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Satellite and Oceanographic Observations of the Warm Coastal Current in the Chukchi Sea

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ABSTRACT. Selected infrared images obtained by the NOAA satellites have increased our understanding of the formation and extent of the Alaskan Coastal Current, a movement of relatively warm water from the vicinity of Bering Strait northward along the Alaskan coast past Point Barrow and eventually into the Arctic Ocean where it disperses. Oceanographic measurements made from an icebreaker during the same period give spot checks on the depth of the warm layer, as well as the outline of a downward trend of the current when it is blocked by the ice. A study of satellite and oceanographic observations over a seven-year period, 1974-1980, reveals many interesting features of the flow and shows the annual variability. The northward flow and the shape of the ice edge are interrelated in that the flow is partially blocked by the ice and the ice is melted by the oncoming warm water. The solar-heated waters in Kotzebue Sound, Norton Sound, and along the coast to the south are seen as a major source of the heat in the coastal current.

Key words: satellite, infrared, temperature, current, ice edge, eddies, oceanography, Chukchi Sea, Bering Strait

RÉSUMÉ. Certaines images infra-rouges obtenues par des satellites NOAA ont accru notre compréhension de la formation et de l'étendue du courant côtier de l'Alaska, un mouvement d'eau relativement chaude partant des environs du détroit de Béring, longeant en direction nord la côte de l'Alaska, passant par la pointe de Barrow et se dirigeant éventuellement dans l'océan Arctique où il se disperse. Des mesures océanographiques prise à bord d'un brise-glace durant la même période donne des prises intermittentes de la profondeur de la couche chaude, ainsi que le profil de la tendance descendante du courant lorsque la glace lui barre le chemin. L'étude des observations océanographiques et de satellites recueillies au cours d'une période de sept ans, de 1974 à 1980, révèle de nombreuses particularités intéressantes du courant et signale sa variabilité annuelle. Le courant vers le nord et la forme du bord de la glace sont reliés l'un à l'autre de sorte que le courant est en partie entravé par la glace et la glace est fondue par l'arrivée de l'eau chaude. Réchauffées par le soleil, les eaux des détroits de Kotzebue et de Norton et du long de la côte plus au sud sont proposées comme sources majeures de chaleur dans le courant côtier.

Mots clés: satellite, infra-rouge, température, courant, bord de la glace, remous, océanographie, mer Chukchi, détroit de Béring

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INTRODUCTION

A study of satellite imagery and synoptic oceanographic measurements reveals interesting properties of the flow of warm, less saline water through Bering Strait and along the northwestern coast of Alaska. This flow is especially pronounced in the summer. Along the coast, where the flow is strongest, it is referred to as the Alaskan Coastal Current. Before addressing specific observations, a review of the measurements of the current and the oceanographic changes produced by it is desirable.

Current measurements in the vicinity of Bering Strait from 1964-1973 are summarized by Coachman *et al.* (1975). They estimated a summer transport averaging about 1.5 Sv (10^6 $m^3 \cdot s^{-1}$) northward which appears to coincide with a generally northward-sloping sea level. They gave evidence of a correlation between the current through the strait and the air pressure difference between Barrow and Nome. Theories about the cause of the flow have been discussed by Gudkovich (1962) and by Coachman and Aagaard (1966). Additional measurements made by Coachman and Aagaard (1981) of current across a section from Cape Lisburne to Siberia revealed a considerable southerly flow in the winter and a generally weaker flow in the western half of the section.

The Coastal Current was observed by Paquette and Bourke (1974) along the northwest coast of Alaska, and by Hufford (1973), who noted its eastward extension around Point Barrow to 147°W. Paquette and Bourke (1981) studied the interaction between the warm flow and the ice edge along the outer boundaries of the current. Garrison *et al.* (1973) observed strong currents along the coast near Point Barrow in August and found that branch flows to the north resulted in large masses of 8-10°C water in the central Chukchi Sea.

Satellite imagery often provides a synoptic view of coastal changes. Selected imagery from the period 1974-1980 shows the formation and dispersion of the Alaskan Coastal Current. Most of the satellite data used in this study are derived from satellites whose orbits passed near the pole and which had daily simultaneous coverage in the visible and infrared wavelength bands.

The Applied Physics Laboratory, University of Washington, has been conducting oceanographic surveys in the Arctic since 1971 (Garrison and Pence, 1973). Several icebreaker cruises through the Bering Strait and into the Chukchi Sea (Garrison and Becker, 1975), followed by ice camps on drifting floes, have provided the opportunity to study the changes in the water properties caused by the coastal flow. Helicopters have been used along with a lightweight conductivity-temperature-depth (CTD) probe to gather data quickly in a short period (Garrison and Paquette, 1982). The warm intrusion has been monitored through October as far north as latitude 73°N.

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SATELLITE IMAGERY

The satellite imagery used in this study was derived from the National Oceanic and Atmospheric Administration (NOAA) series of environmental satellites. The system became operational for direct readout in Alaska in early 1974. For 1974-1978, we used imagery from a very high resolution radiometer (NOAA-VHRR) which gave daily, simultaneous coverage in the visible (0.6-0.7 μm) and infrared (10.5-12.5μm) wavelength bands. For 1979 and 1980, we used imagery from the four-channel advanced VHRR (AVHRR) series of both the TIROS-N and NOAA-6 satellites with an IR channel in the 10.5-11.5 μm band. The ground resolution of both the visible and IR bands is about 1 km at nadir (0.9 km for the VHRR and 1.1 km for the AVHRR). One frame can cover the entire Bering Sea or the Chukchi Sea and the Beaufort Sea combined.

In this study, all surface temperatures based on satellite imagery were derived from brightness temperature, which is related to intensity of radiation in the IR band. The spacecraft radiometers were calibrated at 100% efficiency before launching (Lauritson *et al.*, 1979). The TIROS/NOAA radiometers are routinely calibrated at intervals during their orbits, and a correction for decreasing efficiency is made for each orbit. The satellite data are recorded on magnetic tape with a temperature resolution of about 1°C. A bias is sometimes produced in the brightness temperature by the intervening atmosphere. Over widespread water areas where the moisture content is high, the actual surface temperature can be up to 2°C higher than the brightness temperature recorded by the satellite. We were unable to correct for the atmospheric effect. However, in the Arctic the moisture content is generally low and our satellite data were chosen from periods of low cloudiness; thus the atmospheric errors were probably less than 2°C. For some comparisons in the Bering Sea, the satellite brightness temperatures have agreed closely with oceanographic measurements, indicating that the atmospheric effect was negligible.

A standard IR image consists of 32 gray tones that represent a wide temperature range. For more detail and contrast, the entire gray scale is enhanced to cover only the temperature range expected for the feature of interest (Jayaweera, 1976). Temperatures above and below this range are shown as black and white, respectively; the temperatures between are shown in gradated shades of gray. Each gray shade on the image corresponds to a specific temperature. Along one edge of the image is a scale giving the gray shades for the 32 temperatures covered. For even greater detail, multiple enhancements can be used, especially for large geographic areas with many temperature regimes.

The usefulness of satellite data in revealing the structure of the surface temperature field of the ocean has been demonstrated by Royer and Muench (1977), who supplemented their study of the ocean surface temperature distribution in the Gulf of Alaska with NOAA-VHRR satellite imagery, and by Ahlnäs (1979) who applied satellite IR enhancement techniques to identify water masses and the origin of oceanic eddies.

In this study, the gray scale of selected images was enhanced in the IR band to show some features related to the warm coastal current. The temperature enhancements and photographic work were performed at NOAA's National Environmental Satellite Service (NESS) Tracking Station at Gilmore Creek, Alaska, using radiometer corrections relevant to each individual pass. At Gilmore Creek, the satellite negatives are continually monitored to maintain consistency in the gray scale. To determine temperature, a photographic densitometer was used to compare the gray shades of each IR image with the accompanying 32-tone gray scale. Numerous densitometer readings were made and averaged for each area of interest.

OBSERVATIONS OF COASTAL WATERS

Spring Conditions

In late winter the Bering Sea is ice-covered, with the southern boundary of the ice lying somewhere between St. Matthew Island and the Pribilof Islands (Muench and Ahlnäs, 1976). Figure 1, a typical satellite view, shows that north of 59°N the ice cover was nearly complete although fragmented. Measurements (Garrison and Becker, 1975) in March 1973 in the Bering Sea during an icebreaker cruise from Adak toward Lawrence Island showed an extremely uniform water column with temperature gradually decreasing from 3°C to 0°C going north. A cold upper layer of near-freezing water with salinity near 33 ‰ appeared near the ice edge. This layer became thicker until at 62°N it occupied the entire 100-m column of water.

