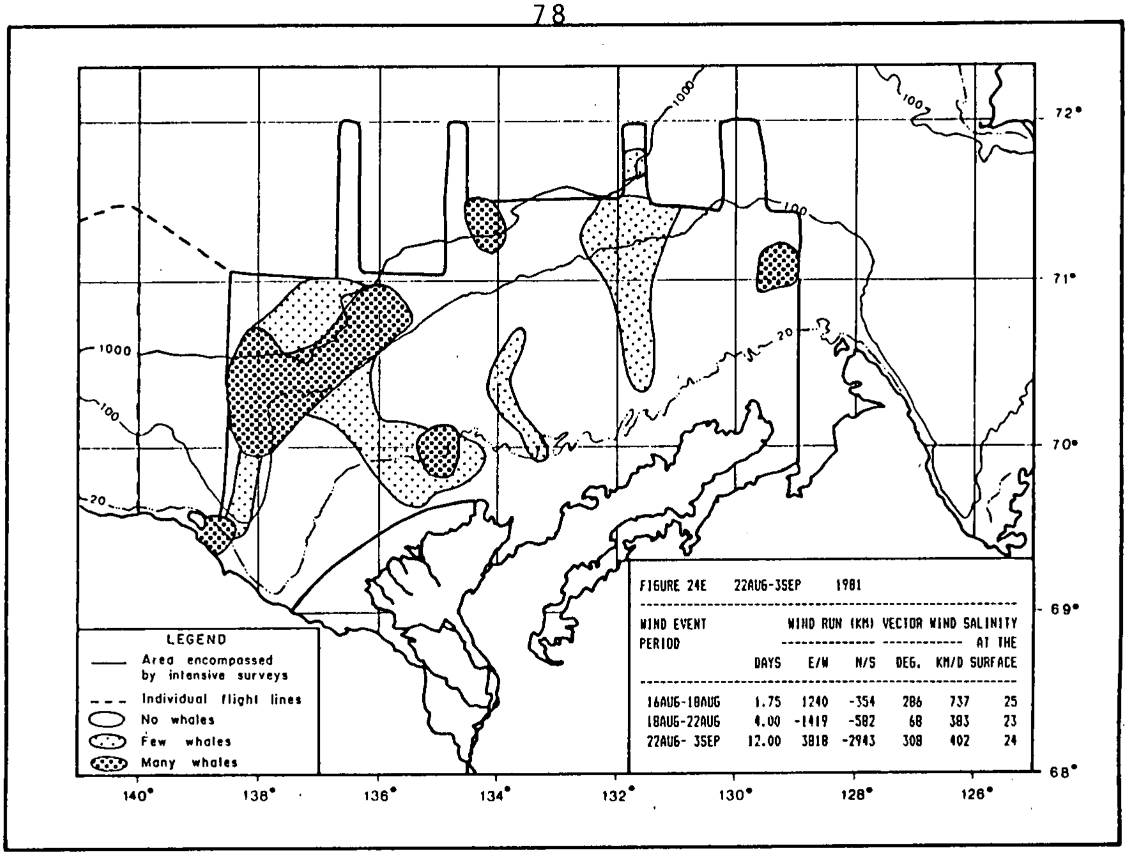

FIGURE 24E 22AUG-3SEP 1981

WIND EVENT PERIOD		WIND RUN (KM)		VECTOR WIND		SALINITY AT THE SURFACE
	DAYS	E/W	N/S	DEG.	KM/D	
16AUG-18AUG	1.75	1240	-354	286	737	25
18AUG-22AUG	4.00	-1419	-582	68	383	23
22AUG- 3SEP	12.00	3818	-2943	308	402	24

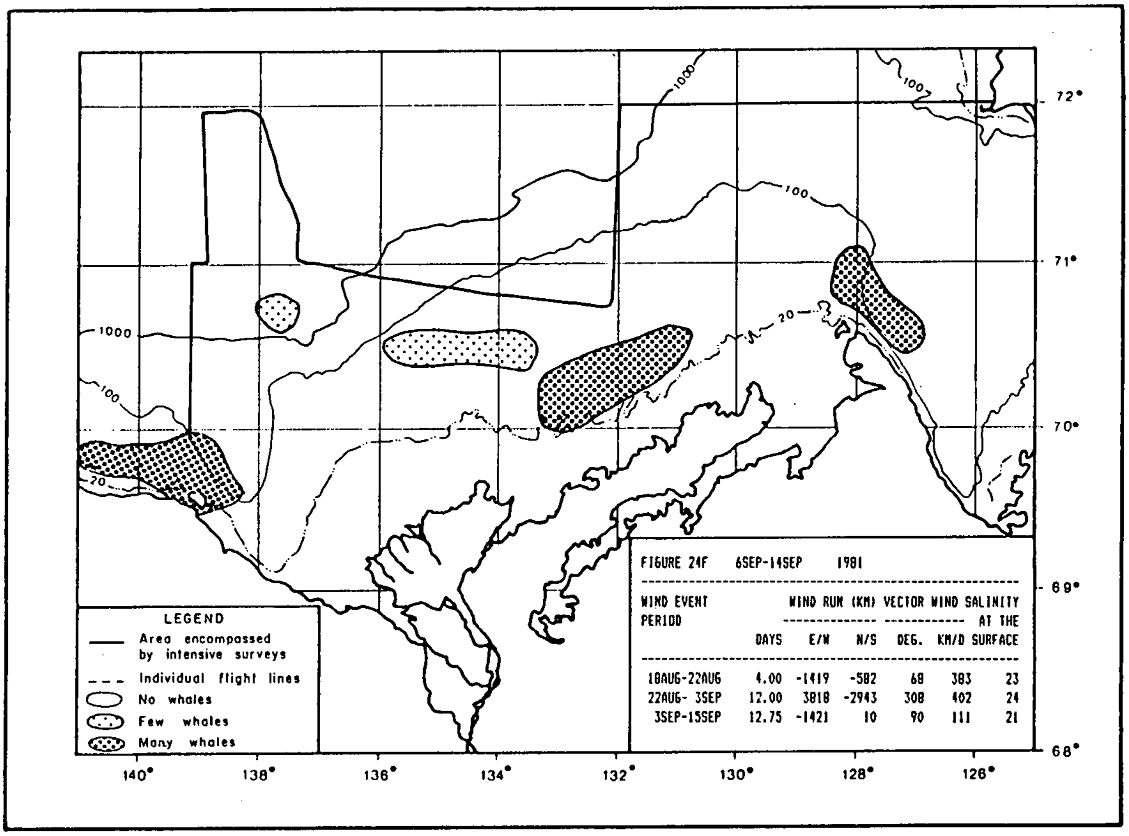

FIGURE 24F 6SEP-14SEP 1981

WIND EVENT PERIOD		WIND RUN (KM)		VECTOR WIND		SALINITY AT THE SURFACE
	DAYS	E/W	N/S	DEG.	KM/D	
18AUG-22AUG	4.00	-1419	-582	68	383	23
22AUG- 3SEP	12.00	3818	-2943	308	402	24
3SEP-15SEP	12.75	-1421	10	90	111	21

Figure 24. Cont'd.

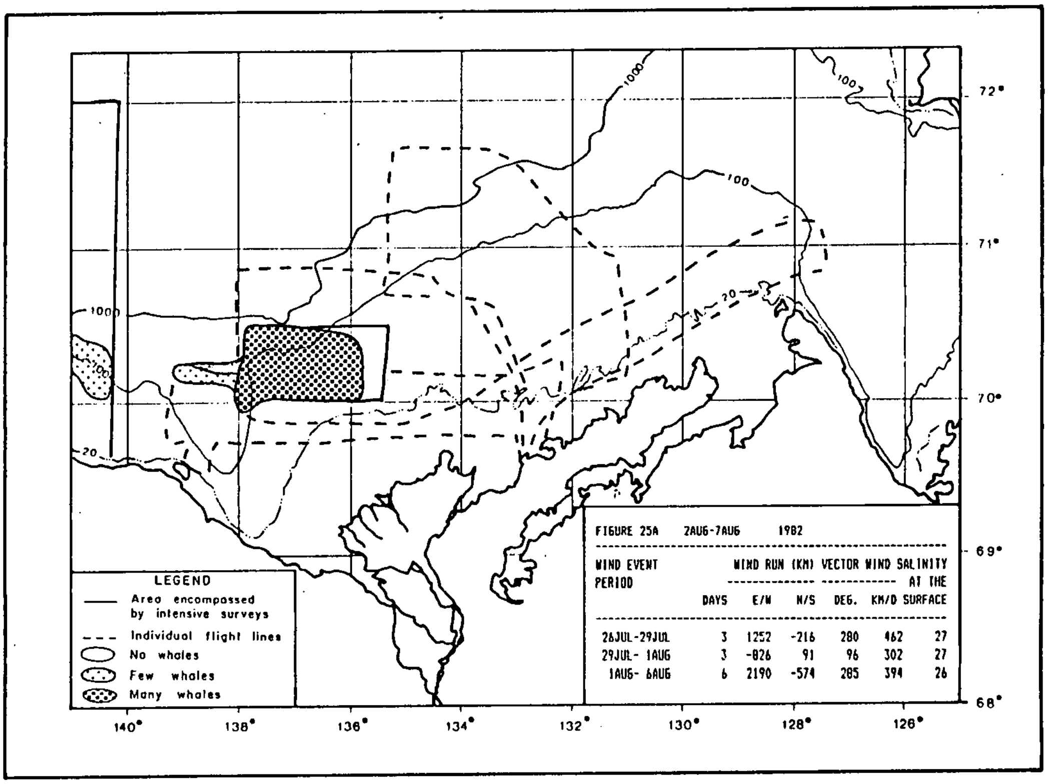

FIGURE 25A 2AUG-7AUG 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
26JUL-29JUL	3	1252	-216	280	462	27
29JUL- 1AUG	3	-826	91	96	302	27
1AUG- 6AUG	6	2190	-574	285	394	26

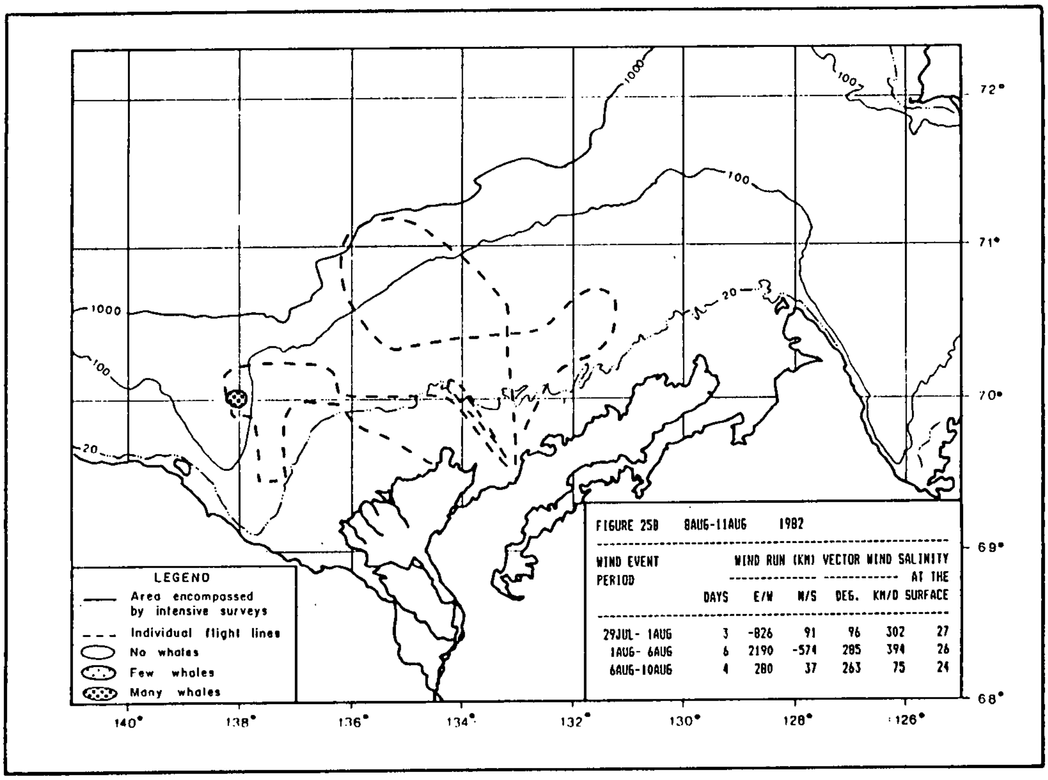

FIGURE 25B 8AUG-11AUG 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
29JUL- 1AUG	3	-826	91	96	302	27
1AUG- 6AUG	6	2190	-574	285	394	26
6AUG-10AUG	4	280	37	263	75	24

Figure 25. Distribution of bowhead whales in the southeastern Beaufort Sea from late July to mid September of 1982. Distributions were mapped by wind event periods, but started and ended 24-36 h after the wind event period. Areas encompassed by surveys and intensive behavioral and photogrammetric work are indicated by solid lines. Individual flight lines in areas where little work was conducted are indicated by dashed lines. Data on the total east/west and north/south wind runs, the vector wind (to), and mean salinity in the area north of Richards Island are presented as in Table 9 for the indicated and two preceding wind event periods.

