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EARTH RESOURCES TECHNOLOGY SATELLITE OBSERVATIONS OF HIGH LATITUDE ESTUARINE CIRCULATION

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ABSTRACT

Sea surface circulation in Alaskan coastal waters can be monitored effectively using Earth Resources Technology Satellite (ERTS) imagery. Turbid river waters and ice have proven to be excellent tracers for such studies. In the summer, runoff from the recently deglaciated hinterland carries large quantities of fine sediment which may remain in suspension at the surface throughout the estuarine zone and often beyond the shelf. When runoff is restricted during the winter, ice preferentially forms from the fresher waters at the heads of estuaries and it, too, follows the trajectory of the outflowing waters. ERTS imagery in the MSS 4 or 5 Bands (0.5-0.6 or 0.6-0.7 mμ) clearly shows the turbid waters; the MSS 7 Band (0.8-1.1 mμ) readily distinguishes floating ice.

ERTS studies of Cook Inlet, a large estuary in southcentral Alaska, have clarified the complex local circulation regime. Cook Inlet is a long, shallow estuary with high amplitude mixed tides. Currents, tidal bores, shoaling, and weather make Cook Inlet an extremely difficult area to study. Conventional oceanographic techniques cannot remotely provide synoptic coverage of the inlet. The circulation pattern becomes intelligible, however, when standard techniques are combined with satellite observations. The circulation is tide-forced with considerable Coriolis influence, resulting in a marked counterclockwise movement of water in the lower inlet. An area in the southeast Bering Sea near Nunivak Island has been studied to illustrate the use of sea ice as a tracer of current patterns. Similar satellite observations of high latitude circulation are useful to predict sediment and pollutant trajectories and to evaluate coastal engineering parameters in inaccessible sites.

INTRODUCTION

Coastal environment studies—particularly on sparsely-settled high latitude shorelines—often must depend upon very scanty field observations. In particular there is rarely adequate data on such critical features as estuarine current patterns which by customary methods require careful observation over a considerable length of time. Pressure upon such coastal areas as potential sites for population centers, for fisheries exploitation (both commercial and recreational), and for a wide variety of industrial developments is growing rapidly in both North America and Europe. Currently engineers are being forced both to design coastal construction and to evaluate environmental impact on the basis of very little factual data, using criteria developed for more temperate zones. Both oceanographic and geomorphologic factors may be significantly different in high latitudes, particularly due to low temperatures (which may cause fluvial or sea ice), highly seasonal hydrologic regimes, or a geologic history of contemporary or very recent glaciation in the hinterland.

Satellite images of the earth's surface are one of the more promising current technologic developments which permit the study of large-scale or remote areas. The utility of such imagery in meteorologic studies of weather patterns and the overall distribution of sea ice has been well established and is now in routine use (1, 2). Unfortunately, until very recently there were no civil satellites with resolution capabilities suitable for coastal engineering studies. The new Earth Resources Technology Satellite (ERTS) launched in August of 1972 definitely has such potential. This paper is a review of the application of ERTS imagery to estuarine circulation studies in Alaska and a discussion of its utility in delineating surface circulation patterns in unstudied areas.

THE ERTS SYSTEM

The ERTS satellite follows a roughly circular polar orbit at an altitude of 914 km, making a complete revolution every 103 minutes (3). The orbit is adjusted to be sun-synchronous, so that imagery of a given point on the surface is obtained at the same local time each pass. The orbits precess slowly about the earth to permit coverage of the entire earth's surface every 18 days. Overlap of successive orbits is approximately 14% at the Equator and as much as 60% in high latitudes. The satellite contains three different systems, one a telemetering data collection system, the other two direct imaging systems. One of these imaging systems, the Return Beam Vidicon, became inoperative soon after the launch but the other, a Multispectral Scanner, has now functioned effectively for over a year. The Multispectral Scanner (MSS) system produces simultaneously four images of the Earth's surface by the analysis of carefully filtered reflected light. Each image is 185 km square, approximately 34,000 km^2, and the resolution limit—dictated by the system's optics—is 79 m. The four simultaneous images are all from the visible and near-infrared, including MSS 4 (0.5-0.6 μm), MSS 5 (0.6-0.7 μm), MSS 6 (0.7-0.8 μm), and MSS 7 (0.8-1.1 μm).