In the shallow Chukchi Sea, the water column is near the freezing point, about −1.8°C. The higher-salinity water formed by salt displacement during freezing in the shallower areas settles along the bottom and moves down the Barrow Canyon (Garrison and Becker, 1976). In May, openings (polynyas) are often produced along the Alaskan coast by the prevailing easterly winds (Fig. 2) and this allows some solar warming of the coastal waters.

Warming in the Sounds Adjacent to Bering Strait

During May the Bering Sea ice edge recedes rapidly northward, and by June the sea is essentially ice-free (Muench and Ahlnäs, 1976). Freshwater from the Yukon River provides a low-density surface layer which absorbs the solar heat and gradually mixes with heavier water below.

A satellite image taken in late June 1979 (Fig. 3) shows the areas where warming has occurred. The image is a multiple enhancement showing three temperature regions. The warmest waters (area A) are in the effluents of the Yukon and Anadyr rivers and around Kotzebue. The coldest water, area C, occupies the western part of the Bering Strait from St. Lawrence Island to the Chukchi Sea. Area B consists of a continuous water mass along the eastern side of the Bering Sea, which passes close to the east side of the Bering Strait and extends all the way north to a tongue surrounding Point Hope. Within each temperature area, the highest surface temperatures are dark and the lowest are light. A light gray color in area A is warmer than a dark gray in area B, although a dark shade within each individual area shows the highest temperature in

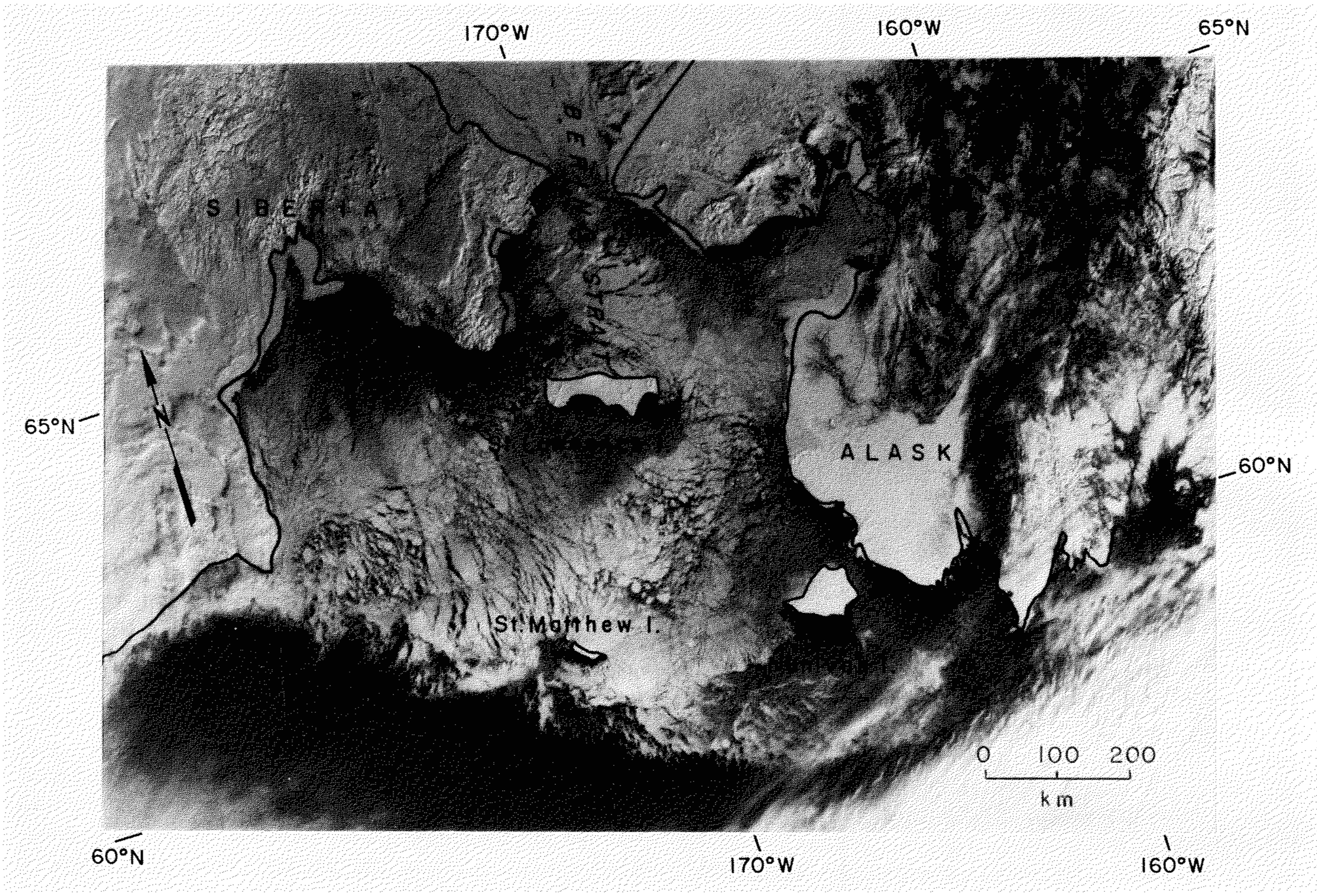


FIG. 1. Winter view of the Bering Sea ice cover, 18 March 1978. NOAA-5 satellite image in the visible band.

that specific area. Measurements by Lohrmann (1979) in June 1969 showed that the warm mass eventually extends nearly to the bottom. Later the warm mass builds up on the eastern bays, with the surface waters of most of Norton and Kotzebue sounds becoming warmer than 12°C in July. Patches of warm water are detected east of St. Lawrence Island, outside the Yukon delta, and in Ledyard Bay north of Cape Lisburne. A narrow, warm band stretches north from Cape Prince of Wales. During this time patches of cold water persist in the western part of Bering Strait.

Mid-July satellite imagery shows the warm water advancing farther northward. An IR image taken on 15 July 1977 (Fig. 4) shows a large mass of surface water east of St. Lawrence Island, with a temperature >9°C, which extends about 350 km in a north-south direction and about 100 km across. This large patch of warm water outside the mouth of Norton Sound appears to be one of the sources of the Alaskan Coastal Current. The satellite image also shows some bands of >9°C water which reveal the direction of flow: one narrow warm band less than 10 km wide extends 100 km north of Cape Prince of Wales; and three similar bands lie parallel to the coast southeast of Point Hope.

In late July 1975, a thick surface of warm water with a salinity of 31‰ was found during another icebreaker cruise through the Bering Strait (Fig. 5). An earlier station than those shown, near Nome, had a 12°C layer 10 m thick with a salinity of 24‰. An enchanced IR satellite image taken on 24 July 1975 (Fig. 6) confirms the hydrographic section. The warmest area in this picture, with a temperature of 12°C, is in Norton Sound. Outside the Yukon River delta the surface temperatures are 10-13°C.

Progression into Chukchi Sea

In mid-July the warm areas at the forefront of the intrusion north of Bering Strait indicate the advancement of the warm water. By this time in most years, a warm surface layer has usually formed beyond Point Hope and spread toward Wrangel Island.

A clear indication of northward flow can be seen in Figure 6, which shows three north-south-trending isothermal bands through Bering Strait. The band next to the Alaskan coast is warmest and extends from the Yukon delta past Wales. Farther north it joins the 7-8°C water extruding from Kotzebue Sound along the coast and around Point Hope to the ice band connecting Ledyard Bay with the ice edge. The ice edge is still far advanced; 1975 was a year of heavy ice.