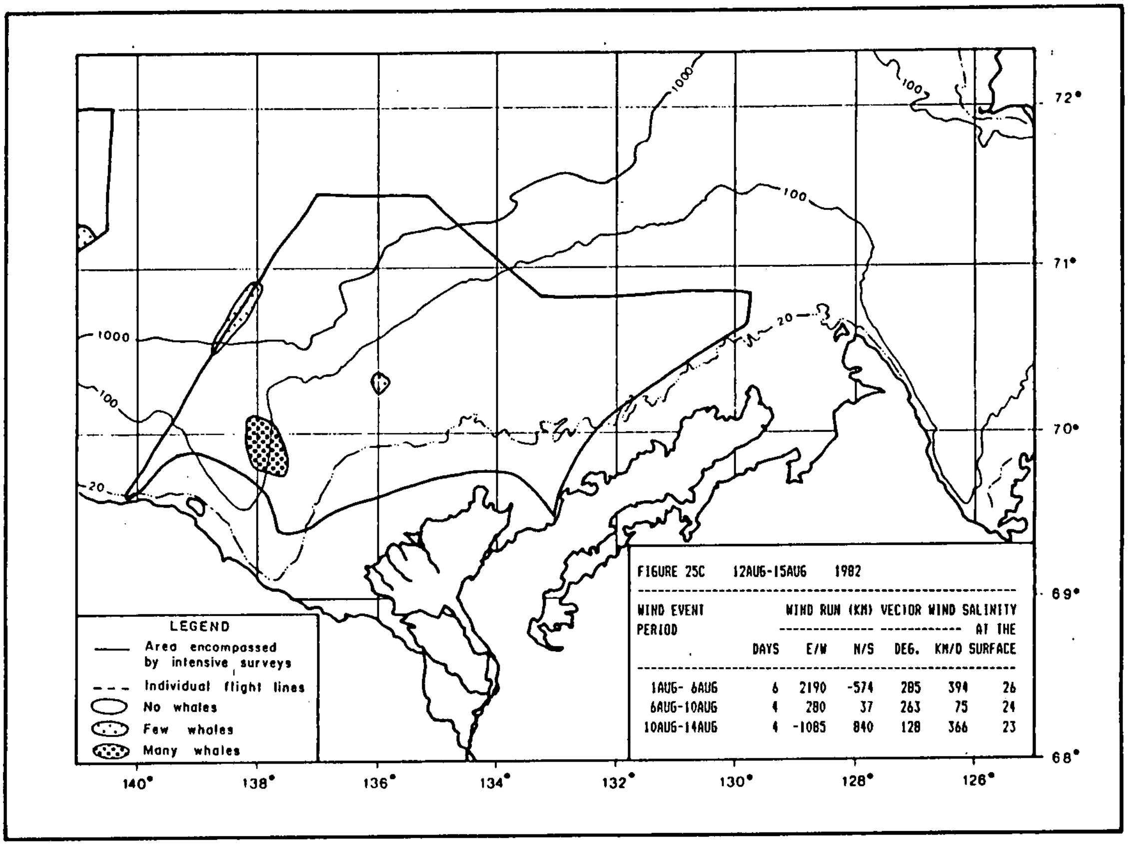

FIGURE 25C 12AUG-15AUG 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
1AUG- 6AUG	6	2190	-574	285	394	26
6AUG-10AUG	4	280	37	263	75	24
10AUG-14AUG	4	-1085	840	128	366	23

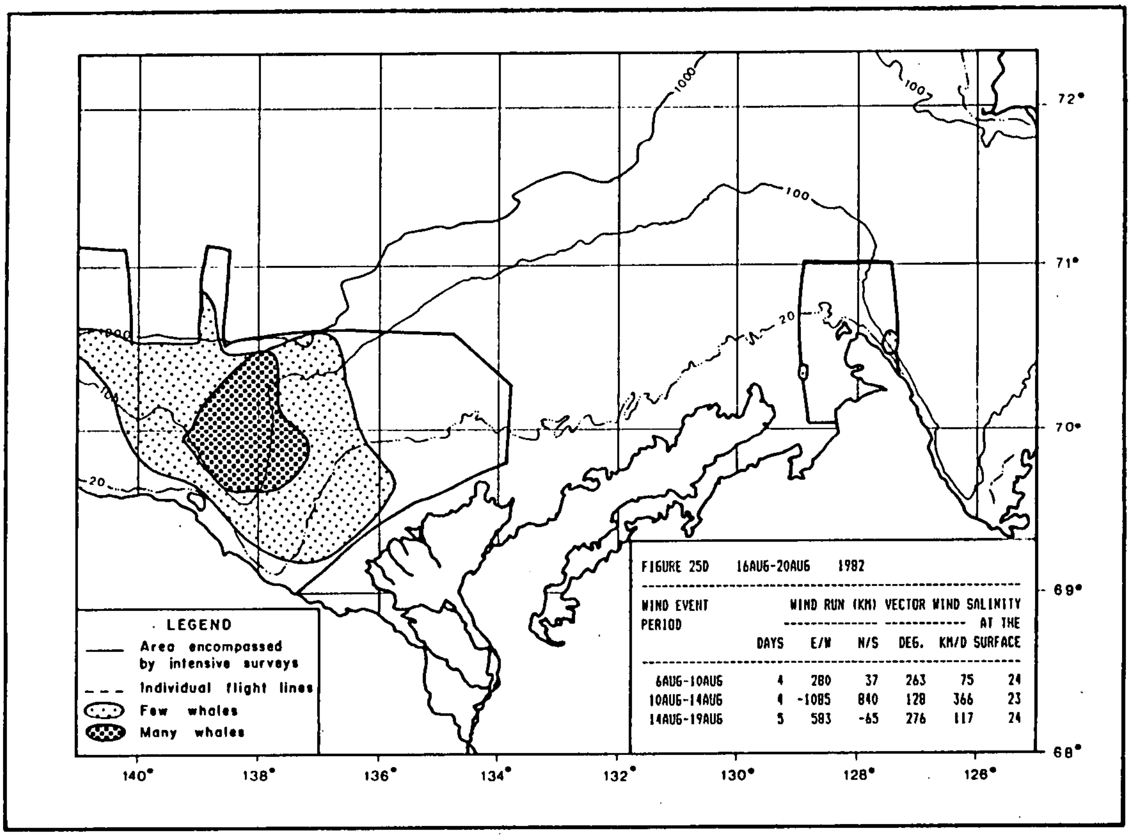

FIGURE 25D 16AUG-20AUG 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
6AUG-10AUG	4	280	37	263	75	24
10AUG-14AUG	4	-1085	840	128	366	23
14AUG-19AUG	5	583	-65	276	117	24

Figure 25. Cont'd.

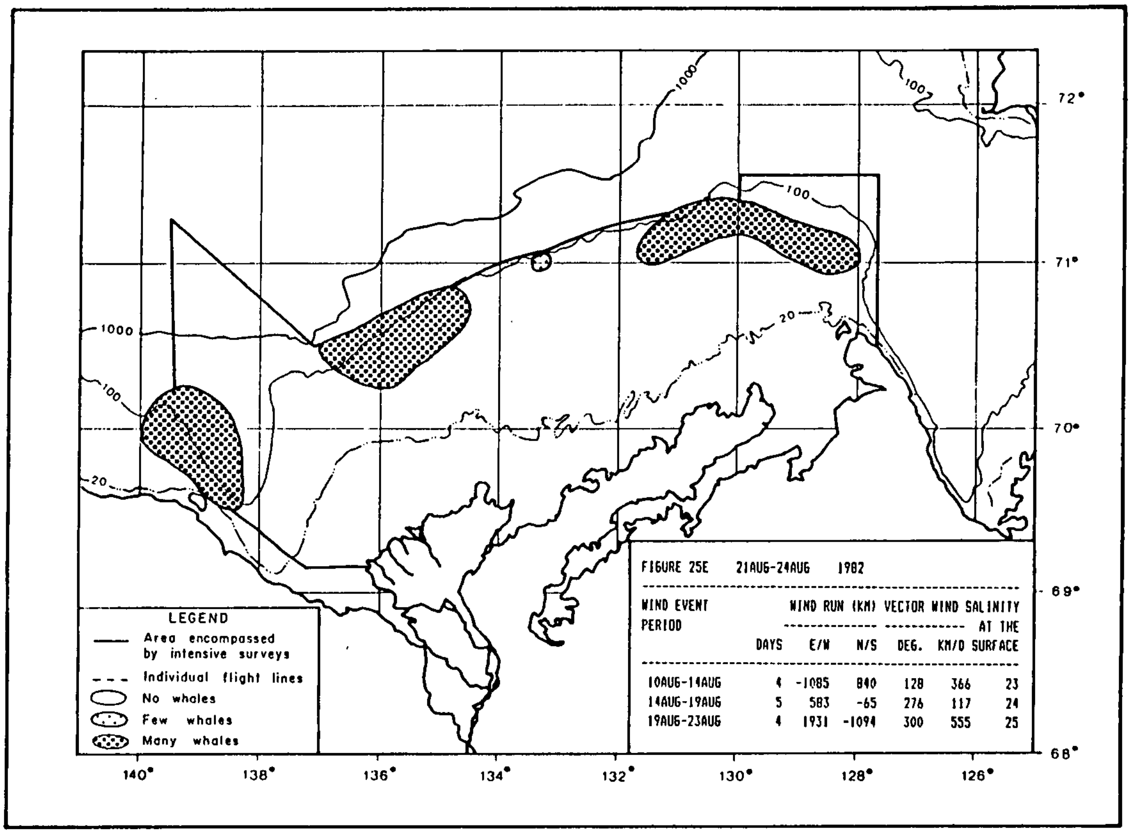

FIGURE 25E 21AUG-24AUG 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
10AUG-14AUG	4	-1085	840	128	366	23
14AUG-19AUG	5	583	-65	276	117	24
19AUG-23AUG	4	1931	-1094	300	555	25

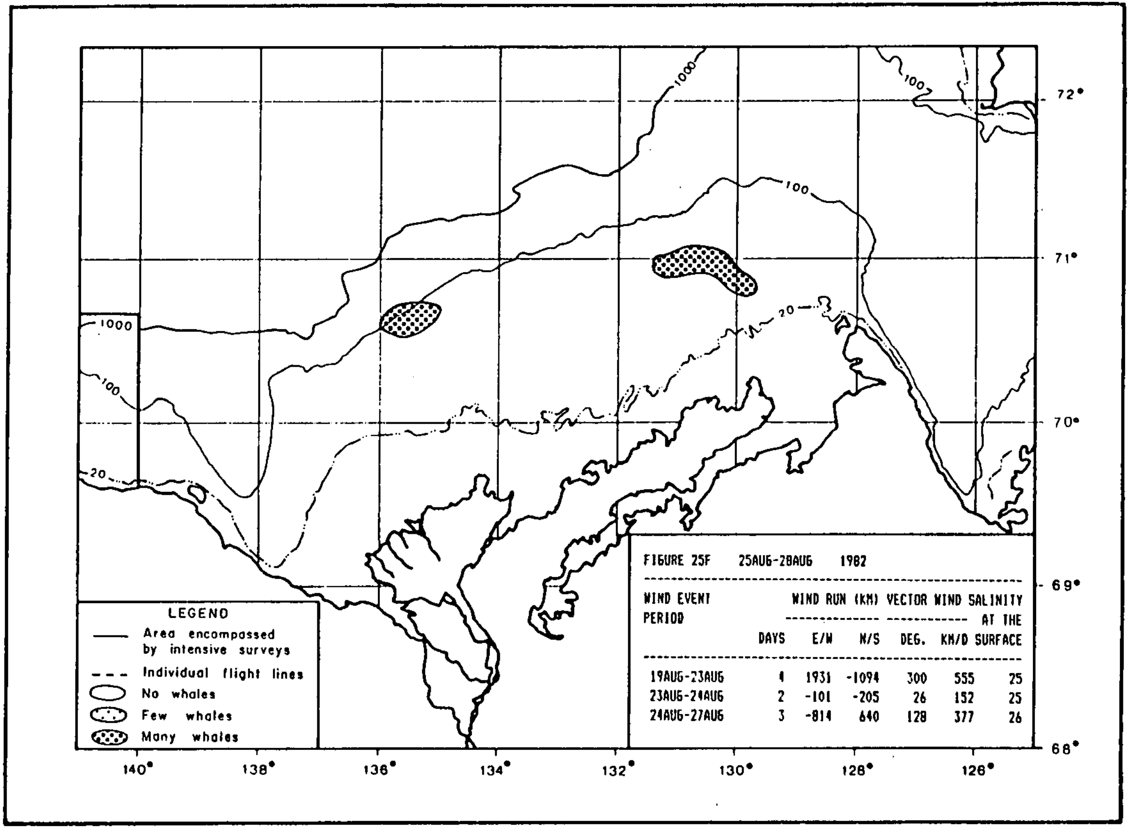

FIGURE 25F 25AUG-28AUG 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
19AUG-23AUG	4	1931	-1094	300	555	25
23AUG-24AUG	2	-101	-205	26	152	25
24AUG-27AUG	3	-814	640	128	377	26

Figure 25. Cont'd.