Three MSS Bands have proven to be particularly useful in studies of estuarine circulation patterns: MSS 4 and 5, in the blue-green portion of the spectrum which best penetrates water, and MSS 7, the near-infrared band which has no penetration of water (4). The imagery is available either as it is transmitted from the satellite in digital form or as photographic images somewhat analogous to television pictures. The only major problem with the system is weather–since it functions in the visible spectrum, cloud cover completely nullifies ERTS observations. Roughly 75% of the earth's surface has been imaged at least once and repetitive coverage is available for many areas. The satellite was designed and launched by the U.S. National Space and Aeronautical Agency and ERTS imagery is available to the public–internationally–through the U.S. Department of the Interior, Earth Resources Observation Systems Data Center.

NATURAL TRACERS OF HIGH LATITUDE CIRCULATION

There are, of course, two fundamentally different approaches to studies of natural water movements. One may either remain stationary and with some sort of metering device measure the passing waters or one may directly follow the path of some specific parcel of water. For construction design criteria or quantitative studies of sedimentation, the first philosophy must be adopted. For an understanding of general circulation patterns, particularly as they may apply to sediment or pollutant trajectories, it is necessary to take the second approach. This requires the use of some sort of tracer–often a drogue that may be tracked from shipboard or some distinctive substance that can be used to label waters–for example, from the vicinity of a single sewage outfall. Many materials have been used as tracers, usually bright colored or ultraviolet fluorescent dyes, but it is obviously better where possible to use some natural characteristic of the waters that can readily be identified as a tracer. Unusual minerals, natural oil seeps, and various other components of the environment have been used in various places (5), but in high latitudes we are fortunate to have two very distinctive, completely non-injurous natural tracers–highly turbid river waters and both fluvial and sea ice.

Turbid River Waters

Most of the rivers and streams in high latitudes flow from terrains that either are presently glaciated or were in the recent geologic past. Because of the nature of glacial erosion, such streams often carry large loads of finely divided rock debris, the so-called "glacial flour." Concentrations of this material can be very high indeed, and have been measured at over 10,000 mg/l in a turbid meltwater river (6, 7). These turbid waters enter the sea where they may persist for considerable time and distance of travel. The suspended sediments may or may not flocculate upon mixing with sea water, but often the floccules formed may have a very low density and hence a slow settling velocity. The result is an excellent natural tracer to the movement of fluvial waters at the sea surface. Depending upon the conditions in an individual estuary, the turbid waters may be spreading as only a thin surface film a few meters or centimeters thick or the waters may be well mixed, as an estuary of vertically homogenous circulation, in which case the surface expression characterizes the entire water column (7). Whichever situation occurs, turbid waters on the surface are an excellent tracer for many pollutants such as industrial and domestic liquid wastes, which tend to stay at the surface for they are usually of lower specific gravity than the receiving waters.

Sea Ice

In many high latitude estuaries the ice that appears on the surface is not strictly sea ice. It actually forms largely in tributary rivers or from the fresher water lens at the surface of the estuary. True sea ice will form later in the season, and of course in the true Arctic land-fast ice may completely cover the sea surface. Under less extreme climatic conditions, particularly where there is significant tidal amplitude, the ice in estuaries may remain in a state of flux throughout the winter and thus—during the season of minimal runoff—can constitute an alternate tracer to the movements of the surface waters. Even in embayments quite well clogged with ice, streamlines of flow will show in the ice surface which reflect water currents. In the open ocean such estuarine ice may still function as a reliable tracer to water movements, for often sediments will become incorporated in the ice and very distinctly mark the inshore ice masses (9). This effect is particularly noticeable in the spring when melting at the headwaters of Arctic rivers may cause floods of turbid water to spread over the ice down stream (8, 9). Unfortunately, ice has some serious drawbacks when used for circulation studies. Depending upon its thickness it may be very sensitive to movement by local winds or, in the case of thicker, more massive blocks such as ice islands, it may be influenced by deeper currents. Caution must then be exercised when interpreting circulation solely from ice patterns.

ALASKAN COASTAL CIRCULATION

Two areas from the Alaskan coast have been selected to demonstrate the application of ERTS data to the study of inshore circulation (Fig. 1). These areas were selected not because they were typical but because good imagery was available and they show certain features of the circulation patterns in a dramatic fashion. Cook Inlet is a large, enclosed estuary on the Pacific coast. It drains a mountainous hinterland of active deglaciation and the routine suspended load in the waters of the inlet is among the greatest in the world. Large amplitude tides combined with a very considerable runoff produce a striking circulatory regime (10, 11). Farther west, on the Bering Sea coast, lies the Nunivak Island area. Tidal circulation is relatively mild here, but turbid drainage from the nearby Kuskokwim River and sea ice for half the year produce another outstanding example of circulation which can be observed with satellite imagery.