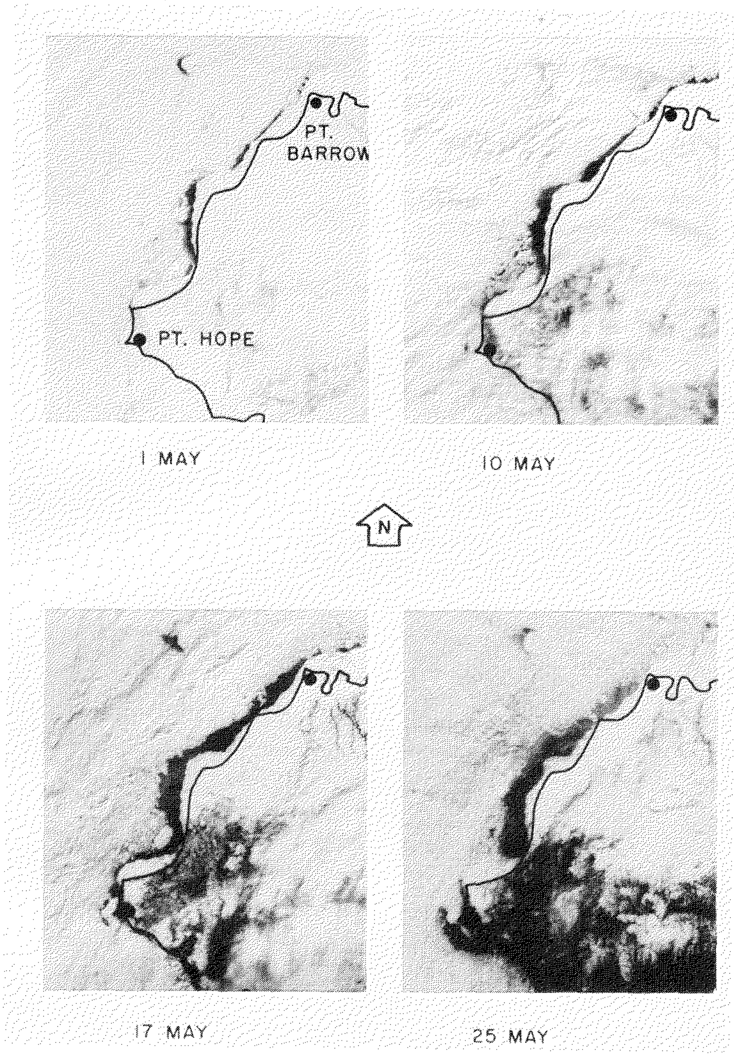


FIG. 2. Satellite images of the eastern Chukchi Sea in May 1977. The lead that opened in early May has become a large polynya by 25 May. NOAA-5 satellite images in the visible band.

In 1978 the intrusion was further advanced and the ice edge was farther to the north. The location of the ice edge in different years and annual variations in surface temperature are discussed later. According to IR satellite imagery on 15 July 1978, the waters were 13°C in Kotzebue Sound, decreasing to 10°C off Point Hope and 6°C in Ledyard Bay north of Cape Lisburne.

This advancement of the intrusion in late July is indicated by conditions in Ledyard Bay. In 1974, according to satellite imagery, the intruding water was unusually warm (8-9°C), much warmer than in 1978. Although 1977 was a warm year, the July surface temperature in Ledyard Bay remained below 5°C because of the presence of an ice band blocking direct flow of warm water from the south; circumstances were similar to those of 1975 (Fig. 6). The melting and warming beyond the ice band in 1975 and 1977 might have been caused by warm water flow under the ice followed by upwelling and solar heating. A hydrographic section for 24 July 1974 (Fig. 7) shows a 4°C intrusion below the low-density layers of ice-melt water off Icy Cape. Warm water also appeared along the Siberian coast in 1974 and 1977.

Some observations off Wainwright show the effect of the ice on the intrusion. In late July 1977 oceanographers took measurements from the icebreaker *Burton Island* at stations along the coast (Garrison *et al.*, 1979). Oceanographic stations (Fig. 8) off Wainwright and near the ice edge give information on the depth of the warm intrusion. Station 40 in open water shows a 5°C surface layer extending to a depth of 30 m; at station 54 in the ice, freezing temperatures exist throughout the column. Stations 56-60, in open water beyond the ice tongue, have a 2°C surface layer with a salinity of 30‰. A week later, station 145 shows 6-8°C water in a 20-m layer in the coastal polynya. The intrusion appears to have passed around the ice-covered area.

A satallite image taken on 31 July 1977 (Fig. 9) shows a broader view of conditions at this time. Densitometer readings show that the warm water around Icy Cape is at 8°C and that the warmest water in the Chukchi Sea (15°C) is found in Kotzebue Sound. This water extends north along the coast, forming a 12°C tongue past Point Hope. The shape of the ice edge suggests that the warm intrusion is split in the central Chukchi Sea. Ice floes between Point Hope and Kotzebue Sound two weeks earlier have melted and the warm water is hugging the coast. The warmest water south of Bering Strait is now in Norton Sound. Off Nome a temperature of 13°C was deduced from the enhanced IR image. The large mass of warm water east of St. Lawrence Island has dissipated.

The extension of the warm water northwestward off Icy Cape seen in Figure 9 is illustrated by the isotherms in Figure 10 (prepared from shipboard measurements), which show the

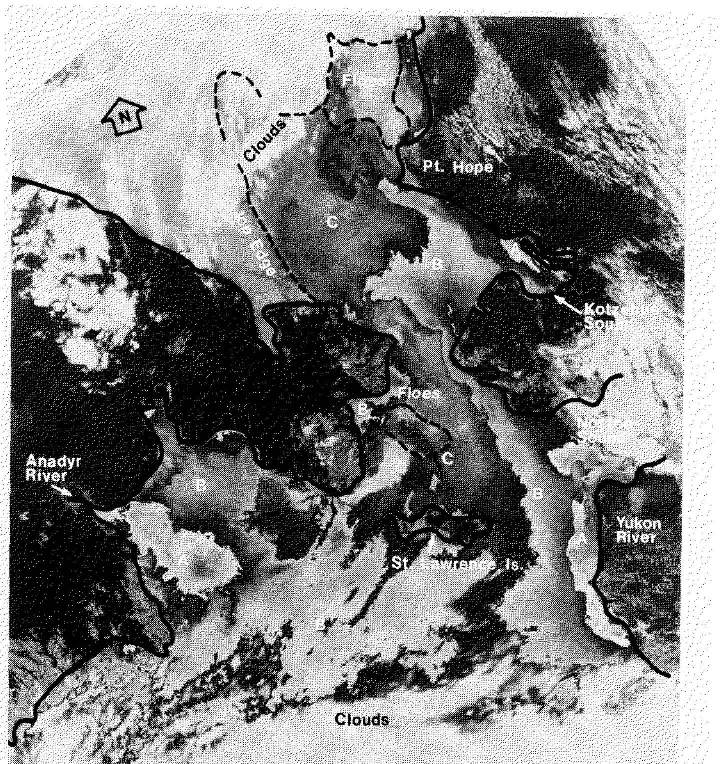


FIG. 3. Indication of northward flow through the Bering Strait, 30 June 1979. Multiple enhanced TIROS-N IR image showing three successively lower temperature regions from A to C.

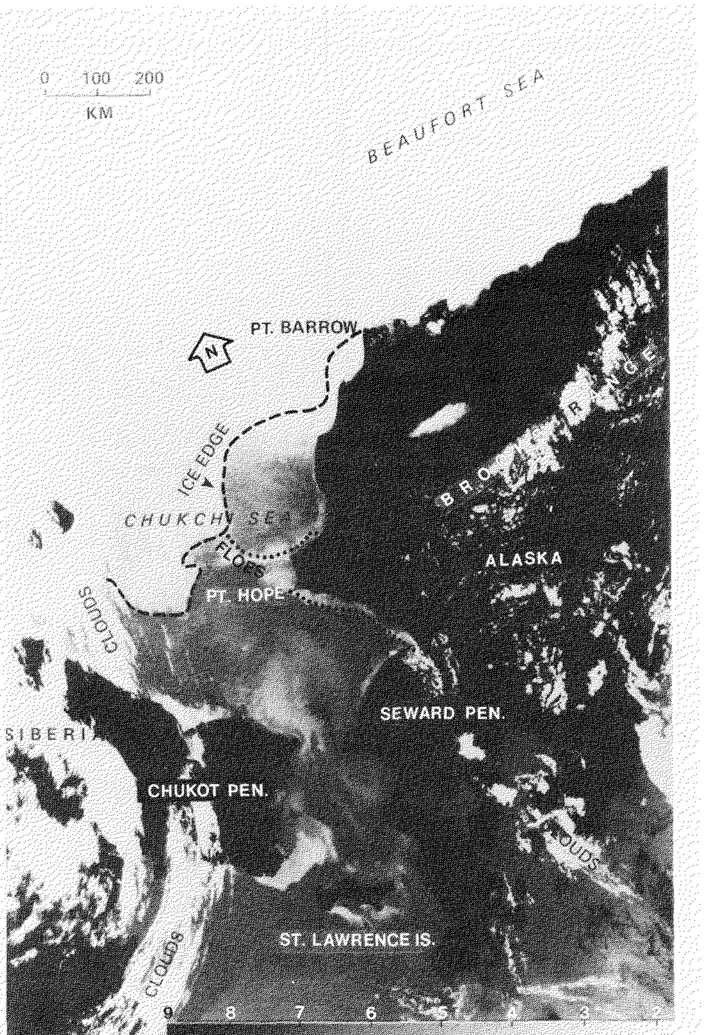


FIG. 4. Large area of warm water east of St. Lawrence Island on 15 July 1977. NOAA-5 temperature-enhanced IR image, 0°C to 9°C. Reproduced from Ahlnäs, 1979.

warm water split between a coastal flow and a northward flow. The depth of the warm intrusion shown here is 20 m along the coast and 10 m in the central area.