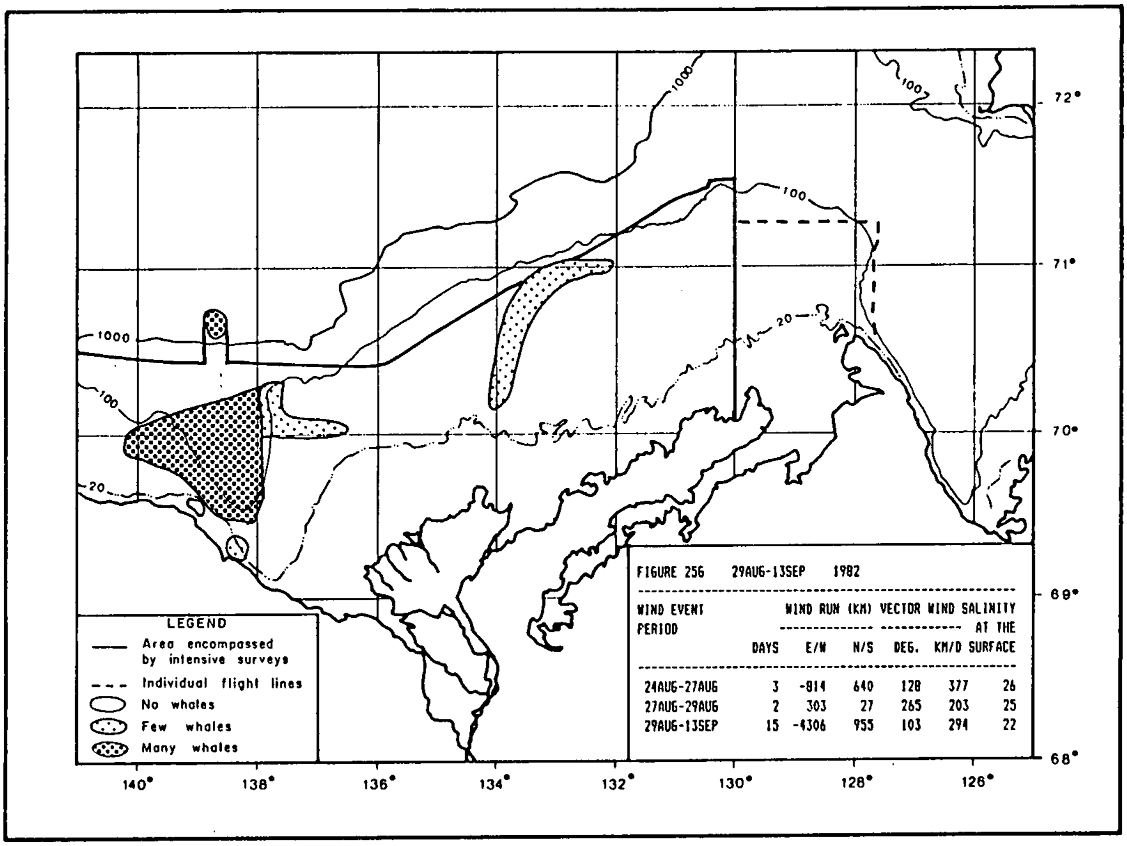

FIGURE 25G 29AUG-13SEP 1982

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
24AUG-27AUG	3	-814	640	128	377	26
27AUG-29AUG	2	303	27	265	203	25
29AUG-13SEP	15	-4306	955	103	294	22

Figure 25. Cont'd.

numbers were also seen north and northwest of Herschel Island. However, there was little coverage of any other parts of the study area. There was little coverage of any part of the study area during the 6-10 August period (Fig. 25b); bowheads were seen only in the Herschel Canyon area during this period. Similarly, most bowheads seen during the 10-14 August period (Fig. 25c) were near Herschel Canyon, although coverage of the study area was considerably more extensive.

During the 14-19 August wind event period (Fig. 25d), bowheads were common in much of the study area west of 136°W. They were especially numerous in the Herschel Canyon area. Small numbers were also seen near Cape Bathurst. However, there was no coverage north of the Tuktoyaktuk Peninsula during this period. During the 19-23 August period, extensive coverage was obtained over much of the study area (Fig. 25e). Bowheads were numerous at this time in waters near the shelf break (100 m depth contour) and in the Herschel Island-Herschel Canyon area, including nearshore waters near Herschel Island.

There was no coverage during a wind event period on 23-24 August, and coverage was sparse during the 24-27 August period. During the latter period, groups of bowheads were noted in waters near the shelf break off the Tuktoyaktuk Peninsula (Fig. 25f). No coverage was obtained during the 27-29 August wind event period.

The final wind event period considered for 1982 was 29 August-13 September (Fig. 25g). During this period, in which survey coverage was extensive, bowheads were numerous in the Herschel Island-Herschel Canyon area and in nearshore waters off King Point. Small numbers were seen far offshore north of the Tuktoyaktuk Peninsula.

1983

There were five wind event periods from late July to mid September 1983. Because of irregular survey coverage during the first three events (29 July-13 August) and because few bowheads were observed during these events, the distribution data are shown together for these periods (Fig. 26a). During this time, bowheads were seen primarily in deep waters (>50 m depth) northwest of Herschel Island, in or near the ice. Small numbers were also observed in the Mackenzie Delta. Coverage during the 13-17 August period was restricted to waters between Richards Island and Herschel Island (Fig. 26b); bowheads were numerous off King Point and in the shallow waters of the Mackenzie Delta. Bowheads were still very numerous in the King Point area during the 17-21 August period, and smaller numbers were seen north of Herschel Island, far offshore in the northwesternmost part of the study area and off the Tuktoyaktuk Peninsula (Fig. 26c). This distribution was generally similar during the 21-23 August

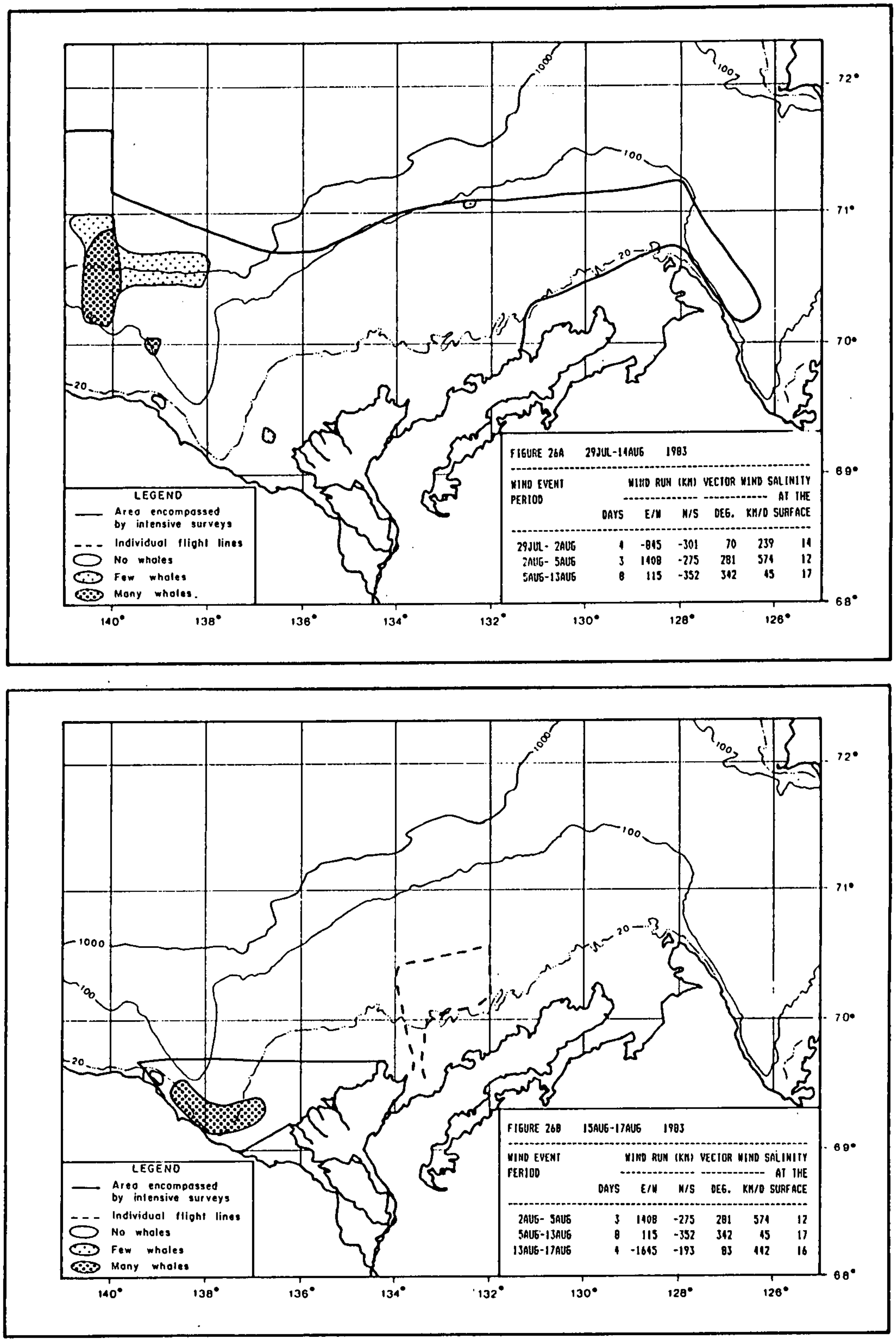

FIGURE 26A 29JUL-14AUG 1983

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
29JUL- 2AUG	4	-845	-301	70	239	14
2AUG- 5AUG	3	1408	-275	281	574	12
5AUG-13AUG	8	115	-352	342	45	17

FIGURE 26B 15AUG-17AUG 1983

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
2AUG- 5AUG	3	1408	-275	281	574	12
5AUG-13AUG	8	115	-352	342	45	17
13AUG-17AUG	4	-1645	-193	83	442	16

Figure 26. Distribution of bowhead whales in the southeastern Beaufort Sea from late July to mid September of 1983. Distributions were mapped by wind event periods, but started and ended 24-36 h after the wind event period. Areas encompassed by surveys and intensive behavioral and photogrammetric work are indicated by solid lines. Individual flight lines in areas where little work was conducted are indicated by dashed lines. Data on the total east/west and north/south wind runs, the vector wind (to), and mean salinity in the area north of Richards Island are presented as in Table 9 for the indicated and two preceding wind event periods.