Cook Inlet

Cook Inlet is one of the world's most dramatic examples of tide-forced circulation. The inlet is relatively large, roughly 270 km long and averaging 45 km in width, with an average (low tide) depth of approximately 40 m. The maximum depth observed is 137 m, and there are extensive mud flats developed in the upper inlet. The tidal amplitude is among the greatest in the world, averaging over 6 m throughout the inlet and, on Spring Tides, exceeding 12 m in the upper inlet. The tides are typically of mixed form with both diurnal and semidiurnal components. A tidal bore, sometimes over two meters, may appear in Turnagain Arm, a branch of the upper inlet, and the situation is so complex at Anchorage that 140 tidal constituents were necessary to calculate a tide curve (10). As might be anticipated in so shallow an estuary with high amplitude tides, the tidal prism represents a significant percentage of the water volume, estimated to be as high as 10%. As well, there is considerable drainage into the inlet, particularly during the summer, but continuing to some degree throughout the year. Currents in the inlet are strong, and have been reported to routinely exceed 4 m/s, ranging upward to 7 m/s. The size and the navigation problems of Cook Inlet make it very difficult to survey by conventional oceanographic procedures. A typical series of observations of water characteristics in the inlet are shown in Figure 2. Notice that it required four days to complete the study, but that—as is customary in reporting oceanographic data—values for the major characteristics are displayed as if all the data were collected simultaneously. In such an actively circulating region as Cook Inlet, this "synoptic assumption" verges upon the ridiculous. One of the prime benefits of satellite imagery is that it can obtain an instantaneous picture of the circulation of such a large, complex area. Only surface water characteristics are shown, but repeated sampling in the inlet has demonstrated that the waters are relatively well mixed—in a vertical sense—throughout. The salinity and particularly the suspended sediment plots show well the general circulation scheme of the inlet, with tide-driven, coriolis-directed currents of "fresh" sea water entering the inlet on the east and turbid, brackish waters departing on the west. The constriction just north of Kenai divides the upper and lower inlets and is the site of strong and often very confusing currents.

A superficial study of ERTS imagery in the MSS 4 Band of Cook Inlet shows us a number of major features (Fig. 3). A boundary between incoming and outgoing currents is very clear, and surface observations demonstrate that it corresponds to an effective concentration of 3-4 mg/l of suspended sediment in the water. In the image, this limit can be seen along the eastern shore between Cape Ninilchik and Kenai. It can also be clearly distinguished between Ushagat and Augustine Island at the southern margin of the scene. The quality of the print does not permit discrimination of finer features of the shear zone at the boundary, but these can be seen well in comparisons of the MSS 4 and 5 imagery, and are particularly prominent in color-coded, density sliced versions of these views. In the upper inlet, the broad tide flats of Turnagain Arm south of Anchorage can be seen, as well as indications of shoaling at the mouth of the Susitna River to the west. On these prints the upper inlet appears to have a very high, homogenous turbidity. The suspended load is extremely high—routinely over 100 mg/l—but distribution is not nearly as uniform as the images and data shown in Figure 2 would indicate. Instead—as is shown in certain of the density sliced imagery—the prime source of suspended material is Knik Arm, north of Anchorage, and the Susitna River is actually a source of relatively clean water. This demonstrates that the turbid water may be used here as a natural tracer for pollutants from the Anchorage metropolitan area.

An enlarged view of the lower inlet (Fig. 4) taken from MSS 5 imagery shows many interesting features. This shows the situation just after the tide has turned and has begun to flood strongly at Homer. The terminus of the clean sea water lens lies near Cape Ninilchik with apparent interdigitation of the water masses. To the west, in the middle of the inlet, a mushrooming gyre has formed in the shear zone between the water masses. Clouds obscure much of the data, but towards the south off Cape Douglas the outflowing turbid water is very clear. This material appears to remain in suspension for a considerable time after it exits Cook Inlet. Much of it passes through Shelikof Strait between the mainland and Kodiak Island and then is finally carried across the shelf to be dumped in the Aleutian Trench. If—as is probable—this is sediment originating at the head of Cook Inlet north of Anchorage, the total pathlength of the suspended material in the coastal waters would be over 600 km.

Nunivak Island and Etolin Strait

As an example of the use of sea ice as a tracer of coastal currents, Figure 5 shows an MSS 7 composite made in May of 1973 near Nunivak Island. The MSS 7 imagery does not penetrate the water surface at all, but it defines clearly the coastline and also shows the ice surface more clearly than the shorter wave length imagery. This area lies in the eastern Bering Sea between the mouths of the Kuskokwim and Yukon Rivers. Circulation in the area is influenced by a variety of factors, including a general northward drift of surface waters towards Bering Strait and the Arctic Ocean (12). This flow is considerably reduced during the winter, and relatively local wind-driven currents may produce current reversals in the shelf area bounded by Nunivak Island and the Pribilofs. Tidal amplitudes in the region are relatively low, usually less than 2 m and the tidal component of the currents is slight. Particularly important throughout the year are transitory, basically storm-driven effects that can produce wild fluctuations in both direction and velocity of circulation. Water depths throughout the area (shown in the figure) are never greater than 40 m and the deepest part of Etolin Strait is less than 35 m. This means that wind-induced mixing and water movement may involve the entire water column. Only rather close inshore, within about 20 km, is there a consistent current. This flows to the northwest in all seasons, carrying coastal waters towards Bering Strait.