The intrusion past Point Barrow often clings to the coast. Figure 11 shows 8°C water off the point with 0°C water 20 miles away. About the time that a path forms past Point Barrow, the coastal current becomes very strong. In both 1971 and 1972, occupied floes drifted southward into the current and were swept to speeds up to 150 $cm \cdot s^{-1}$ along the coast and past Point Barrow, as shown by the drift patterns in Figure 12 and the ice plume along the edge of the coastal current in Figure 13.

In 1973 information on the flow near the bottom in the Barrow Canyon was obtained by Mountain *et al.* (1976) using moored sensors. They recorded a maximum current in late July followed by a decrease to a small value by the end of their measurements on 18 August. On 11 August the warm intrusion arrived at the 96-m-deep temperature sensor, as indicated by a sharp rise from − 1°C to 4°C between 11 and 14 August.

September Abatement of the Coastal Current

In late August the coastal current reaches a maximum and decreases. In September there are only stationary remnants of the warm intrusion. On 8 September 1974, eddies are present south of the ice edge showing the scale of the mixing process (Fig. 14). Here, rows of finger-like warm intrusions, approximately 20 km long and about 50 km apart, interface with the cold-water mass. The tips of the intrusions appear to form into spirals. Eddy-like features at the ice edge off Point Barrow have previously been discussed by Solomon and Ahlnäs (1980). They are probably related to the large amount of temperature finestructure found in the vertical profiles taken by Paquette and Bourke (1979) within several kilometres of the ice edge.

Figure 14 shows that the intrusion past Point Barrow has developed a 70-km-long fork to the west, indicating the influence of either the Beaufort Gyre or easterly winds. The core of the intrusion off Point Barrow is visible as a 110-km-long, narrow, winding current with an arrow-like point. This current, mirroring the Barrow Canyon over 100 m below, could easily be missed by serial oceanographic observations. Bering Strait remains longitudinally stratified, with temperature increasing to the east. Norton and Kotzebue sounds remain the

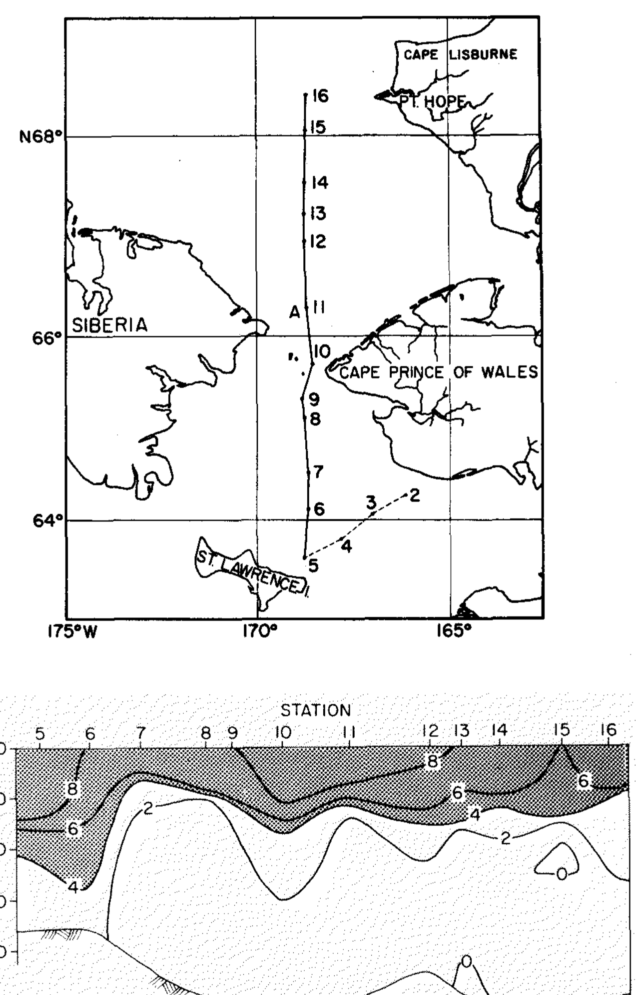


FIG. 5. Isotherms (°C) for a section through Bering Strait on 31 July 1975. Stations 2-4 had 10-m thick layers of 10°C water. Waters warmer than 4°C are shaded.

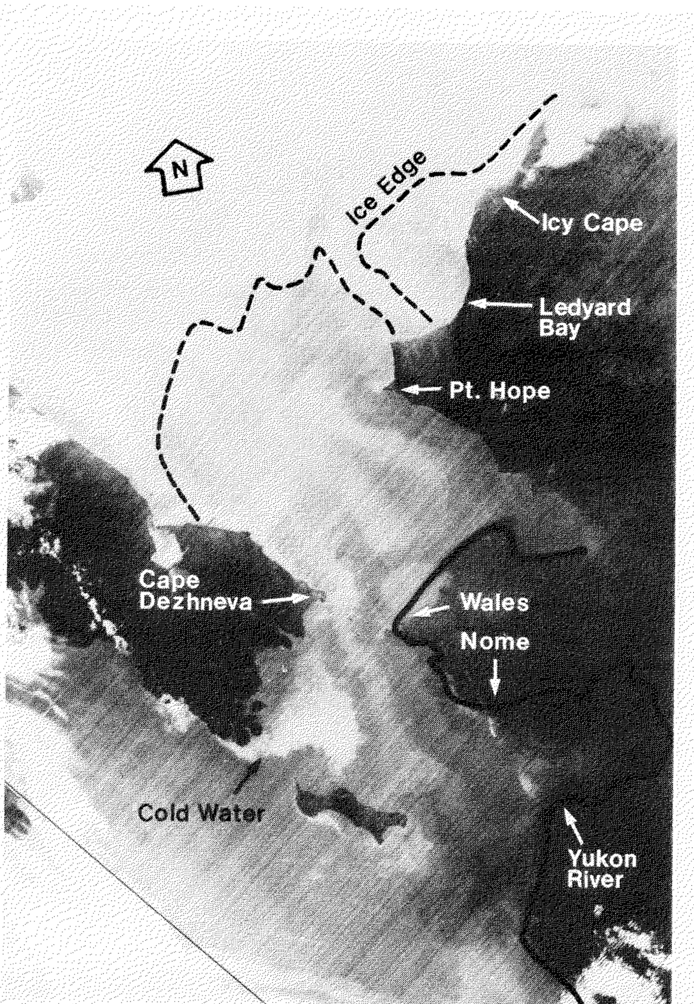


FIG. 6. Lengthwise-stretched bands of different temperatures through the Bering Strait, 24 July 1975. NOAA-4 enchanced IR image, −2°C to 15°C.

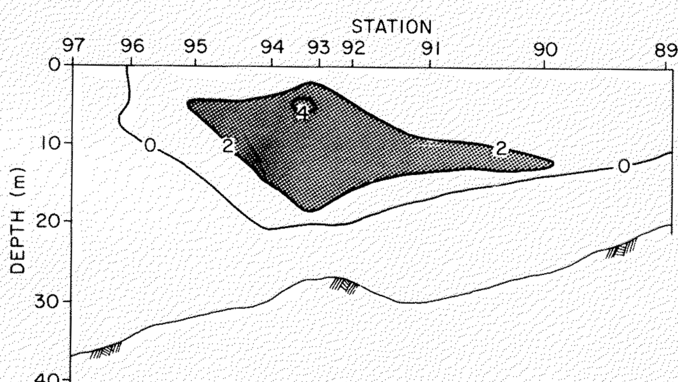


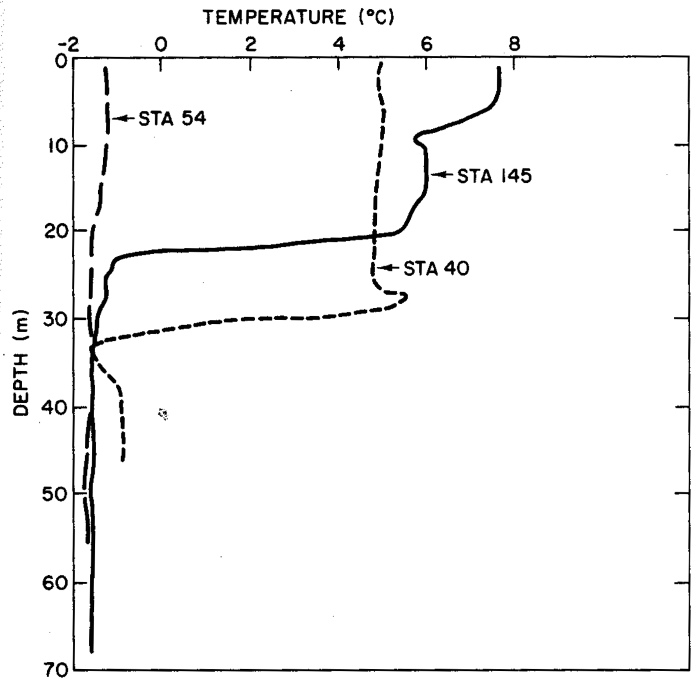
FIG. 7. Isotherms (°C) for a section off Icy Cape on 24 July 1974 which shows a warm layer beneath ice meltwater. Waters warmer than 2°C are shaded.

warmest areas. The double enchancement emphasizes the location of the warmest water along the coast of Alaska and the divided intrusion past Point Barrow. A speckled area marks the border between two enhancement regions at about 8°C. Extensive layers of 6-8°C water were observed off Point Barrow in oceanographic measurements on 19 September 1974.