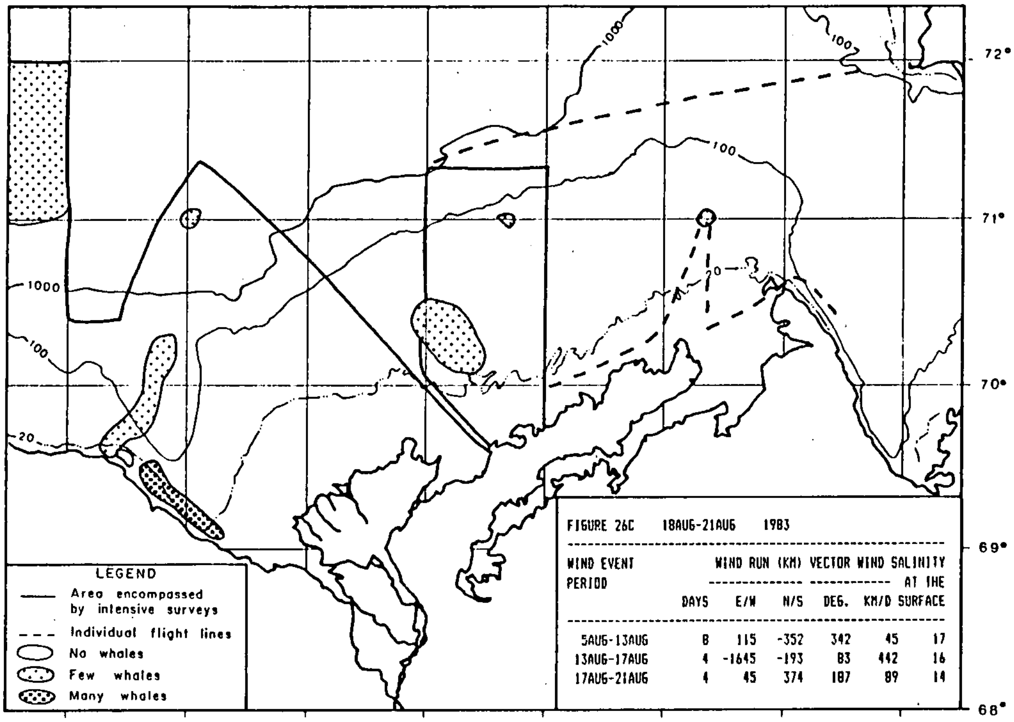

FIGURE 26C 18AUG-21AUG 1983

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
5AUG-13AUG	8	115	-352	342	45	17
13AUG-17AUG	4	-1645	-193	83	442	16
17AUG-21AUG	4	45	374	187	89	14

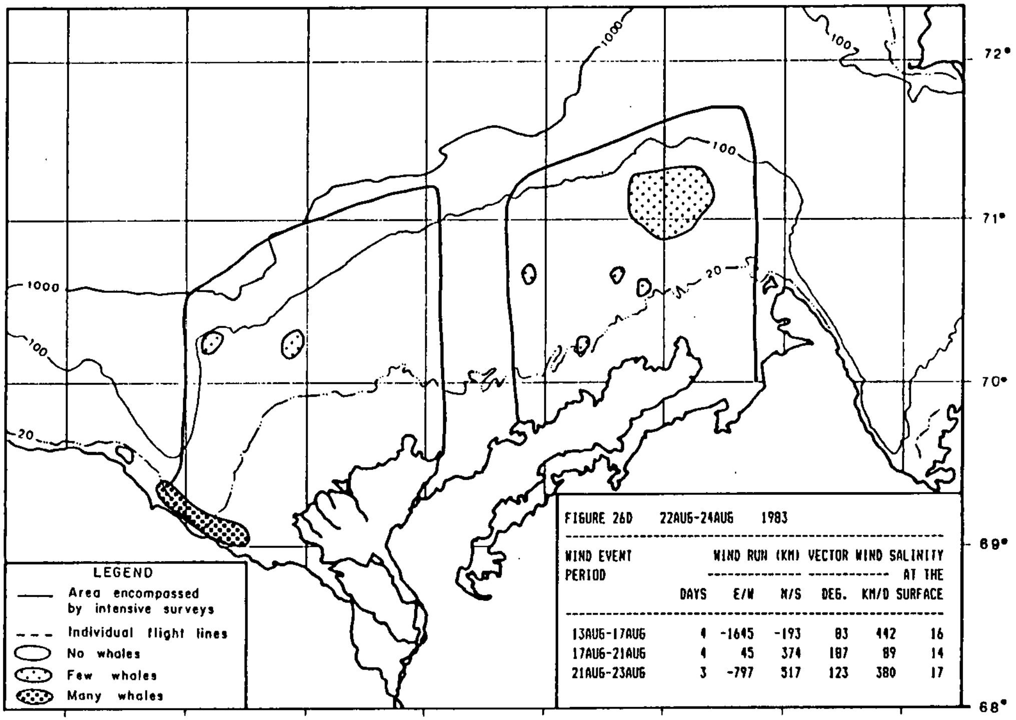

FIGURE 26D 22AUG-24AUG 1983

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
13AUG-17AUG	4	-1645	-193	83	442	16
17AUG-21AUG	4	45	374	187	89	14
21AUG-23AUG	3	-797	517	123	380	17

Figure 26. Cont'd.

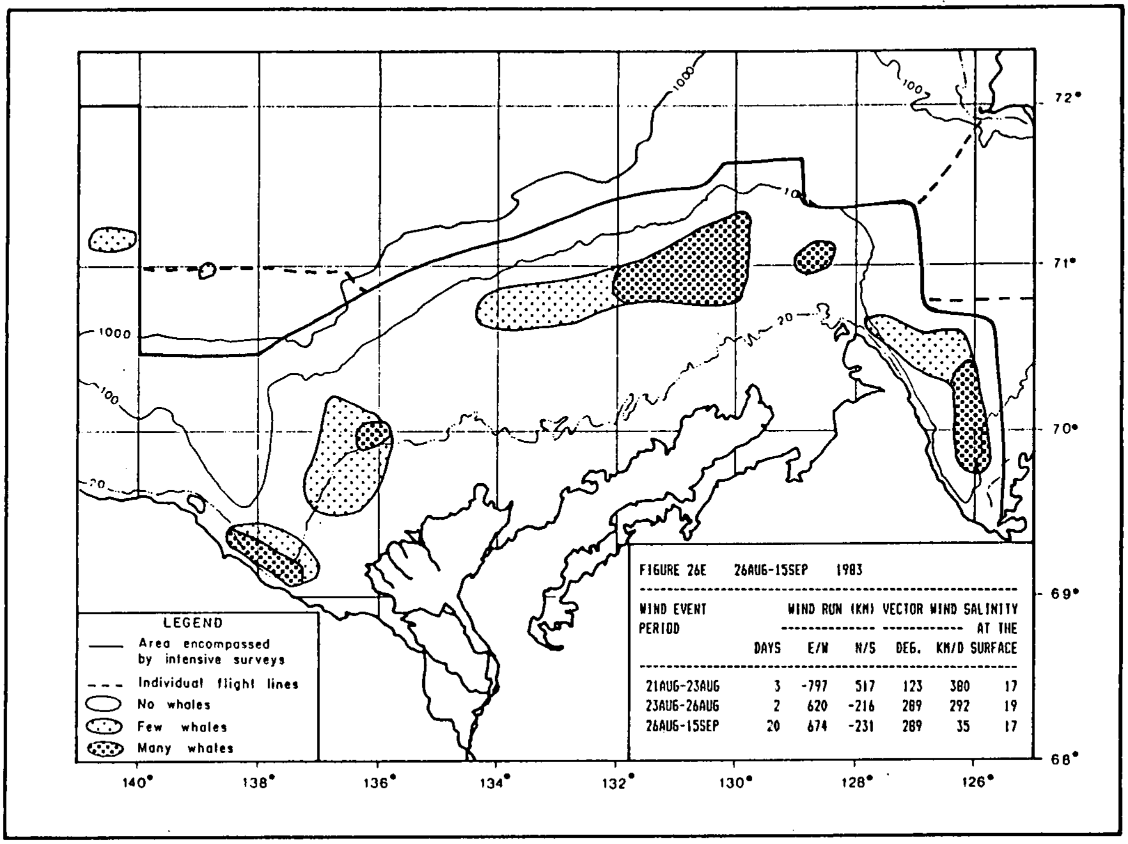

FIGURE 26E 26AUG-15SEP 1983

WIND EVENT PERIOD	DAYS	WIND RUN (KM) E/W	WIND RUN (KM) N/S	VECTOR WIND DEG.	VECTOR WIND KM/D	SALINITY AT THE SURFACE
21AUG-23AUG	3	-797	517	123	380	17
23AUG-26AUG	2	620	-216	289	292	19
26AUG-15SEP	20	674	-231	289	35	17

Figure 26. Cont'd.

period, at least in areas where coverage was obtained (Fig. 26d), and small numbers of whales were seen near the shelf break (100 m depth contour).

No coverage was obtained during a wind event on 23-26 August. During the final period considered, 26 August-15 September, bowheads were numerous off King Point (until 28 August), at or near the shelf break north of the Tuktoyaktuk Peninsula, in Franklin Bay east of Cape Bathurst and, to a lesser extent, northwest of Richards Island.

Seasonal Summary

The observed distribution of bowhead whales in the Canadian Beaufort Sea differed somewhat over the four years considered (1980-1983). In **early August** 1980, bowheads were common in shallow waters north of the Mackenzie Delta (including Richards Island); there were no data on numbers in areas to the west. In 1981, bowheads were widely distributed on the outer part of the continental shelf, mainly near the ice edge and the shelf break. In early August 1982, whales were not as widely distributed; the only area with sightings was on the outer part of the shelf off the western Delta and the Yukon coast. Similarly, in early August 1983, virtually all of the bowheads seen in the Canadian Beaufort Sea were on the outer shelf far north of the Yukon, in or near the ice.

In **mid August** 1980, the major nearshore concentration was in shallow water off the eastern Mackenzie Delta and western Tuktoyaktuk Peninsula. In 1981, it was off the central Mackenzie Delta. In 1982, the major concentration was much farther west, in the rather deep water of the Herschel Canyon, just northeast of Herschel Island. In 1983, the major nearshore concentration was in very shallow water along the Yukon coast southeast of Herschel Island.

In **late August** 1980, there was a large area of bowhead concentration off the Tuktoyaktuk Peninsula and eastern Mackenzie Delta. Few whales were found farther west, although survey coverage there was meagre. In 1981, the areas of greatest abundance were in shallow waters off the central Mackenzie Delta and in deeper waters near the shelf break off the eastern Yukon, Mackenzie Delta and, to a greater extent than in mid August, the Tuktoyaktuk Peninsula. In late August 1982, whales were still concentrated in the Herschel Canyon-Herschel Island area, but there were also concentrations near the steep shelf break off the Mackenzie Delta and, to a lesser extent, off the eastern Tuktoyaktuk Peninsula. In 1983, the major nearshore concentration of bowheads persisted along the Yukon coast in late August. Small numbers of whales were widely distributed on the outer shelf, especially off the Tuktoyaktuk Peninsula.

There were also considerable year-to-year differences in **early September.** In 1980, numerous whales remained off the Tuktoyaktuk Peninsula, although farther offshore than in August. Also, whales appeared close to shore off Herschel Island. In 1981, whales were closer to shore off the Tuktoyaktuk Peninsula in early September than they had been in August. There were many whales near Herschel Island, and some off the Mackenzie Delta and near Cape Bathurst. In 1982, the largest concentration was near and north of Herschel Island, but there were a few sightings off the Mackenzie Delta and Tuktoyaktuk Peninsula. In 1983, whales were widely distributed on the outer shelf off the Tuktoyaktuk Peninsula, with a few off the Mackenzie Delta and Yukon.

DISCUSSION

BOWHEAD WHALES AND THE MACKENZIE PLUME

It is clear that the distribution of bowheads has been quite variable over the four years of study, 1980-83. These variations have been especially marked along the Yukon coast, and in the zone of industrial activity north of Richards Island and the western Tuktoyaktuk Peninsula. This zone is also the area of most direct potential influence from the estuarine plume emanating from the Mackenzie River. Thus, it is important to determine how bowhead distribution is affected by the presence and movements of the plume.

It is reasonable to assume (BEMP 1984), and there is some evidence (Griffiths and Buchanan 1982), that bowheads frequent those parts of the Beaufort Sea that contain substantial concentrations of their zooplankton food. Evidence cited earlier in this report shows that zooplankton densities tend to be low in the low salinity, relatively warm waters of the Mackenzie plume. It can be hypothesized, therefore, that bowheads tended not to occur in the Mackenzie plume. If this hypothesis is true, then we would not expect to find bowheads in the industrial zone at those times when the Mackenzie plume covers the zone.

The evidence available to test this hypothesis is reviewed in the following sections. It should be noted that if the hypothesis were true, it would help explain why bowheads are not present in certain areas; it would not explain why bowheads are present in some but not all other areas. However, the hypothesis is attractive because the Mackenzie plume is a very large and highly variable oceanographic feature. Some large-scale and highly variable phenonemon seems necessary to explain the major seasonal and annual variations in bowhead distributions in the industrial zone.

The position and extent of the Mackenzie plume are primarily determined by wind conditions. In preceding sections we divided the data into 'wind event periods' and evaluated changes in the extent and location of the plume, allowing an appropriate lag time for the physical oceanographic regime to respond to the wind. These data can now be compared with the information on whale distribution. There is no information on the response time of whales to changes in oceanographic conditions.

The available data for each year are reviewed below.

1980

In 1980, whales were found in large numbers in the industrial zone off Richards Island during the 1-12 August period (Fig. 23a). During subsequent periods very large numbers were also found off the Tuktoyaktuk Peninsula (Figs. 23b-f). By early September, whales were not found off Richards Island but were concentrated to the northeast off the Tuktoyaktuk Peninsula. Several oceanographic changes that occurred during this period paralleled these changes in whale distribution.

Comparisons of the thermal satellite images from 5-31 August (Figs. 14b,c,f,h,i) with whale distributions during the period (Figs. 23a-d) show that the northeastward shift in the edge of the diffuse plume was accompanied by a corresponding northeastward shift in the distribution of whales. Large numbers of whales were found just to the east of the plume, in an indentation in the plume (compare Fig. 23b with Fig. 14f), and in the cold water between the bifurcated plume (Plate 1 and compare Figs. 23c and 14h). Bowheads were apparently moving ahead of the advancing plume.