In May, when the ERTS image was obtained near Nunivak Island, over 50% of the sea surface was covered with ice. Most of the ice seen in this image is true sea ice formed offshore, but in this region, except for small areas of landfast ice at the shores, the ice remains mobile as discrete, fractured floes. The largest floes in the view, north of Nunivak, are on the order of 20 by 18 km, roughly 300-400 km^2, but the vast majority have an irregular, rounded form and do not exceed a few square kilometers in area. Also visible, particularly in Etolin Strait, are what appear to be "wisps" of ice. These are patches of fragmented smaller floes, mostly with maximum dimensions of a few meters and ranging up to a few tens of meters. Such features are technically below the resolution capability of the ERTS system, but particularly on the MSS 7 images, such ice contrasts so strongly with the surrounding water that these areas can readily be distinguished. In the MSS 7 image, suspended sediment does not show, but a north-flowing turbid current can be seen clearly on the MSS 4 and 5 views at the eastern side of Etolin Strait. Very faintly, in the streamlines of small sea ice fragments, the shear zone at the western margin of this current can be seen in this view. At the instant when the ERTS image was obtained near Nunivak, the dominant features of the circulation regime included a general surface drift from the northwest produced by a continuing high pressure area centered 300-400 km to the southwest and there was a brisk local surface wind from the northeast. The offshore current is counter to the normal current here through the year. Direct wind influence upon the ice would have tended to move it toward the west. The effects of both these forces can clearly be seen in the imagery. Nunivak Island appears to show a "bow wave" of ice piling up to the north with clear water in its lee to the southeast. The effect of the local wind has been to move ice off the southwest shore of the island. Close to the mainland, the persistent northward current carrying turbid waters from the Kuskokwim continues.

APPLICATION OF SATELLITE DATA TO HIGH LATITUDE CIRCULATION PROBLEMS

Where ERTS imagery is available for high latitude regions, clearly it can be most useful for studies of surface circulation patterns. Turbid fluvial waters in the summer and sea ice in the winter provide excellent tracers to the movements of the water. Although it is patently impossible to derive a full understanding of a three or four dimensional phenomenon such as ocean circulation from two dimensional information, careful comparison of satellite imagery and surface data from conventional techniques has demonstrated in Alaska the general utility of such observations for at least the first approximation of many critical features of the circulation. These data can be applied to the solution of a wide variety of engineering and environmental problems.

Environmental Impact Studies

Circulation patterns deduced from ERTS imagery are particularly useful for studies of the potential trajectories of pollutants. Cook Inlet is a particularly clear example of this application, since the major sources of suspended sediment lie immediately in the vicinity of Anchorage, the primary source of both industrial and domestic wastes in the state (13). Upper Cook Inlet is presently an area of active petroleum production, and drilling rigs, pipelines and loading facilities are scattered both in the inlet and ashore. Particularly in the winter when large masses of ice move in the complex currents of the inlet there are many opportunities for accidental spills. Such an accident occurred at Drift River on the west shore of the inlet in December of 1967 and very little could be done to predict or control the movement of the slick. Now, because of ERTS observations and related studies, we can predict the most probable trajectory of such a pollutant in the inlet with some precision. Monitoring of spills in remote areas can probably be accomplished (14). ERTS imagery may be used in the same fashion in other, unstudied areas where there are turbid waters or sea ice to serve as tracers. Without additional information in an unfamiliar area it would be impossible to predict velocity, but most probable direction of transport and potential areas of dispersion or concentration can readily be distinguished. Such information can be very important when development is planned for areas in which there may be large populations of wild fowl or marine mammals susceptible to damage from pollutants.

Coastal Engineering Studies

When docks and other shore facilities are needed, it is essential to understand the local oceanographic climate. Satellite observations will never completely replace field studies, but many critical features that cannot be assessed effectively in a brief visit can be deduced from a study of satellite imagery. Directions of littoral drift, areas of potential shorefast ice or places where floes may be impounded, and probable areas of erosion or siltation can be identified, once the basic circulatory regime is understood. As well, ERTS images can be most useful in the initial evaluation of a proposed facility, for their scale encourages the integration of plans into their appropriate regional context.