An enhancement of the Bering Strait on 9 September 1980, Figure 15, shows considerable detail. Warm water remains along the east side of the strait, with a warm spiral extending into the Chukchi Sea off Wales. The warm water in Kotzebue Sound extends past Point Hope. The warmest water is in Norton Sound. The blackness indicates that its temperature is above the upper limit of the enchancement (7°C). Cold (white) areas, probably caused by upwelling, are present along the coasts southeast of Point Hope and between Wales and Nome.

Warm patches of water near the strait are still present in October, as seen in an infrared image of Bering Strait taken on 22 October 1974 (Coachman *et al.*, 1975). The highest temperature observed is 4°C, and stratification through the strait persists.

A large layer of 0.5°C water (S = 32‰) was found in the central Chukchi Sea at 73°20′N latitude in mid-October 1978,



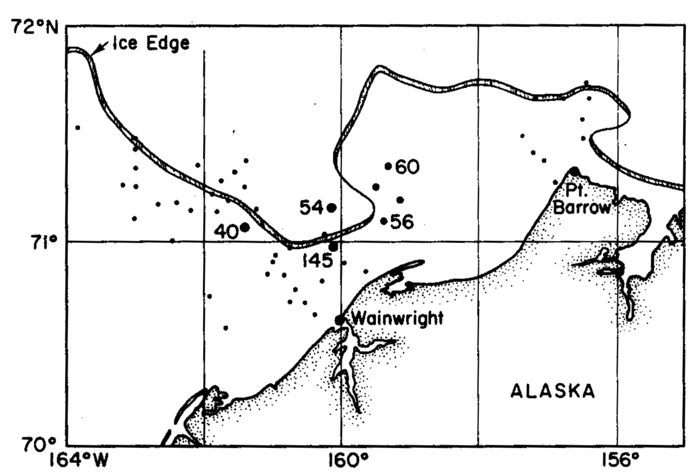


FIG. 8. Water temperature profiles for three selected stations off Wainwright in late July 1977 which compare the existing water beneath the ice with the intruding surface layer. Station 145 was taken six days later than the other stations.

and large layers of 2.5°C (S = 31‰) water were observed at 72°30′N in late September 1980 (Garrison *et al.*, 1982). In the Beaufort Sea a −0.6°C layer (S = 32‰) at 75 m depth persisted on 6 November 1975 at 149°W. It would probably have been larger in a normal ice year. These remnants in the Arctic Ocean have the proper density (1.025-1.026) to contribute to the "temperature-maximum layer" (Coachman and Barnes, 1961), a layer at about −1.5°C with a salinity of 32‰ that persists through the winter at depths of 75-100 m in the western basin. Its broad distribution results from the circulation of the Beaufort Sea Gyre.

Annual Variations

To examine the relationships between the different years, Table 1 and Figure 16 were compiled to show sea surface temperatures in mid-July, as derived from the satellite imagery. Figure 16 shows 1975 to have been the coldest year, closely followed by 1976. An average warming trend of about 5°C from 1975 to 1980 can be seen. The most drastic annual change occurred in 1977.

The geographical locations chosen for Figure 16 show areas of generally occurring extreme temperatures. The patch of cold water near Cape Chukotskiy can possibly be attributed to upwelling. The cold water off Point Hope is influenced by drifting ice and that off Siberia mainly by shorefast ice. Beyond the ice are bands of warm water.

Figure 17 shows the mid-July location of the ice edge in the Chukchi Sea for the same seven-year period shown in Figure 16. The warm intrusion into the Chukchi Sea is one of the factors affecting the shape of the ice edge. At the same time, the ice acts as a barrier for the northward flow of warm water. Some characteristics of the Chukchi Sea ice edge are: (1) a bulge, about 200 km in width, extruding about 100 km to the

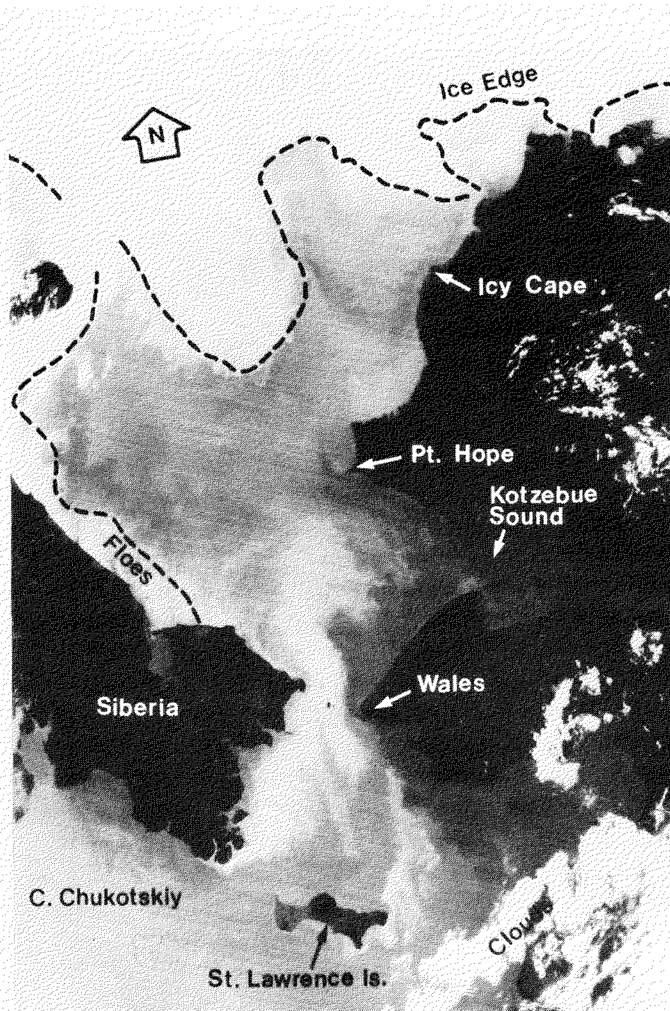


FIG. 9. Distribution of warm surface water in the Chukchi Sea showing a connection with warm water in Norton Sound, 31 July 1977. NOAA-5 enhanced IR image, 1°C to 19°C.

TABLE 1. Sea surface temperatures (°C) in July 1974-1980

Date	Norton Sound	Off Nome	NW Yukon Delta	Tongue Off Wales	Kotzebue Sound	Point Hope	Ledyard Bay	Siberian Coast	Cape Chukotskiy
14 July 1974 *[1-19]*[a]	12	12	11-13	9	11-12	4 (8)[b]	8-9	4-6 (9-11)	3
20 July 1975 *[−2-15]*	10	11-12	6-7	5-6	5-6 Clouds?	2	Cloudy	0-1	−1-0
24 July 1975 *[−2-16]*	12	12	10-13	—	7-8	1-3	−1-0	0-2	0
12 July 1976 *[−2-16]*	11-12	11	7-8	6-8	9-11	1	1	—	0
12 July 1977 *[−2-11]+[12-21*	14-15	13	Cloudy	8	14	4-6 (9)	4	3 (8)	2
15 July 1977 *[0-9]+[9-18]*	—	12	11	9	12	2 (6-7)	3-4	2-3	2
31 July 1977 *[1-19]*	13	13	—	11	15	12	Cloudy	4 (8)	3-4
15 July 1978 *[0-9]+[9-18]*	12	11	6-7	Cloudy	13	10	6	Cloudy	1
20 July 1980 *[3-16]*	15-16	12-14	15	10-11	14-16	12	—	—	3

[a]Values in brackets indicate the temperature range of the IR enhancement.
[b]Values in parentheses indicate a warm band of water outside the influence of floating ice.