There was a general trend for the salinity in the industrial area north of Richards Island to decrease after early August (Table 9). The high salinities in early August were associated with northeasterly winds that kept the plume to the west of Richards Island (Fig 14b). The Koakoak and Orvilruk drillsites were on opposite sides of the plume edge at this time (see Figs. 27, 28a). Westerly winds in late August and early September moved the plume to the east causing a decrease in salinity in the Koakoak area. A brief period of easterly winds (1-3 September) during the prevailing westerly winds of late August and early September kept the plume extended to the north (see Fig 14l).

1981

In 1981, whales were rare in the industrial zone north of Richards Island and the Tuktoyaktuk Peninsula before mid August (Plate 1, Figs. 24a-b). In the last half of August, large numbers of whales were found offshore of Richards Island but not in shallow waters off Tuktoyaktuk Peninsula (Figs 24c-e). In September, whales were found off the Tuktoyaktuk Peninsula but not off Richards Island (Fig. 24f).

Salinities north of Richards Island were low in the first half of August (Table 9). A short period of strong westerly winds on 17-18 August caused a 10 °/oo increase in the previously low salinity and a precipitous drop in sea surface temperature (Table 9, Fig. 8). At this time, large numbers of bowheads first appeared close to shore (Fig. 24c). The following period (17-22 Aug) of easterly winds was accompanied by a slight decrease in salinity. In the subsequent 12-day period (22-Aug-3 Sep; Fig. 24e) moderate westerly winds pushed the plume closer to shore and caused salinity to increase in the area to the north of Richards Island (Table 9). Whales were common north of Richards Island at this time. During the final period (6-14 Sep) of 1981, easterly winds pushed the plume offshore causing a reduction in salinity and an increase in surface temperatures north of Richards Island (Figs. 8 and 24f). Whales were not present off Richards Island at this time. Substantial numbers were present off the Tuktoyaktuk Peninsula (Fig. 24f), but no temperature/salinity data are available for this area. However, the numbers of whales utilizing this area in 1981 were not as great as numbers in 1980 (Richardson et al. 1985).

The data from both 1980 and 1981 are consistent with the hypothesis that bowheads avoid the low salinity waters of the Mackenzie plume. The maps of whale distribution do not indicate significant concentrations along the plume edge. This is also consistent with the interpretation that whales are avoiding the plume rather than being attracted to food concentrations at the edge of the plume.

1982

Very few whales were present in the industrial zone north of Richards Island and the western Tuktoyaktuk Peninsula in 1982 (Figs. 25a-g). This finding was surprising since the Mackenzie plume was also absent from this area for much of the 1982 season.

In 1982, salinity was high in the industrial zone from late July through mid September (Table 9). From 1 August to 29 August, winds were predominantly from the west for 20 days. Thus, for most of August, the Mackenzie River plume was close to shore along Richards Island and the Tuktoyaktuk Peninsula, as depicted in Figure 16. A wind reversal from the east (10-14 August) pushed the plume offshore and caused somewhat elevated temperatures and slightly depressed salinities for the period 10-19 August; a subsequent four day period of strong westerly winds (19-23 August) depressed temperatures and increased salinities (Fig. 9, Table 9) by driving the plume inshore and eastward (Fig. 16c-f). Easterly winds would have pushed the plume offshore in early September and caused increased temperatures and decreased salinities within the industrial zone (Plate 2, Table 9, Fig. 9).

The results from 1982 clearly indicate that whales were absent from the industrial zone even though much of this area was basically unaffected by the Mackenzie plume. These findings do not invalidate the hypothesis that bowheads avoid the low salinity plume waters. However, the findings do indicate that the mere absence of the plume is not enough to attract bowheads to an area. The situation is obviously more complicated.

1983

Again in 1983, very few bowheads occurred in the industrial zone north of Richards Island and the western Tuktoyaktuk Peninsula. Unlike the situation in 1982, the

Plate 1a. Top: Sea surface thermal imagery of the area north of Kugmallit Bay for 20 August 1980 (NIMBUS-7 CZCS Band 6). Approximate temperature range is from 2°C (blue) to 13°C (red). The land mass is black and cloud and ice are white. Bowhead whale survey data for the period 16-21 August are plotted. From Borstad (1985).

■ 16-30 whales
■ 8-15 whales
■ 4-7 whales
▪ 1-3 whales
□ 1+ whales

Plate 1b. Bottom: Sea surface thermal imagery of the southern Beaufort Sea for 5 August 1981 (NOAA-7 AVHRR Band 4). Bowhead whale survey data for the period 1-5 August are plotted. From Borstad (1985).

■ 16-30 whales
▪ 8-15 whales
▪ 4-7 whales
· 1-3 whales

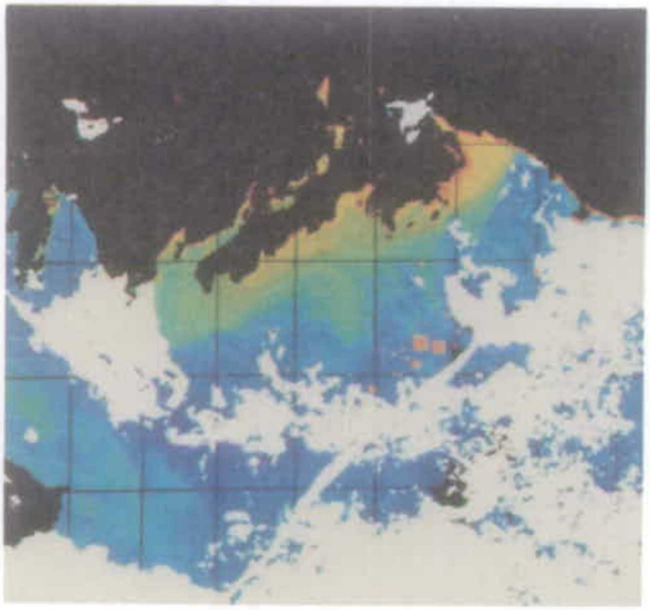

PLATE 1

Mackenzie plume was a prominent feature of this area in 1983 (Plate 2). In 1983, salinity was low in the area north of Richards Island throughout the period of interest with mean surface salinity only reaching 19 °/oo during one wind event (23-26 August, Table 8). The few bowheads seen there were recorded only between 17 August and 21 August. In 1983, the sea ice remained relatively close to shore and may have contained the plume, rather than allowing dispersion and mixing with Arctic Ocean water as in other years. Satellite images show that the plume was concentrated to the north of Richards Island and western Tuktoyaktuk Peninsula and along the Yukon coast (Fig. 17a-i). Thus, the results for 1983 were consistent with the hypothesis that bowheads avoid the Mackenzie plume.

Conclusions

Over the four years of study, there is no evidence to falsify the hypothesis that bowheads avoid the low salinity waters of the Mackenzie plume. In fact, the data from 1980 and 1981 strongly support the hypothesis, since whale movements and distributions were closely related to movements of the plume. Thus, knowledge that the plume is present in a particular area in a particular year may be a sufficient basis for predicting that bowheads would not be present in that area. On the other hand, the results from 1982 demonstrate that the mere absence of the plume is not sufficient to attract bowheads to an area. The lack of whales in the industrial zone in 1982 could have been caused by avoidance of industrial noise and activity or it could have been a function of the absence of large supplies of food. This study was not designed to distinguish between the two alternatives.

The question of what oceanographic features attract bowheads is addressed later in this discussion. First, however, we discuss the usefulness of various oceanographic parameters as simple direct predictors of the plume location and of whale distribution.

PREDICTORS OF PLUME LOCATION

The principal objective of this study was to determine whether easily measured oceanographic parameters can be used to predict the geographic distribution and abundance of bowhead whales in and near the zone of industrial activity in the southeastern Beaufort Sea. Since factors associated with the Mackenzie River plume appear to be the most important natural determinants of whale distribution in the industrial zone, the relevant question is whether easily measured parameters can be used to predict the extent and location of the plume. The parameters examined include surface temperature and turbidity data from satellite imagery, salinity data from drillships, wind data from Tuktoyaktuk, and data on discharge rates of the Mackenzie River.

Plate 2a. Top: Sea surface thermal imagery of Mackenzie Bay for 13 September 1982 (NOAA-7 AVHRR Band 4). Bowhead whale survey data for this date are also plotted using the symbols shown on Plate 1. From Borstad (1985).

■ 8-15 whales
▪ 4-7 whales
· 1-3 whales

Plate 2b. Sea surface thermal imagery of Mackenzie Bay for 14 August 1983 (NOAA-7 AVHRR Band 4). From Borstad (1985).

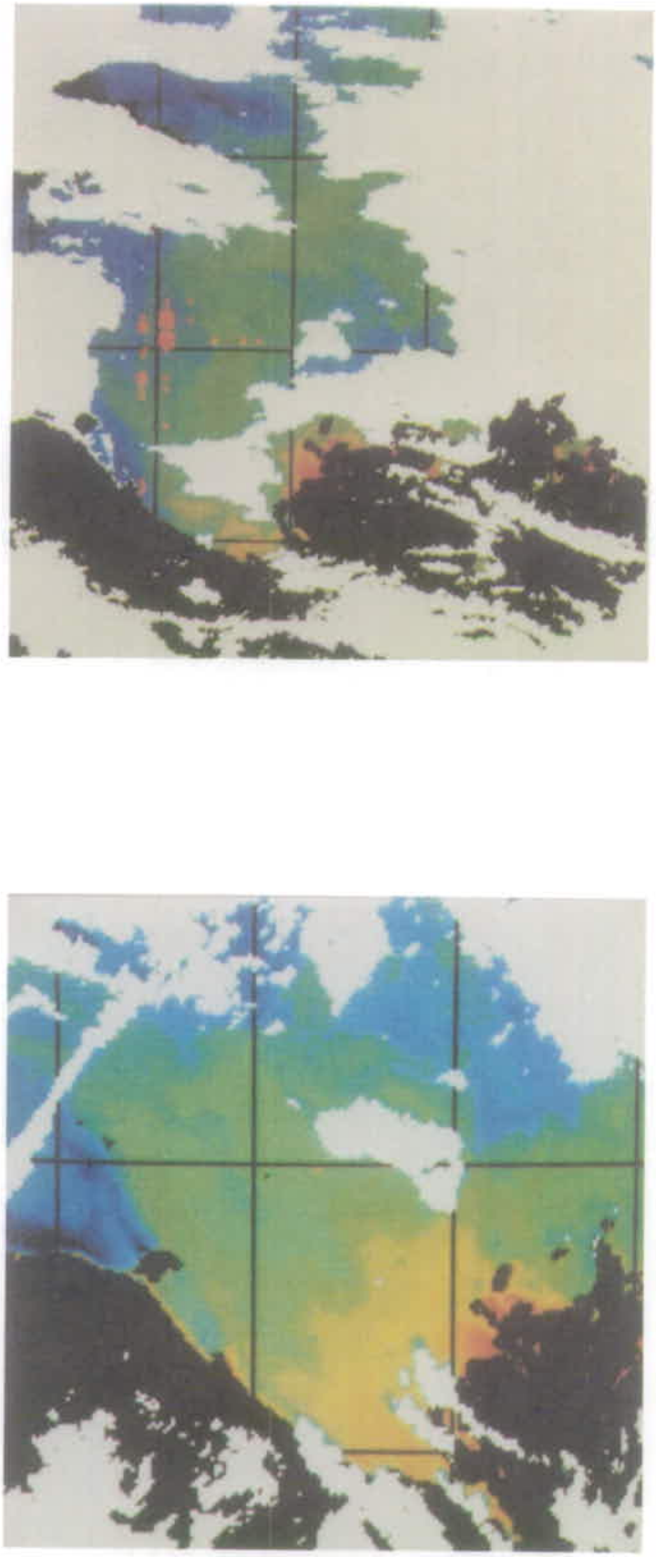

PLATE 2

Satellite Imagery

The most useful predictors of plume location were thermal and visible-wavelength satellite imagery that provided information on sea surface temperature and turbidity levels, respectively. There are three major drawbacks, however.

First, satellite images are only usable for days with clear weather. Such days are infrequent in the southeastern Beaufort Sea during the open water season. Images were available for only 17 days during the 8 months of study over the 4 years, 1980-83. Thus, large gaps in coverage are inevitable if only satellite imagery is used.

The second drawback to the satellite data is that the data on surface temperatures are only relative unless ground-truthing is done. Thus, the satellite date are useful for distinguishing water masses with different surface temperatures but the actual temperature levels usually cannot be determined in the absence of some other data source. The third drawback is that temperature data are not always good predictors of salinity levels in this area. This is important because the zooplankton food of the whales reacts to salinity levels and whales presumably avoid the plume waters because low salinities lead to low zooplankton biomass. Thus, in some instances, independent salinity data are required to supplement the thermal data from satellites. For example, the plume location could not be accurately determined in 1983 without reference to supplementary salinity data gathered from drillships.

Salinity

The present study indicates that ship-based determinations of surface and near-surface salinities provide good evidence of the presence or absence of plume waters at a site. However, it is not practical to sample salinities systematically over the large areas of interest that might be influenced by the plume. Fortunately, data from a few localities used in conjunction with satellite imagery provide good information on plume locations.