Navigation and Coastal Piloting

The ability of ERTS imagery to define even very subtle current patterns in coastal areas can be of great importance to the transportation industry. Barge traffic and log booms, in particular, often travel at no more than a few knots and any favoring or adverse current can be of considerable importance. In Cook Inlet, where tidal currents often exceed the speed of much marine traffic, mariners had deduced the basic pattern long before there were satellite observations. Now, however, by use of the ERTS imagery, we are able to fill in much detail which was unknown, particularly the complex area near the Forelands which often was run in the past only under optimum conditions. Details such as the persistence of the northward inshore current through Etolin Strait, even though all the offshore circulation was temporarily to the south, can be most useful in planning routes. In the High Arctic, ERTS imagery can be used to assess ice conditions, and to monitor the development of open waters or thin ice for icebreaker or icebreaking tanker operations. In many parts of the Arctic permanent or semi-permanent leads persist throughout the winter, and are essential to the ecology of the resident marine mammals. Routing may be planned either to take advantage of such areas or to avoid them entirely.

CONCLUSIONS

The ERTS system can provide much useful information about high latitude estuarine circulation. Current patterns may be distinguished in considerable detail from the distribution of suspended sediment plumes during the runoff season and from sea ice patterns in the winter. Satellite imagery is particularly useful to supplement field data in areas where it is difficult or impossible to maintain observers. Much basic information significant to environmental and coastal engineering studies and to navigation and the transportation industry can be deduced from ERTS imagery.