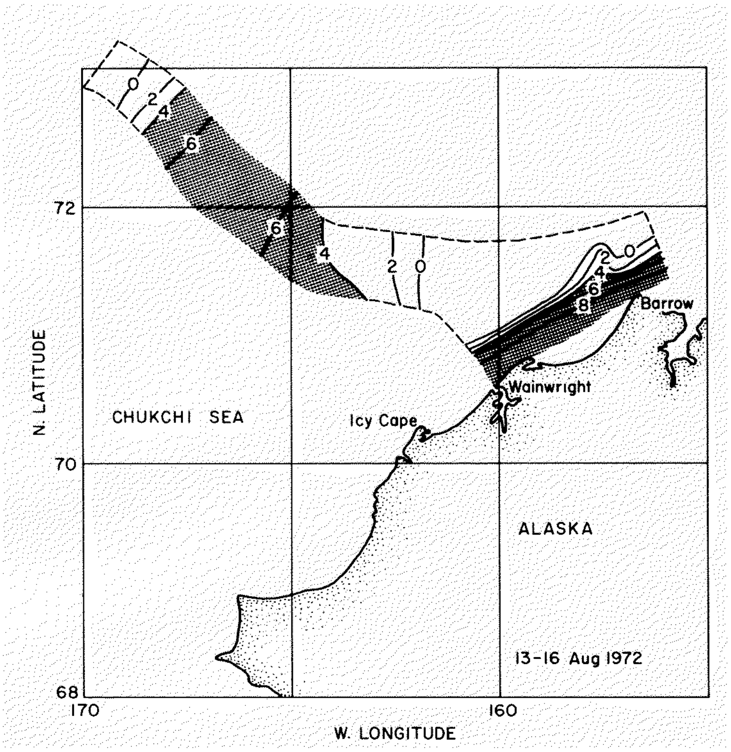


FIG. 10. Isotherms of maximum temperature (°C) in the temperature-depth profile. The surface layers in the central Chukchi Sea were 10 m deep.

south into the central Chukchi Sea (1974, 1977, 1978, and 1979); (2) assorted polynyas along the coast between Point Hope and Point Barrow; (3) a band of ice floes between the ice edge and the vicinity of Point Hope impeding access to open waters farther north (1975, 1976, and 1977); (4) a band of shorefast ice or ice floes along the coast from Point Hope into Kotzebue Sound (1976 and 1977); and (5) a band of ice along the north coast of Siberia extending all the way to Cape Dezhneva (1975 and 1976).

The location of the ice edge along the Point Hope to Point Barrow coastline is of vital importance to the large flotilla of barges that resupply Prudhoe Bay each summer. In 1976, one of the most severe ice winters, icebreaker support was required for navigation along the coast. In years with mild winters, there is usually open water to Point Barrow by mid-July. Figure 17 shows that this was true from 1977 to 1980, with the exception of some ice just south of Barrow in 1979.

SUMMARY

An examination of seven years of satellite and oceanographic observations has added to our knowledge of the origin and behavior of the strong summer flow of warm water along Alaska's northwestern coast.

Origin

Large areas with shallow water such as Norton Sound and Kotzebue Sound that have a low-salinity surface layer produced by river runoff, particularly from the Yukon River, appear in satellite infrared images to be warmed greatly by the long daylight periods of spring.

Pattern of Flow

The warm surface waters appear to mix downward and spread westward to join a northward flow along the east side of the strait. When the warm flow reaches Point Hope it tends to split into a north-trending branch and a fast-moving coastal stream.

Volume of Flow

Satellite infrared images give the area of the warm surface layer, and temperature-depth profiles along the path of the

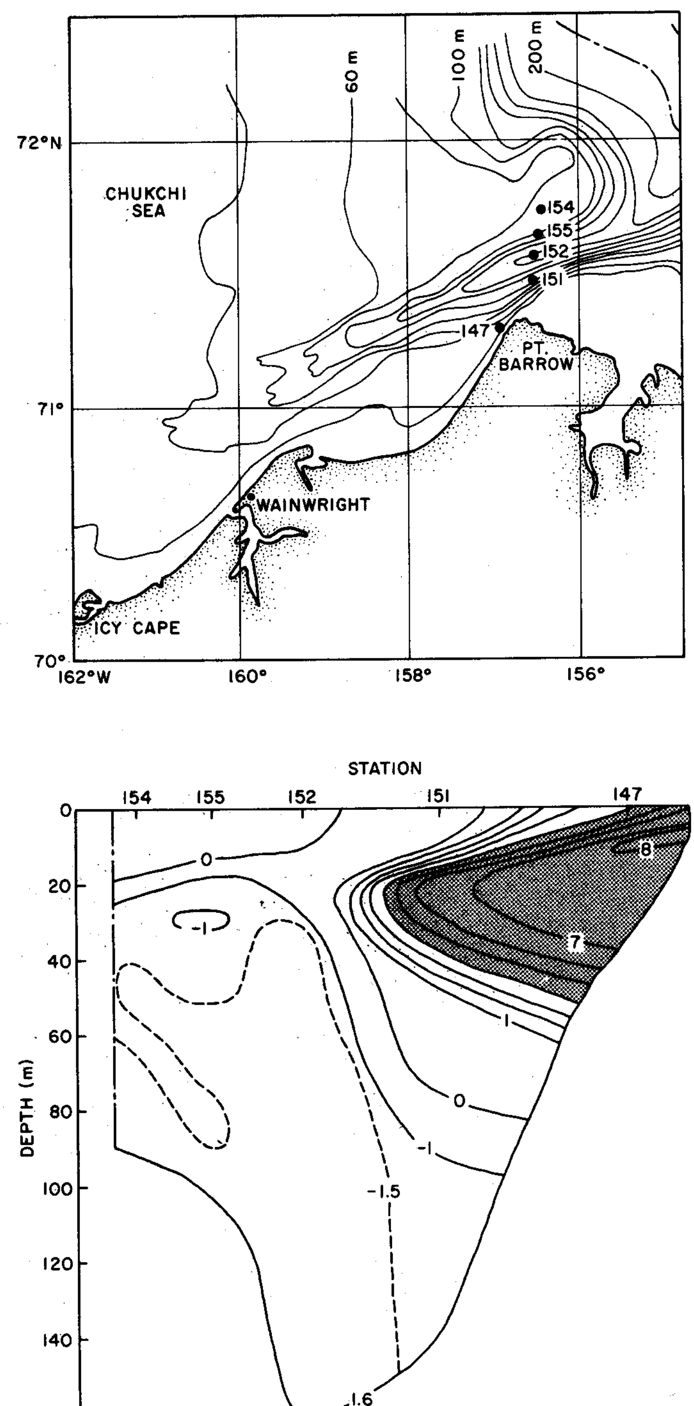


FIG. 11. Temperature section for a line northward from Point Barrow on 5 August 1977 showing the warm layer crowding the shore.

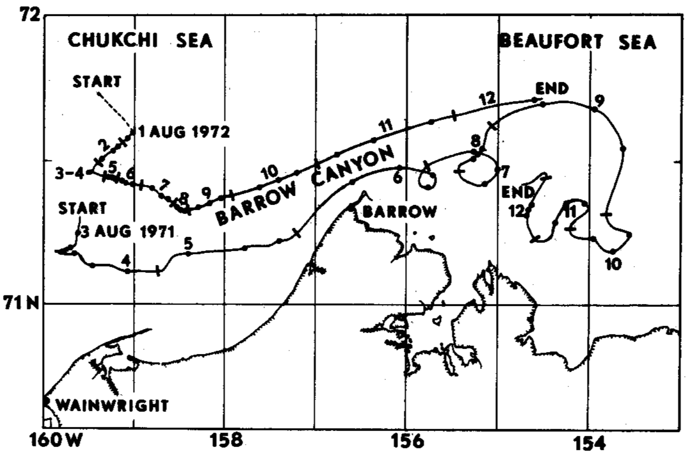


FIG. 12. Drift tracks of occupied floes in 1971 and 1972. A dot represents six hours and a bar marks the end of the day. When the floes entered the coastal current, their drift speed increased greatly.