Data collected by the drillships off Richards Island (Fig. 27) show that surface salinity was generally high in 1980, 1982 and the last half of August and early September 1981 (Figs. 28a-d). Salinity was low in 1983 and in late July and early August 1981. In 1980 and 1981, large numbers of whales were found in the industrial area when salinity was high and the area was under the influence of oceanic water. In 1983 salinity was low throughout the season and bowheads were scarce. 1982 was the anomalous year when salinity measurements indicated that the plume was not present in much of the industrial zone but whales were absent anyway.

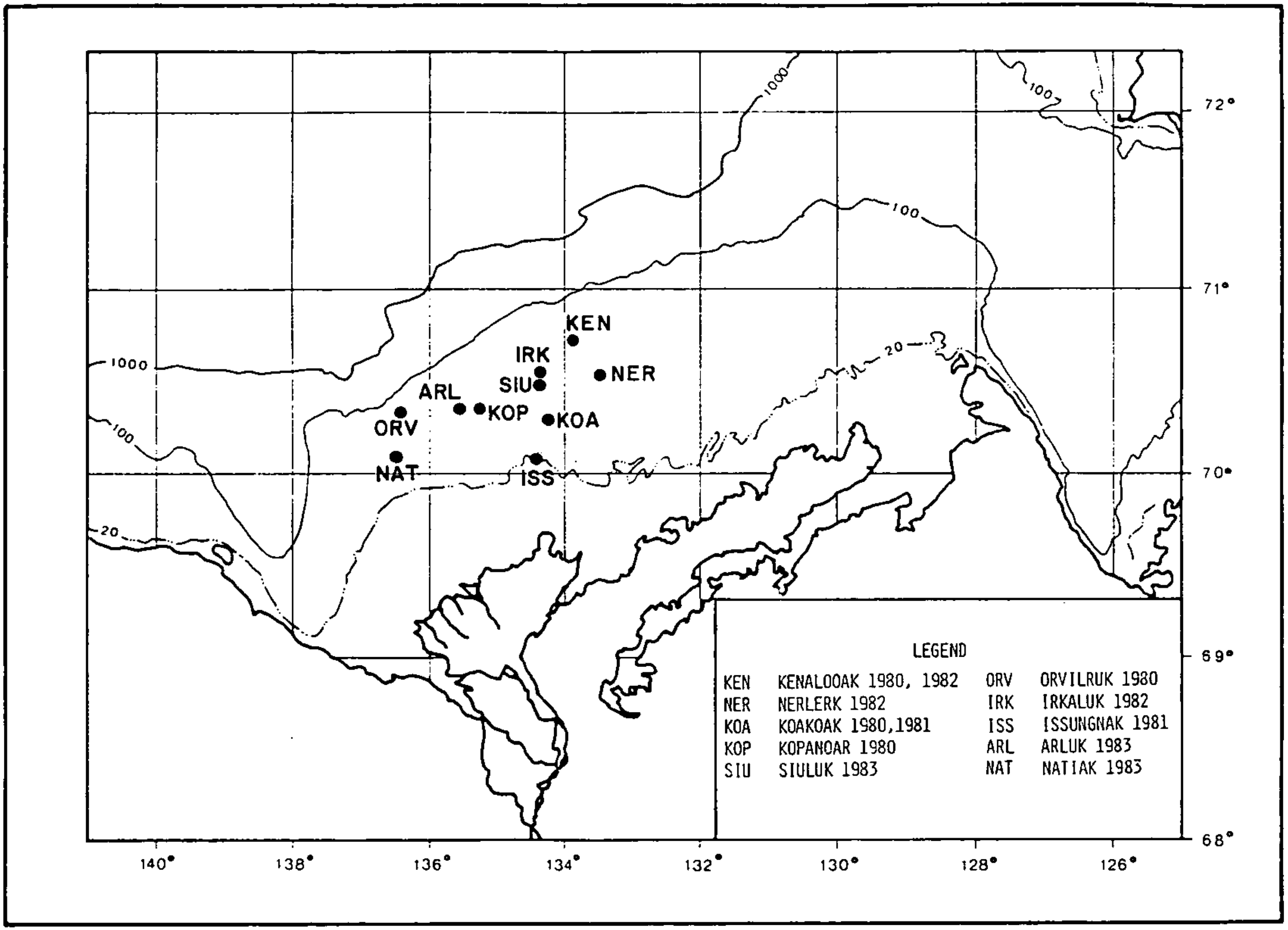

Figure 27. Locations of drilling sites from which salinity data were obtained for the period of late July to early September 1980-1983. The years in which salinity data were obtained are indicated for each site.

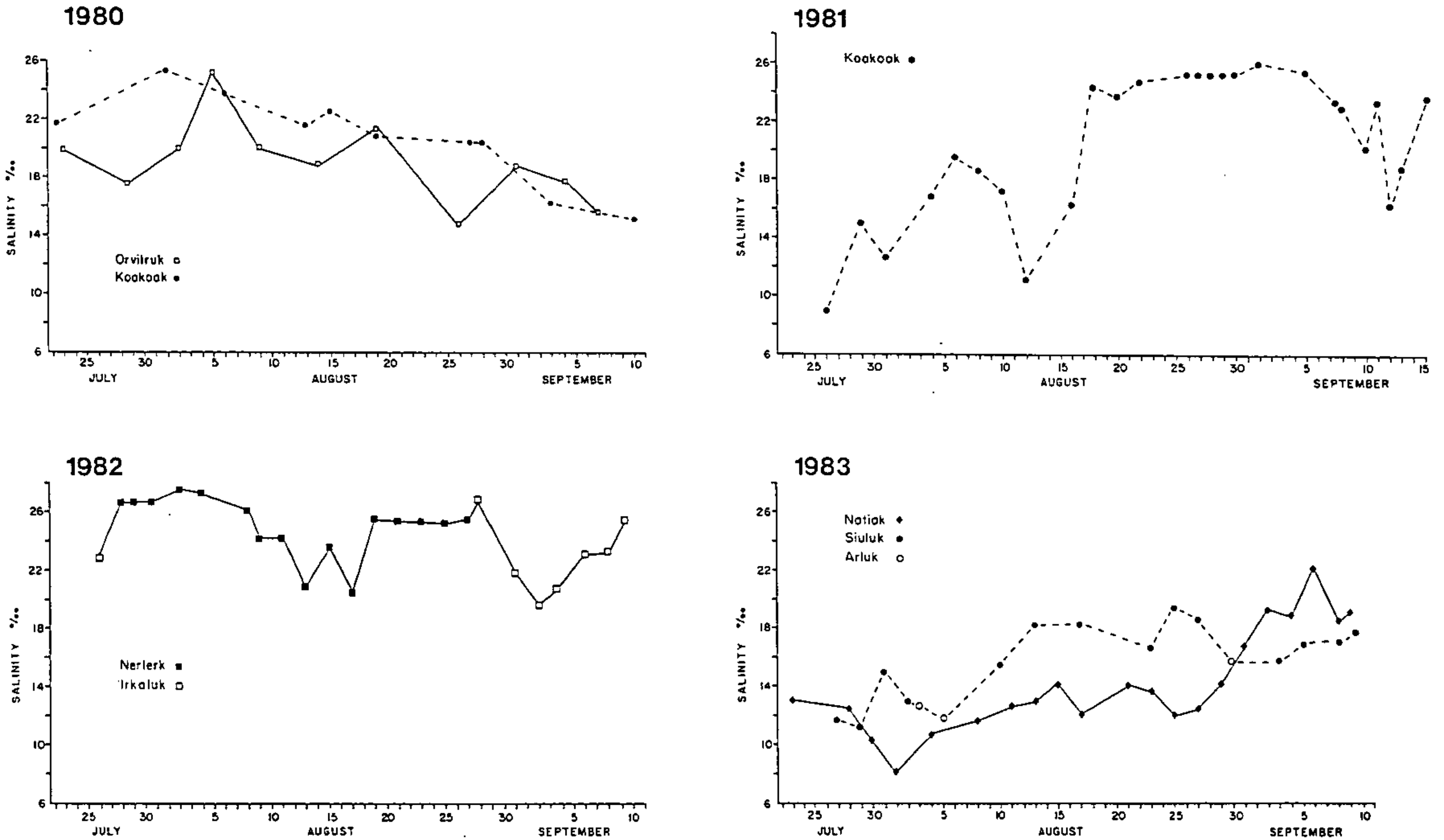

Figure 28. Salinity in the industrialized zone of the southeastern Beaufort Sea from late July to mid September of 1980, 1981, 1982 and 1983. Site locations are shown in Figure 27.

Wind

The location of the Mackenzie River plume is determined by wind conditions, although the relationship is not simple. Examination of winds during periods of increasing and decreasing salinity in the area north of Richards Island (Tables 10 and 11) shows that there is no clear correlation between salinity and wind conditions.

Comparisons of surface temperatures (Fig. 7-10) and salinities (Fig. 28) with winds at Tuktoyaktuk (Fig. 11) indicate that most strong wind events result in a change in salinity and temperature associated with the advection of the diffuse portion of the Mackenzie River plume through the region. However, responses to wind events differ according to such factors as the initial distribution of the plume and the duration of the wind event.

The correspondence of oceanographic conditions to wind forcing must be considered individually for each year. In 1980, the dominant easterly winds experienced in July moved the plume far to the north and west. As a result, the easterly wind events experienced throughout most of August tended to move the plume farther from the industrial zone resulting in increased salinities (decreased temperatures). Only in late August, under the influence of a prolonged westerly wind event, did the plume move eastward through offshore portions of the industrial zone.

In 1981, there was a clear relationship between temperature/salinity and winds (Tables 9 and 10). In all cases, the salinity decreased and temperature increased with easterly wind events, and the opposite changes occurred during westerly wind events.

In 1982, the responses of temperature and salinity to winds were generally consistent with the expected responses. One exception occurred for the westerly wind event of 1-6 August. In that case, the plume had previously been confined to areas east of the industrial zone by the prevailing westerly winds of late July (19-24 July, 26-29 July). Thus, the response in early August was small for temperature and opposite to the expected response for salinity.

In 1983, the easterly winds experienced in July concentrated the plume in a northwest configuration similar to that observed in 1980. As in 1980, the response to winds was not as expected until late August. Moreover, the frequent intrusions of sea ice into the study zone further complicated the response of temperature and salinity to the wind events.

The nature and extent of the Mackenzie River plume are explicable in terms of the prevailing winds, previous wind conditions, and the previous distribution of the plume. Since

TABLE 10

Salinity and wind during wind event periods of increasing and decreasing salinity in the industrial area north of Richards Island

Year	Date	Salinity °/oo at 1 m	Salinity °/oo Difference From Preceding Period	Mean Vector Wind Decreasing Salinity Degrees	Mean Vector Wind Decreasing Salinity km/d	Mean Vector Wind Increasing Salinity Degrees	Mean Vector Wind Increasing Salinity km/d	No. Days in Period
1980	22 Jul-25 Jul	25.1	-	-	-	-	-	3.25
1980	25 Jul-27 Jul	23.2	-1.9	311	647	-	-	1.25
1980	27 Jul-1 Aug	27.3	4.1	-	-	73	347	5.25
1980	1 Aug-12 Aug	26.5	-0.8	45	90	-	-	11
1980	12 Aug-19 Aug	26.0	-0.5	52	453	-	-	7.25
1980	19 Aug-26 Aug	24.0	-2.0	109	66	-	-	7.25
1980	26 Aug-1 Sep	23.2	-0.8	267	306	-	-	5.5
1980	1 Sep-3 Sep	23.6	0.4	-	-	36	555	2
1980	3 Sep-10 Sep	19.6	-4.0	260	292	-	-	7.25
1981	19 Jul-29 Jul	12.1	-	-	-	-	-	9.5
1981	29 Jul-5 Aug	15.9	3.8	-	-	303	435	6.75
1981	5 Aug-16 Aug	14.1	-1.8	116	69	-	-	11.25
1981	16 Aug-18 Aug	24.8	10.7	-	-	286	737	1.75
1981	18 Aug-22 Aug	22.6	-2.2	68	383	-	-	4
1981	22 Aug-3 Sep	24.1	1.5	-	-	308	402	12
1981	3 Sep-15 Sep	20.6	-3.5	90	111	-	-	12.75
1982	26 Jul-29 Jul	27.2	-	-	-	-	-	2.75
1982	29 Jul-1 Aug	26.9	-0.3	96	302	-	-	2.75
1982	1 Aug-6 Aug	25.7	-1.2	285	394	-	-	5.75
1982	6 Aug-10 Aug	24.2	-1.5	263	75	-	-	3.75
1982	10 Aug-14 Aug	23.1	-1.1	128	366	-	-	3.75
1982	14 Aug-19 Aug	23.6	0.5	-	-	276	117	5
1982	19 Aug-23 Aug	25.2	1.6	-	-	300	555	4
1982	23 Aug-24 Aug	25.2	0	-	-	-	-	1.5
1982	24 Aug-27 Aug	25.7	0.5	-	-	128	377	2.75
1982	27 Aug-29 Aug	24.7	-1.0	265	203	-	-	1.5
1982	29 Aug-13 Sep	22.2	-2.5	103	294	-	-	15
1983	25 Jul-29 Jul	11.7	-	-	-	-	-	4.75
1983	29 Jul-2 Aug	13.6	1.9	-	-	70	239	3.75
1983	2 Aug-5 Aug	11.8	-1.8	281	574	-	-	2.5
1983	5 Aug-13 Aug	16.9	5.1	-	-	342	45	8.25
1983	13 Aug-17 Aug	15.7	-1.2	83	442	-	-	3.75
1983	17 Aug-21 Aug	13.5	-2.2	187	89	-	-	4.25
1983	21 Aug-23 Aug	16.8	3.3	-	-	123	380	2.5
1983	23 Aug-26 Aug	19.1	2.3	-	-	289	292	2.25
1983	26 Aug-15 Sep	16.8	-2.3	289	35	-	-	20.25