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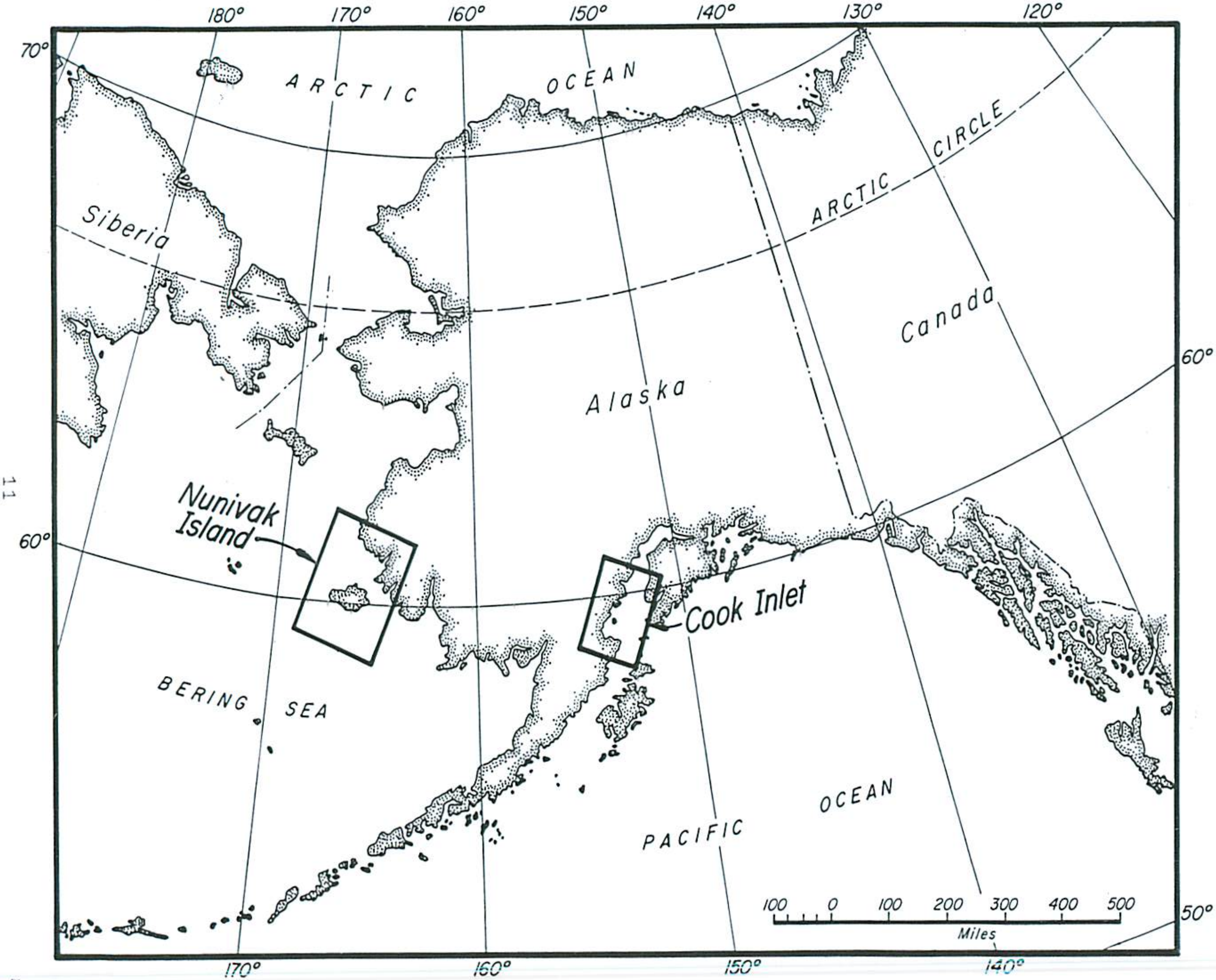
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ARCTIC
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