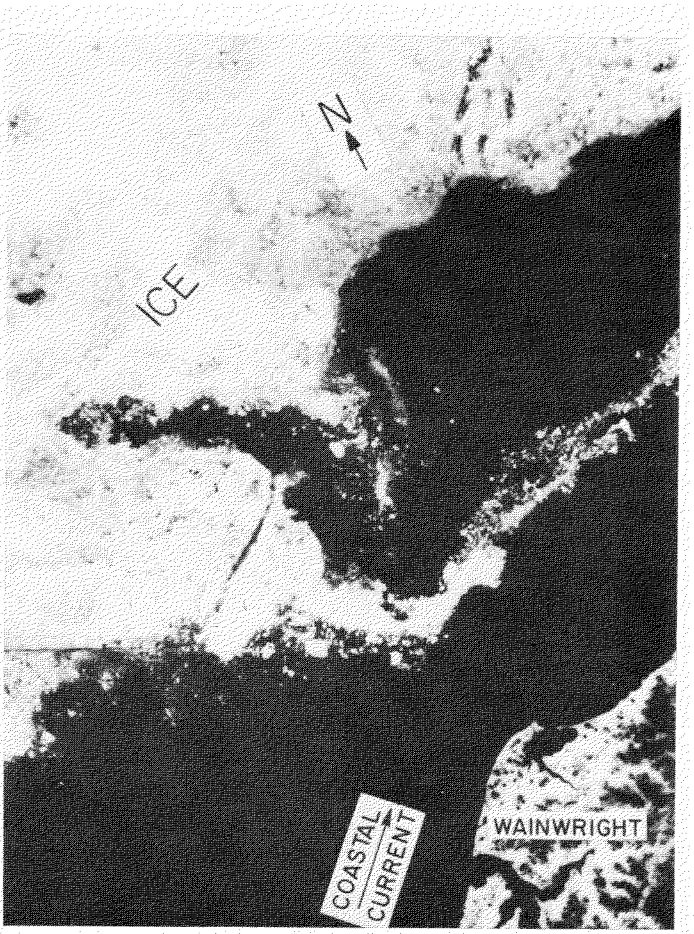


FIG. 13. Satellite image of the ice off Wainwright on 2 August 1972 showing ice in an elongated streamer after it drifted eastward into the coastal current (ERTS-1 satellite MSS band 7).

flow show that the depth of the surface layer is appreciable, i.e., to the bottom in Norton Sound and to 10-30 m through Bering Strait. Ice camp drifts show a current as high as 150 $cm \cdot s^{-1}$ along the coast. However, current measurements by Coachman and Aagaard (1981) across a section of the flow provide the best estimate of its volume, a northerly transport of 1.5 Sv in the summer.

Extent of the Intrusion

Appreciable portions of the warm intrusion have been detected at latitude 73°20′ north of Bering Strait, at 72°30′ north of Point Barrow, and as far east as longitude 145°W. These findings were made as late as November, some three months after the peak of the intrusion. No measurements have been taken in winter to show how long the warm layer persists, but spring measurements have shown that by March the warm layer along the coast has disappeared.

Eddies and Spirals

Such a strong current along a coastline containing many points and bays would be expected to produce an erratic flow. At the confluence of the coastal flow and the Beaufort Gyre spirals are produced. All along the edge of the intrusion are small eddies that indicate a complex mixing process.

Year-to-Year Variations

Surface temperatures of the waters in the vicinity of the Bering Strait are lower when the ice edge in the Chukchi Sea is

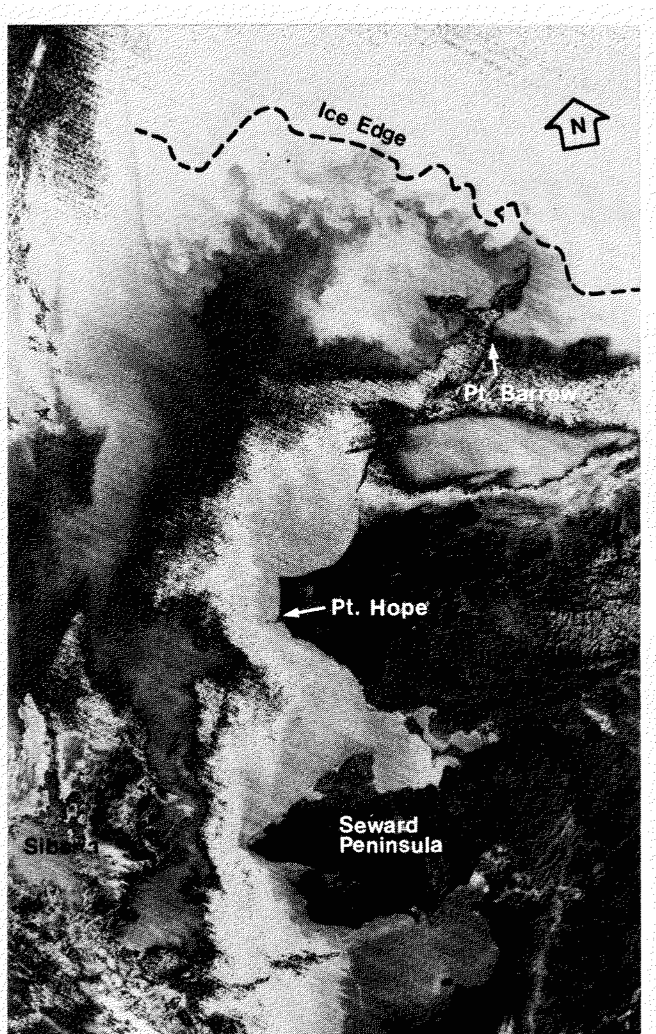


FIG. 14. This double enhancement emphasizes the warm water along the coast of Alaska with a split fork past Point Barrow, 8 September 1974. NOAA-3 enhanced IR image: −1°C to 7°C and 8°C to 16°C.

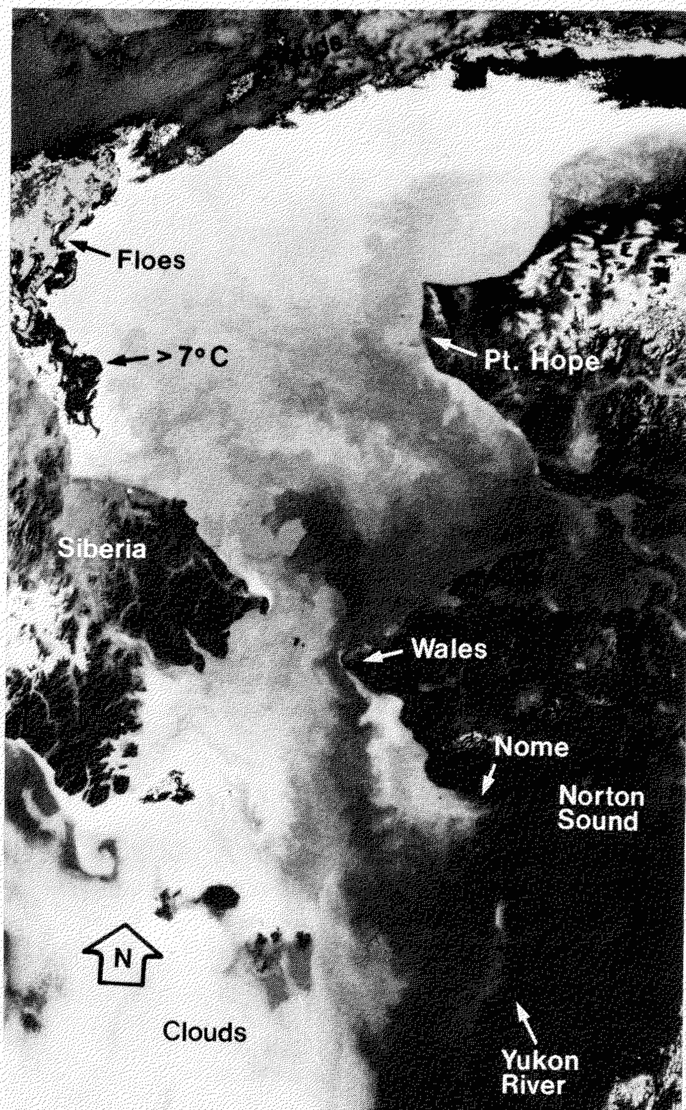


FIG. 15. Northward flow of warm water through the Bering Strait on 9 September 1980. The warmest water appears in Norton Sound. NOAA-6 enhanced IR image, −1°C to 7°C.