TABLE 11

Correlation coefficients between wind variables during the wind event period and (a) mean salinity at 1 m depth north of Richards Island and (b) the difference between mean salinity during the wind event period and mean salinity during the previous wind event (n = 28). ns means $p>0.05$, * means $p<0.05$

		Mean Salinity at 1 m (°/oo)	Difference in Surface Salinity From Previous Period °/oo
No. Days in Period		-0.15 ns	-0.30 ns
Total Wind Run (km/period)	East/West	-0.07 ns	0.18 ns
	North/South	-0.18 ns	-0.29 ns
Mean Wind Run (km/d)	East/West	-0.62 ns	0.21 ns
	North/South	-0.19 ns	-0.26 ns
Total Vector Wind Run (km/period)		0.16 ns	0.37 *

the relationship is not a simple one and salinity may increase or decrease under certain wind conditions, wind alone is not a good predictor of the distribution of the Mackenzie River plume or of salinity in the industrial zone.

River Discharge

Figure 29 shows Mackenzie River discharges from April to September of 1980 to 1983. Total discharge computed from the onset of freshet through the summer months was largest in 1982 and smallest in 1980. However, after the cessation of the freshet by late June of each year, the discharge levels differed little among years. In 1982, discharge levels did reach a secondary peak in mid August. However there was no evidence from either the satellite or oceanographic data of any effect on the plume distribution.

Implications

As previously mentioned, knowledge that the plume is present in a particular area should be sufficient basis for predicting that bowheads would not be present. The use of satellite imagery and salinity data collected by the drill-ships appears to provide an adequate description of the nature and extent of the plume. Because the relationship between wind and the distribution of the plume is not a simple one, wind alone is not a good predictor of the nature and extent of the plume.

BOWHEAD CONCENTRATION AREAS

It was demonstrated earlier that bowhead whales apparently avoid the low salinity waters of the Mackenzie River plume. It is not presently possible, however, to predict where whales will occur in the absence of the plume. It is assumed that feeding is the main activity of bowheads in the summering grounds in Canadian waters. It is, therefore, also reasonable to assume that most summer whale concentrations are related to concentrations of their zooplankton prey. Table 12 summarizes the gross distribution of bowheads in various parts of the southeast Beaufort Sea, excluding the industrial zone north of Richards Island. The locations of these general areas are presented in Figure 30.

Examination of the distribution data from areas surrounding our main study area indicates that bowhead distribution can be quite variable from year to year, even in areas not influenced by the Mackenzie plume (Table 12). For example, the numbers of whales in the two shelf break zones were high in both 1981 and 1982 but low in 1983. Similarly, the King Point area along the Yukon coast supported virtually no whales in 1980, 81, or 82 but large numbers in 1983. [Large numbers were also present in 1984 and 1985--Richardson et al. 1985; LGL Ltd., Unpubl. data.] On the other hand, some

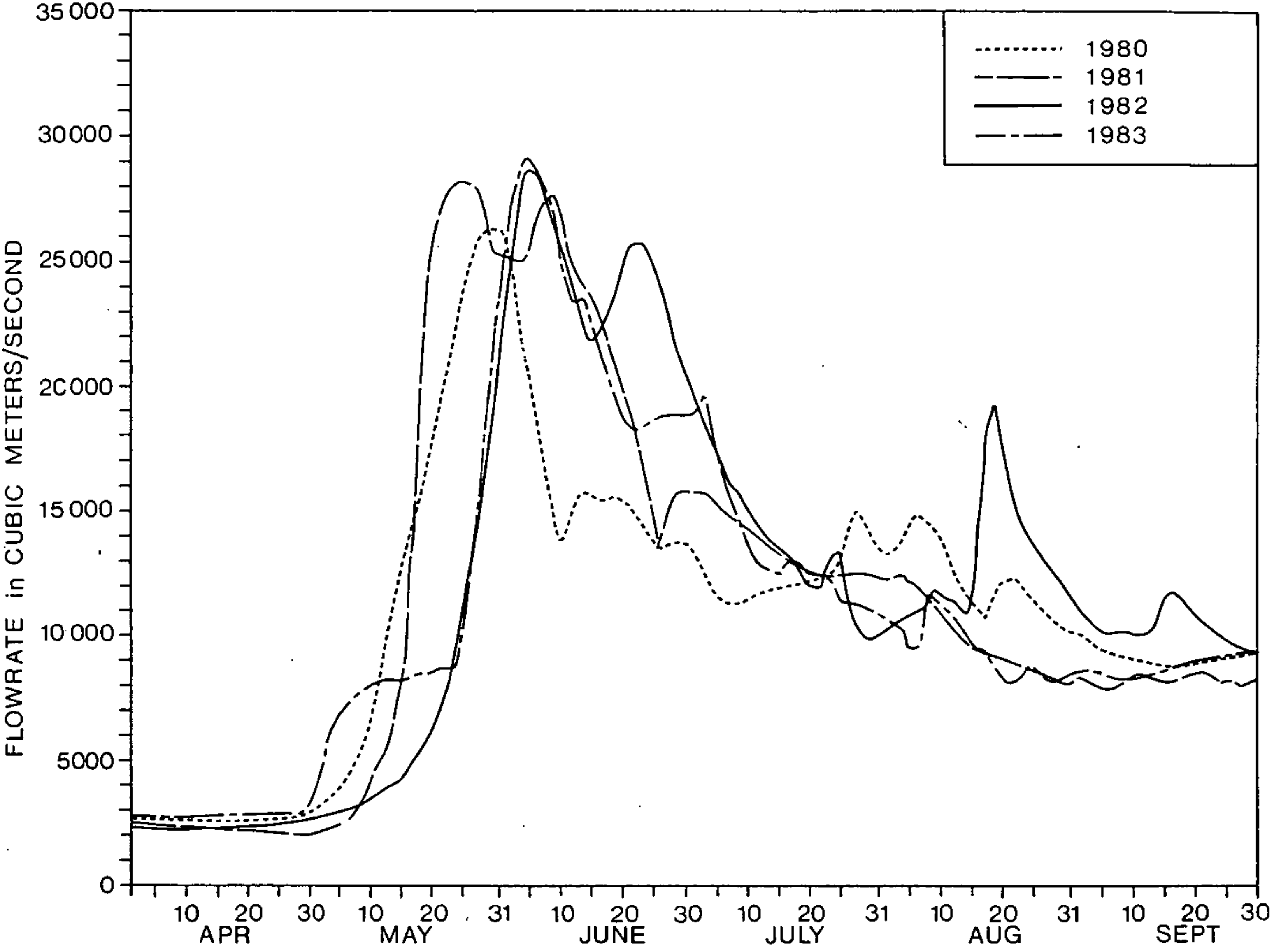

Figure 29. The volume discharge of the Mackenzie River, 1980-1983, for the months April to September. The data were from the permanent gauging station on the Mackenzie River located above the junction with the Arctic Red River, operated by the Inland Waters Branch, Environment Canada.

TABLE 12

General patterns of relative abundance of bowhead whales in various parts of the southeastern Beaufort Sea, 1980-83. (Based on Figs. 23 to 26)

	1980		1981		1982		1983	
	Early[a]	Late[a]	Early	Late	Early	Late	Early	Late
King Point	-[b]	0	0	1	-	1	2	2
Herschel	-	2	2	2	2	2	1	1
Interface	-	0	2	0	0	1	2	2
Tuktoyaktuk Peninsula	2	2	1	2	0	2	0	2
Delta Shelf Break	-	-	2	2	1	2	0	1
Tuk Pen Shelf Break	-	-	2	2	-	2	1	0
Franklin Bay	-	-	-	2	-	1?	-	2

[a] Early is late July to mid August and late is mid August to mid September.

[b] 2 = many whales; 1 = a few whales; 0 = no whales; - = no coverage;
? = marginal/inadequate coverage.

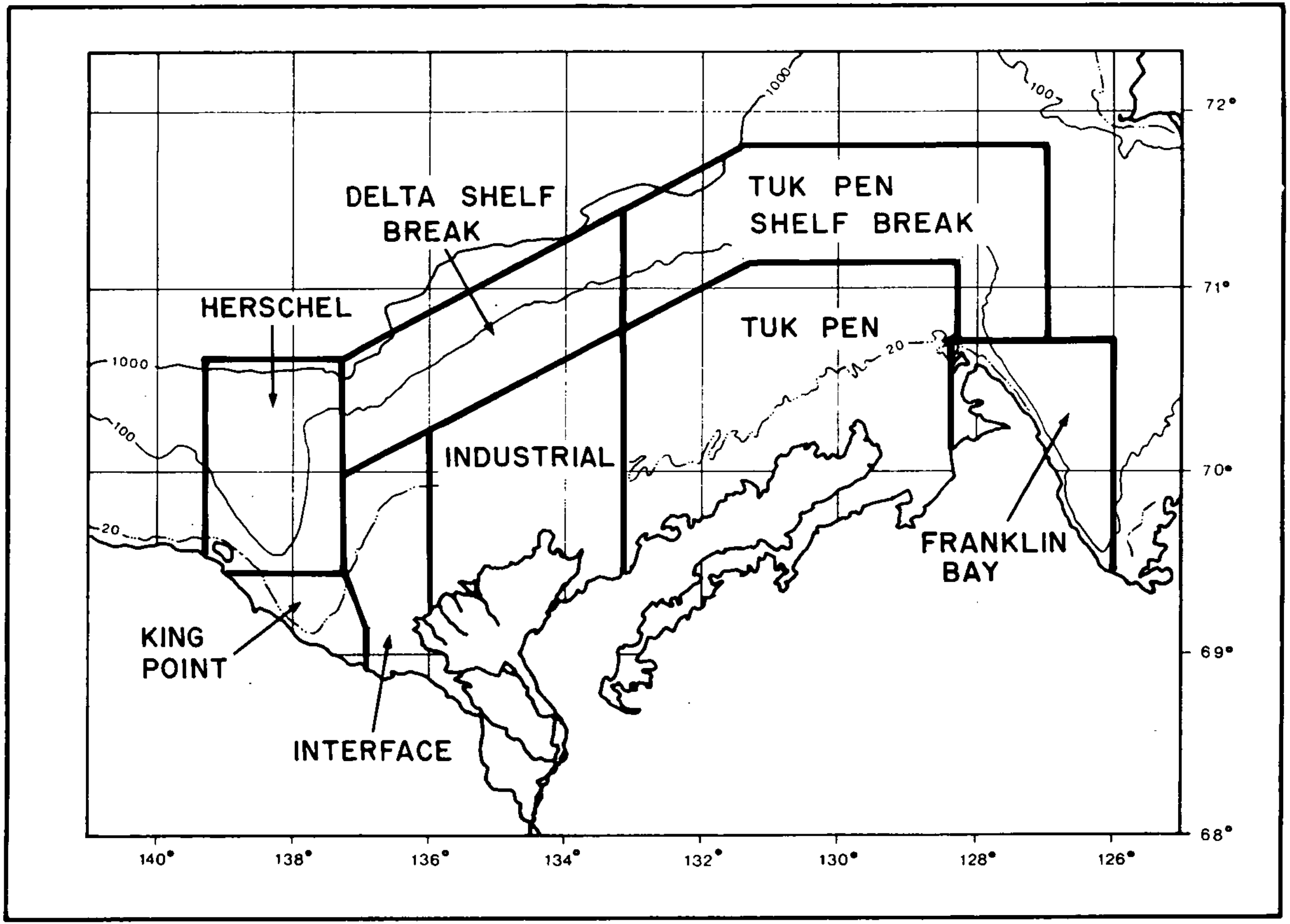

Figure 30. Subdivisions of the Beaufort Sea used in summary table.

areas seem to be used consistently. For example, the Tuktoyaktuk Peninsula zone was used by substantial numbers of whales in the latter half of the study period in each of the four years. Franklin Bay had adequate coverage in only two of the 4 years of study (1981, 1983). However, coverage is also available for 1984 and 1985 and bowheads have been present in all four years with coverage.