Cook Inlet
BERING SEA
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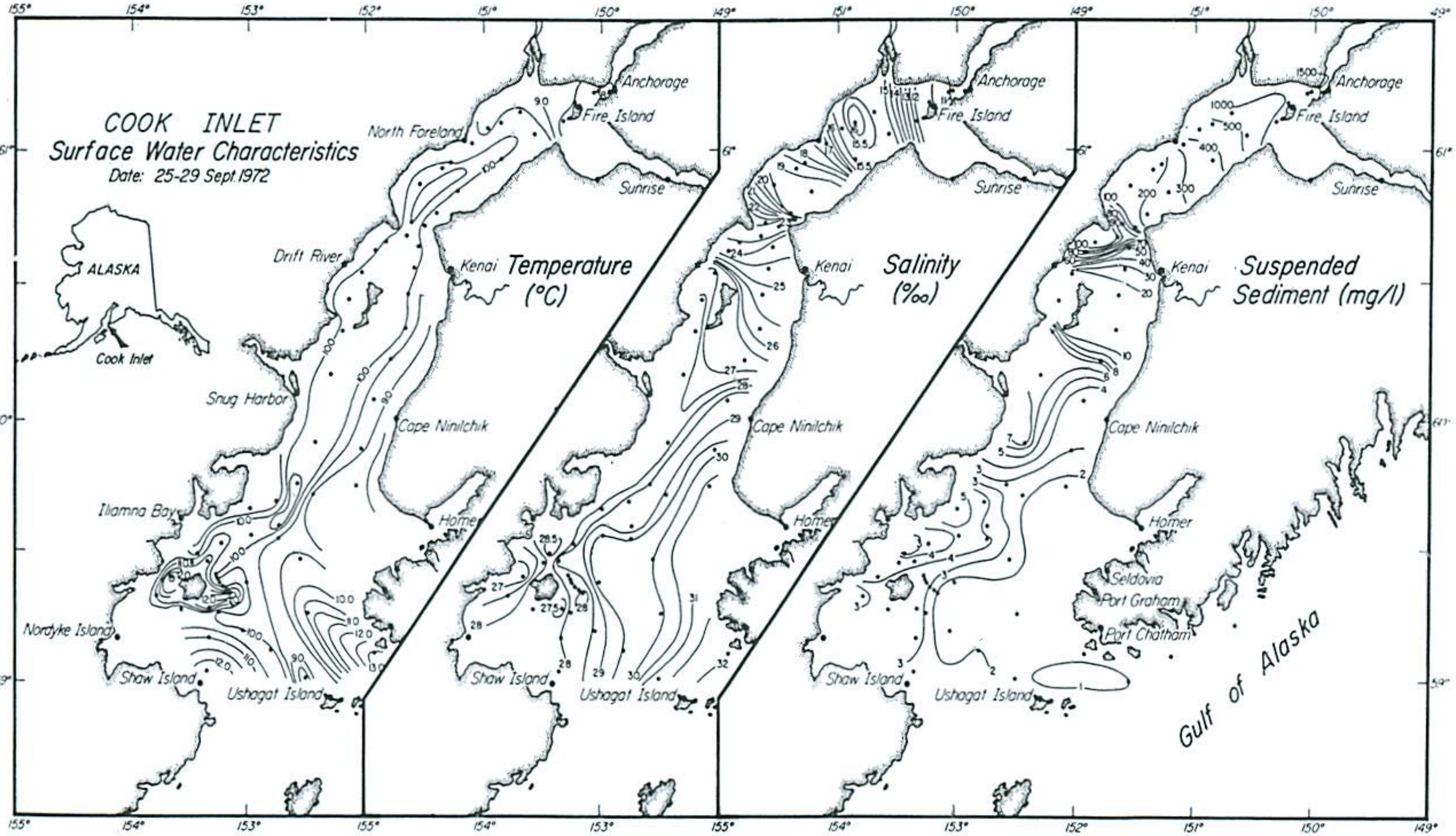
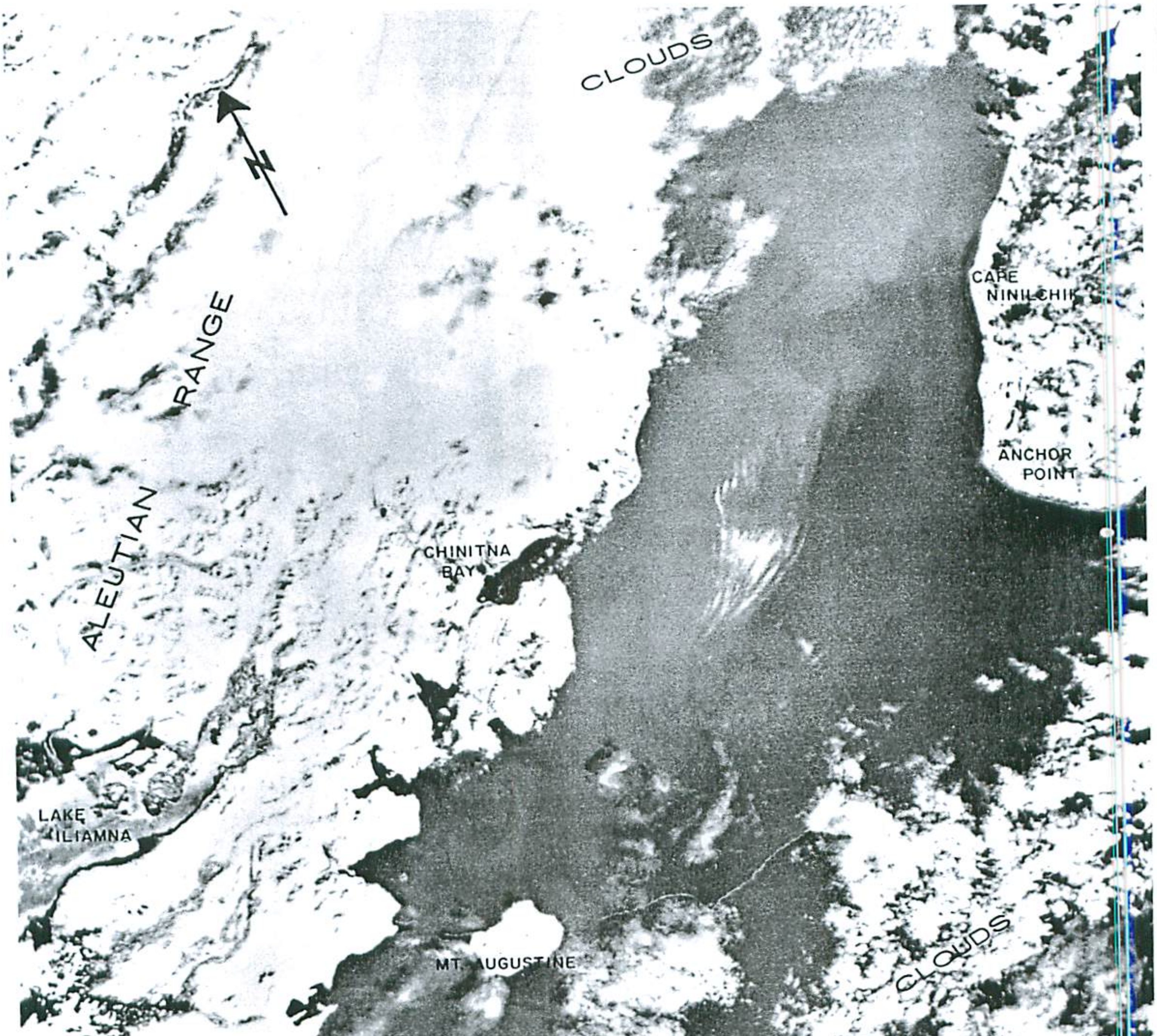

COOK INLET
Surface Water Characteristics
Date: 25-29 Sept. 1972
ALASKA
Cook Inlet
Temperature (°C)
Salinity (‰)
Suspended Sediment (mg/l)
Anchorage
Fire Island
North Foreland
Sunrise
Drift River
Kenai
Snug Harbor
Cape Ninilchik
Iliamna Bay
Homer
Nordyke Island
Shaw Island
Ushagat Island
Seldovia
Port Graham
Port Chatham
Gulf of Alaska


SUSITNA RIVER
ANCHORAGE
WEST FORELAND
DRIFT RIVER
EAST FORELAND
KENAI
ALEUTIAN RANGE
KENAI MOUNTAINS
HOMER
MT. AUGUSTINE
0 SCALE 50
Kilometers
BARREN ISLANDS


CLOUDS
N
ALEUTIAN RANGE
CAPE NINILCHIK
ANCHOR POINT
CHINITNA BAY
LAKE ILIAMNA
MT. AUGUSTINE
CLOUDS
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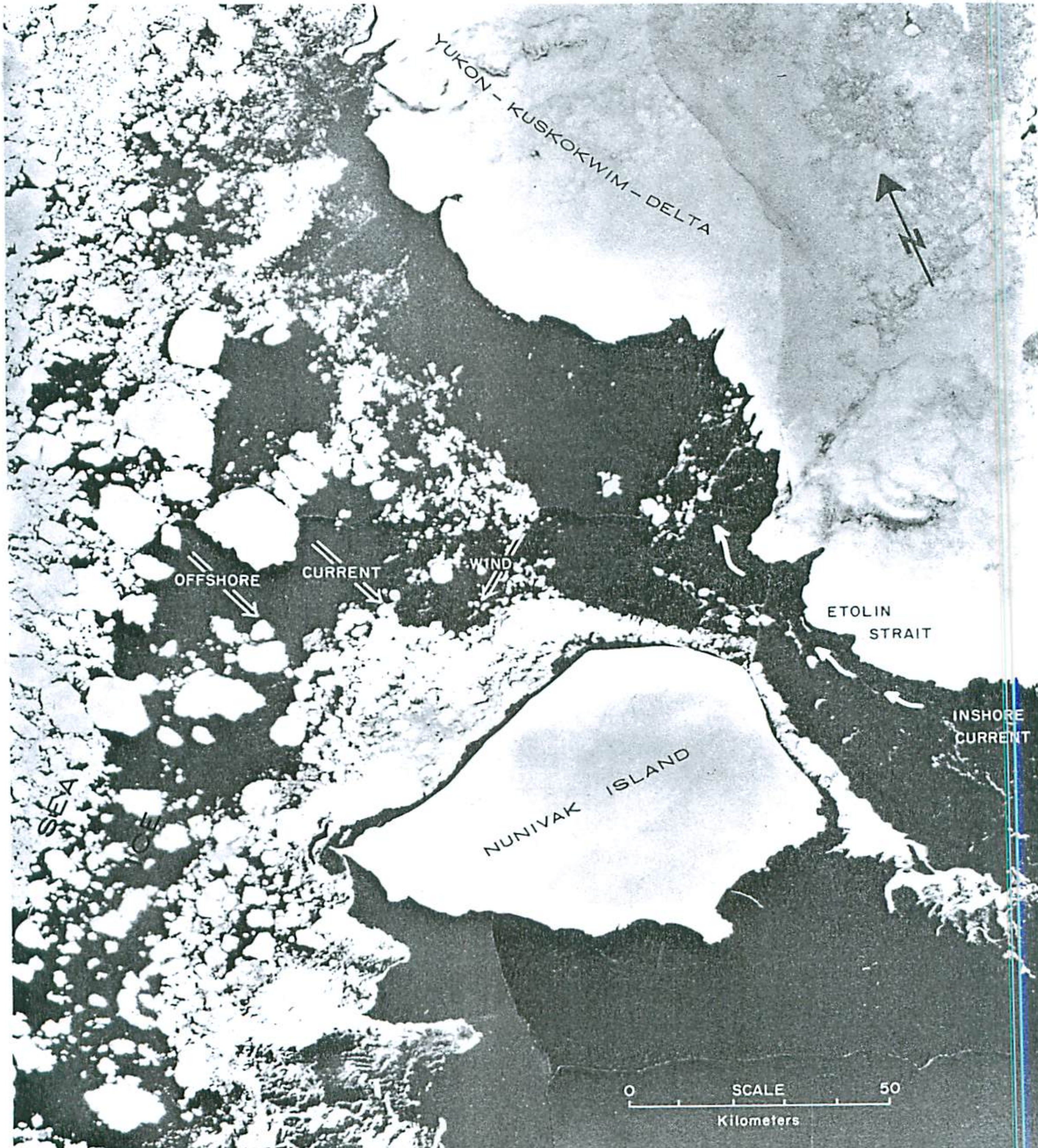
Kilometers
CAPE DOUGLAS


YUKON - KUSKOKWIM - DELTA
OFFSHORE
CURRENT
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ETOLIN
STRAIT
INSHORE
CURRENT
NUNIVAK ISLAND
SEA ICE
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Kilometers