The available satellite imagery provides only infrequent coverage and cannot be used to critically evaluate the oceanography in each of these areas. No other sources of synoptic data are available. It is not possible to make definitive statements about oceanographic mechanisms that are important or about methods by which bowheads find food patches and distribute themselves among the patches.

Certain assumptions can be made about which feeding areas are most important to bowheads. Zooplankton concentrations that are large, predictable and consistent would be most useful to the whales. The advantages of large aggregations of food are obvious. The ecological predictability of the concentrations must also be important. Concentrations that occur in specific geographic areas or under specific oceanographic conditions can be 'predicted' by the whales and can be found and used by the whales. The ability to find relatively small food concentrations in the large oceanic range is probably an important consideration in understanding whale distributions. Similarily, the consistency from year to year in the location of food concentrations is also important.

The data in Table 12 indicate that not all concentration areas are used in each year. It is assumed but not proven that areas with few or no whales in a particular year probably do not contain large amounts of food in that year. An alternate assumption would be that zooplankton food patches are superabundant and hence they do not control bowhead distribution. If the latter assumption were true, then a more even, and annually consistent, bowhead distribution would be expected.

The hydrometeorological conditions that could concentrate zooplankton at any of these areas are as follows. In Mackenzie Bay, off Herschel Island and King Point, and in the area north of Richards Island and the Tuktoyaktuk Peninsula, the estuarine front may act as a zooplankton concentrating mechanism. Bowheads seen in these areas are often associated with the edge of the plume (Richardson et al. 1985). Satellite imagery has shown that there was hydrographic activity conducive to the formation of fronts in nearshore areas adjacent to King Point and Herschel Island (Marko 1975; Marko and Oberski 1982; Borstad 1985). Bowheads seen along the Yukon coast often associated with upwelling, and those observed near Herschel Island often associated with turbulence (Borstad 1985; Harwood and Borstad 1985). Turbulent circulation may enhance zooplankton concentrations off Cape Bathurst (Borstad 1985). In other areas, plankton and its predators are concentrated at the shelf break (see Background). Shelf break phenomena that could concentrate zooplankton may be operating in the Beaufort Sea. Because of the nature of currents, current reversals due to wind, bathymetry and shelf break effects could be particularly enhanced in the Herschel Canyon area.

The frequency of occurrence of the conditions under which most of the above phenomena operate, and even their existence in various parts of the Beaufort Sea, are unknown. The relationship (if any) between concentrations of zooplankton and these hydrographic mechanisms is unknown. It may be possible to speculate about these mechanisms but the critical need now is to obtain a much better understanding of zooplankton population dynamics and the responses of the plankton to the various oceanographic features and processes that are present in the southeastern Beaufort Sea.

FUTURE STUDIES

Future studies need to be designed at two levels. First, additional work on the large-scale synoptic relationships would be useful to verify the main findings of this study. Two years of data (1984 and 1985) could be used to confirm that bowheads do avoid the industrial zone north of Richards Island when the zone is covered by the low salinity Mackenzie plume.

The second level of studies involves a more detailed exploration of the relationships of zooplankton to the oceanographic factors that determine plankton population levels and aggregating mechanisms. The responses of bowheads to the numbers, types, sizes and consistency of zooplankton concentrations are also of direct relevance but cannot be determined until substantially more information on the zooplankton/oceanography interactions is available. Two recently funded studies are addressing aspects of these oceanographic questions.

In the eastern Alaskan Beaufort Sea, a study of the relationships of physical oceanography, zooplankton concentrations, zooplankton energy content, and the responses of bowhead whales is being funded by U.S. Minerals Management Service (MMS). This study began in September 1985 and will continue in September 1986 (W.J. Richardson, LGL Ltd., pers. comm.). The study will use concurrent and retrospective analysis of satellite imagery, airborne remote sensing, aerial photography and surveys, behavioural observations, tagging of whales, analysis of stomach contents, analysis of isotopic composition of the whales and their prey, continuous recording of temperature, chlorophyll and zooplankton, CTD profiles, and conventional zooplankton and benthic sampling. However, oceanographic conditions in the eastern Alaskan Beaufort Sea are not similar to those of the Canadian Beaufort Sea. Freshwater influences are limited, with the result that horizontal discontinuities in surface water properties are much smaller, and the bathymetry and physiography of the coastal waters are much more homogeneous than in the southeastern Beaufort Sea. Although the concepts and relationships determined in the MMS study will be useful, many of the data will not be of direct relevance to the dynamic conditions encountered in the southeastern Beaufort Sea.

A smaller study of zooplankton aggregations and their environmental correlates along the Yukon coast in the Canadian Beaufort Sea is being funded by Canada Department of Indian Affairs and Northern Development (DIAND) (M.S.W. Bradstreet, LGL Ltd., pers. comm.). The DIAND study involves boat-based sampling of zooplankton and physical oceanography. Results will be coordinated with concurrent aerial surveys and satellite imagery, and integrated with the results of the studies being conducted in the Alaskan Beaufort Sea. It would be premature to design field studies for 1986 and beyond until the results of the 1985 MMS and DIAND studies are available. Results of these studies will be presented through BEMP and follow-up studies might best be designed at that time.

The ongoing studies mentioned above should provide some useful information on the relationships between bowheads, zooplankton, and oceanography in the Beaufort Sea. Results that will be especially useful in addressing data gaps that became obvious during the present study will include (1) the biomass and size of zooplankton concentrations associated with feeding bowheads, (2) the nature and extent of these concentrations in the Beaufort Sea, and (3) the physical oceanographic regime associated with these concentrations.

Satellite imagery have been found to be a good tool for mapping surface water properties. Future work should emphasize the acquisition of digitally recorded AVHRR images with the full 10-bit resolution provided by the satellites' analog to digital conversion system. By making prearrangements to acquire all usable imagery in digital form, it should be possible to increase the number of maps of surface water properties available for each season. In this retrospective study, the large time interval between successive digital images limited the interpretation. The increased spatial resolution afforded by 10-bit imagery should also allow analysis at a somewhat finer scale that that presented here, but it will not allow mapping of the mesoscale features (see Appendix A).

The present study has focused on the relationship between large-scale oceanographic processes and the distribution of bowhead whales. There are no data on the nature and extent of small mesoscale oceanographic processes in the Beaufort Sea. The importance and distribution of these small scale processes relative to large scale processes may be important in explaining the distribution of bowhead whales. For example, it would be very useful to know when, and under what conditions, small scale processes occur at the plume edge. Future studies of bowhead whale distribution need to address this topic in order to (1) understand the physical processes that aggregate zooplankton, and (2) relate these to the more easily measured large-scale distribution of physical conditions (plume areas, winds, etc.).

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APPENDIX A

MESOSCALE FEATURES

The distribution of surface oceanographic features shown by the standard image processing utilized in this study and depicted on Figures 14 to 17 was based on average pixel levels; this technique was well-suited to defining large-scale features. In this appendix we evaluate the feasibility of more detailed mapping of the distribution of surface features using a different technique in order to determine if surface features not evident using standard techniques could be resolved. The 6 August 1981 thermal infrared band image was selected for this analysis because it was recorded with a full 10-bit resolution and a high degree of surface water structure was evident on the image.

The image was processed to obtain the maximum value of the digital radiance difference measured between each pixel and its eight nearest neighbors. Although nearest neighbor radiance differences as large as 25 digital units were recorded, approximately 86% of all pixels were found to have difference values less than or equal to seven units. A plot of the positions of the 14% of difference values greater than seven units was assumed to be a measure of mesoscale features. This plot reproduced the water mass boundaries produced during routine analysis and contouring procedures (compare Fig. A with Fig. 15d).

This procedure, however, did not enhance our ability to detect surface oceanographic features and determine potential locations that could serve as focal points for zooplankton aggregations because (1) only a few isolated points were located away from boundaries that were described with other procedures, and (2) surface features producing pixel differences of one to seven units could not be unequivocally distinguished from background noise. Difference values due to noise could be as large as three units. These pixel differences were not plotted.

A comparison of maximum pixel radiance differences with whale distribution data would require that the whale data have a spatial resolution and accuracy better than the 1.1 km AVHRR value. The whale data would also have to be collected simultaneously with the corresponding satellite image. Aerial survey data do not meet these conditions and coverage is too incomplete to permit comparison with the distributions of mesoscale oceanographic features. Moreover, the effort required to obtain whale distributional data with sufficient frequency to allow definitive testing of the hypothesis that whale distribution is related to the distribution of mesoscale features would be large and difficult to justify in view of other evidence (Borstad 1985) that whales tend to congregate at the strong gradients associated with easily-identifiable front structures.

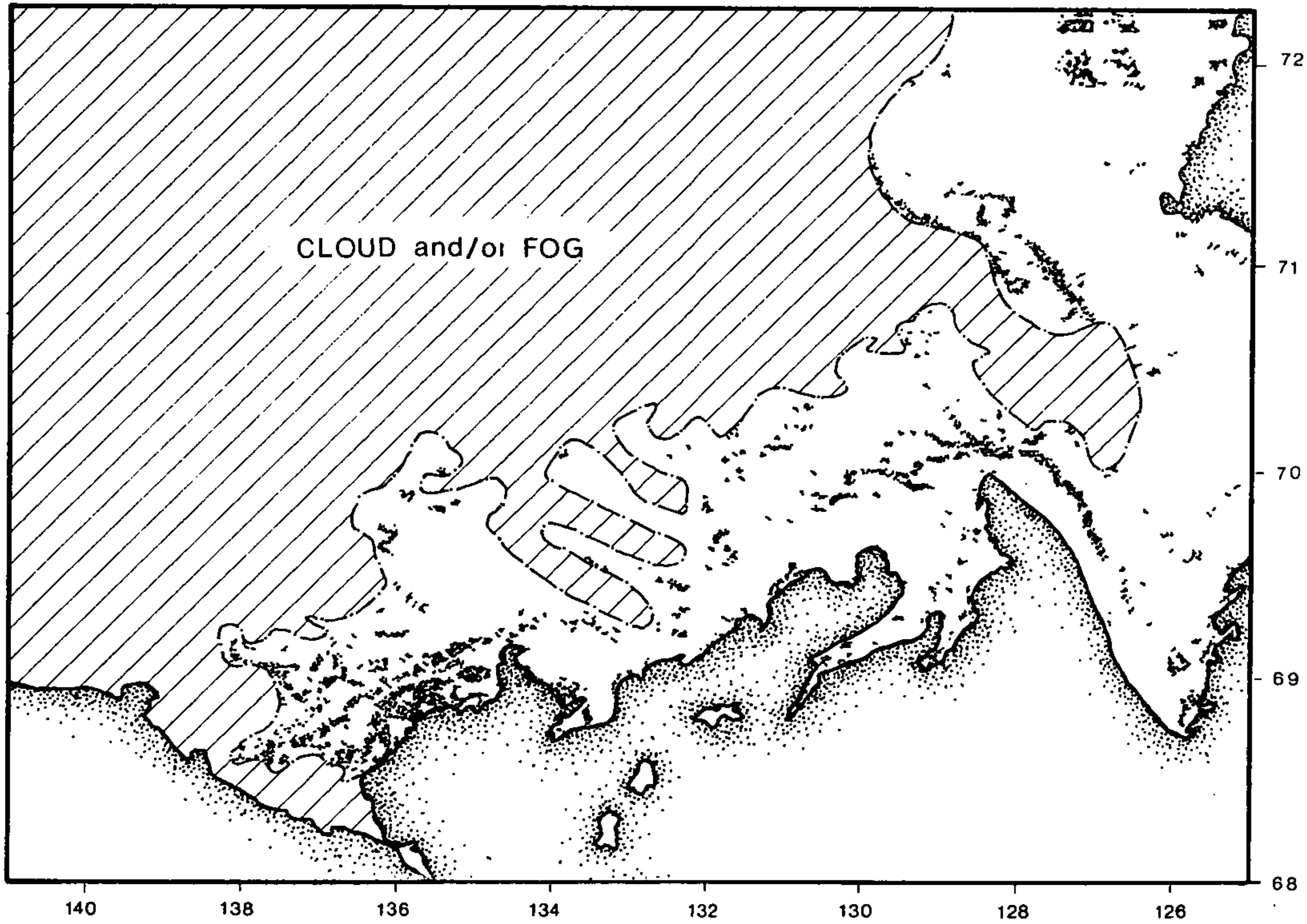

Figure A. A plot of all pixels having maximum AVHRR Band 4 radiance values differing by eight or more levels from values recorded at a neighboring pixel for the image of 6 August 1981. The shaded area excludes ice- and cloud-covered areas and differs from the mask used in Figure 15d, primarily through the additional exclusion of the finger-like areas of light cloud between longitudes 132 and 135. The plotted pixels reproduce much of the waterbody boundaries identified in Figure 15d.