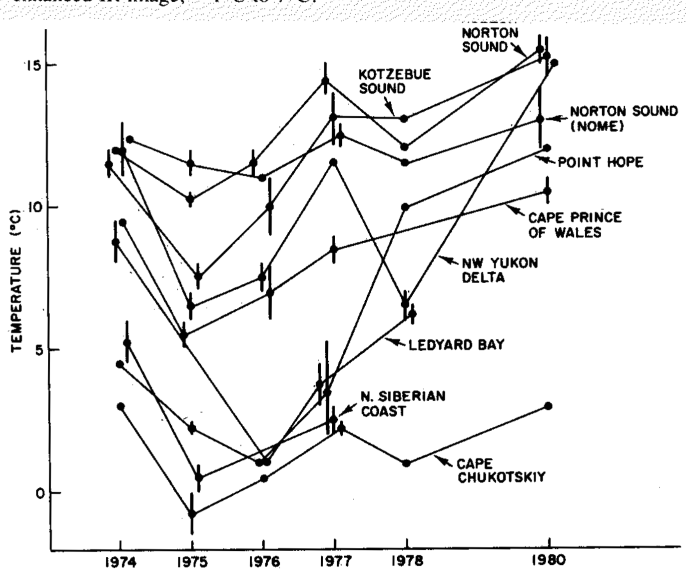


FIG. 16. The trend of sea surface temperatures in northern Bering Sea and the Chukchi Sea in mid-July 1974-1980. Vertical bars indicate variation.

farther south. The coastal current has previously been shown to be related to atmospheric pressure differences between Barrow and Nome. The arctic weather has enough annual variation to produce differences in the coastal flow. In addition, northerly winds can move the ice pack against the coast and temporarily block the coastal flow. This endangers the

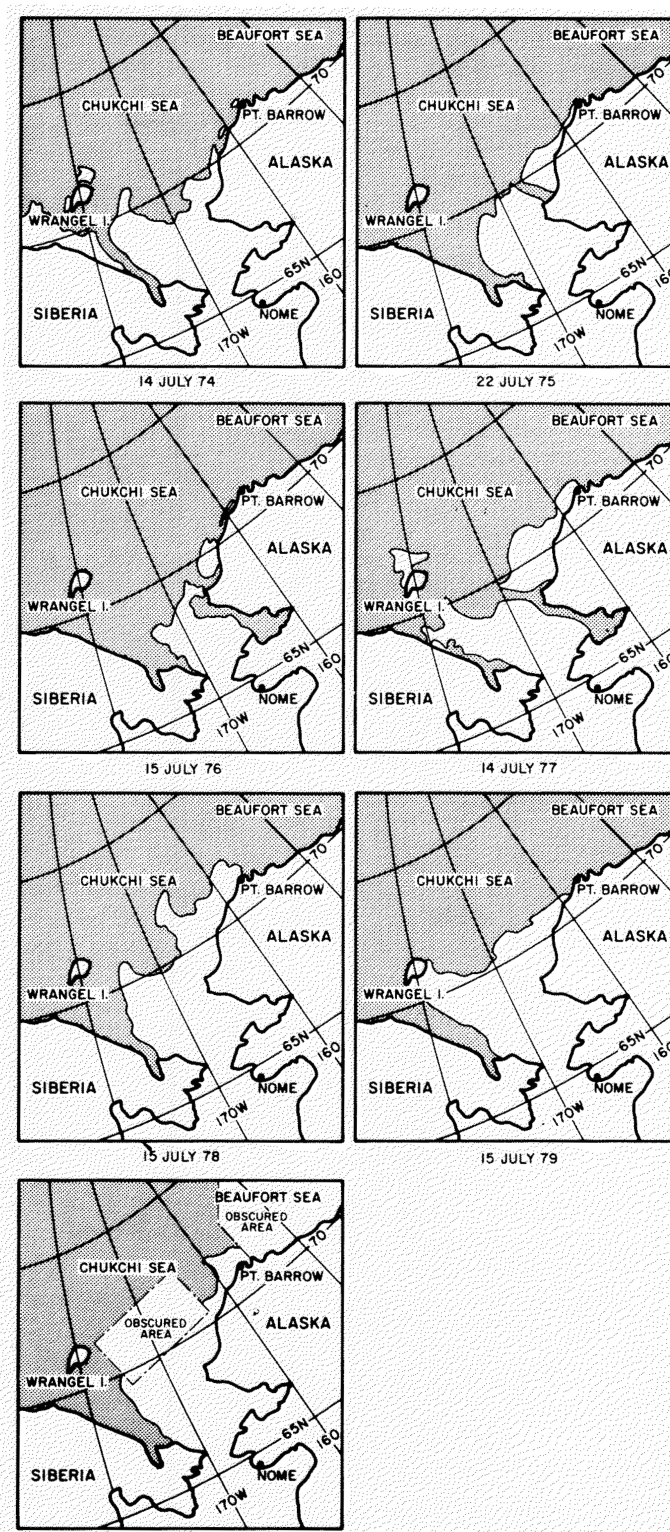


FIG. 17. Location of ice edge in the Chukchi Sea in mid-July 1974-1980.

shipping required to resupply the oil industry along the northern coast.

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REFERENCES

AHLNÄS, K. 1979. IR enhancement techniques to delineate surface temperature and sea-ice distributions. Proceedings, 13th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan. II:1067-1076.

COACHMAN, L.K. and AAGAARD, K. 1966. On the water exchange through Bering Strait. Limnology and Oceanography 11(1):44-59.

______. 1981. Reevaluation of water transports in the vicinity of Bering Strait. In: Hood, D.W. and Calder, J.A. (eds.). Eastern Bering Sea Shelf: Oceanography and Resources. Vol. 1. Washington, D.C.: NOAA/Office of Marine Pollution Assessment. 95-110.

______ and TRIPP, R.B. 1975. Bering Strait: The Regional Physical Oceanography. Seattle, WA: University of Washington Press. 172 p.

COACHMAN, L.K. and BARNES, C.A. 1961. The contributions of Bering Sea water to the Arctic Ocean. Arctic 15(4):251-277.

GARRISON, G.R. and BECKER, P. 1975. Marginal ice zone oceanographic measurements: Bering and Chukchi seas, 1973 and 1974. APL-UW 7505. Applied Physics Laboratory, University of Washington, Seattle, Washington. 150 p.

______. 1976. The Barrow Canyon: a drain for the Chukchi Sea. Journal of Geophysical Research 81:4445-4453.

GARRISON, G.R. and PAQUETTE, R.G. 1982. Warm water interactions in the Barrow Canyon in winter. Journal of Geophysical Research 87(C8):5853-5859.

GARRISON, G.R. and PENCE, E.A. 1973. Studies in the marginal ice zone of the Chukchi and Beaufort seas: a report on Project MIZPAC-71B. APL-UW 7223. Applied Physics Laboratory, University of Washington, Seattle, Washington. 224 p.

______ and FELDMAN, H.R. 1973. Studies in the marginal ice zone of the Chukchi Sea: acoustic and oceanographic data for 1972. APL-UW 7309. Applied Physics Laboratory, University of Washington, Seattle, Washington. 152 p.

GARRISON, G.R., SHAW, J.T., and WELCH, M.L. 1982. Arctic oceanographic measurements: 1978-1980. APL-UW 8112. Applied Physics Laboratory, University of Washington, Seattle, Washington. 95 p.

GARRISON, G.R., WELCH, M.L., and SHAW, J.T. 1979. Oceanographic measurements in the Chukchi Sea: April-August 1977. APL-UW 7824. Applied Physics Laboratory, University of Washington, Seattle, Washington. 131 p.

GUDKOVICH, Z.M. 1962. On the nature of the Pacific current in Bering Strait and the causes of its seasonal variations. Deep-Sea Research 9:507-510 (Translated from Okeanologiya 1(4):608-612 (1961)).

HUFFORD, G.L. 1973. Warm water advection in the southern Beaufort Sea, August-September 1971. Journal of Geophysical Research 78(15):2702-2708.

JAYAWEERA, K.O.L.F. 1976. Use of enhanced infrared satellite imagery for sea ice and oceanographic studies. Ocean Engineering 3:293-298.

LAURITSON, L., NELSON, G.J., and PORTO, F.W. 1979. Data extraction of TIROS-N/NOAA radiometers. NOAA Technical Memorandum NESS 107. 58 p. [National Oceanic and Atmospheric Administration, Washington, D.C. 20233, U.S.A.]

LOHRMANN, W.R. 1979. Winter and spring oceanographic conditions in and under the ice of the Bering Sea. Report 68-79-001. Naval Postgraduate School, Monterey, California. 65 p.

MOUNTAIN, D.G., COACHMAN, L.K., and AAGAARD, K. 1976. On the flow through Barrow Canyon. Journal of Physical Oceanography 6(4):461-470.

MUENCH, R.D. and AHLNÄS, K. 1976. Ice movement and distribution in the Bering Sea from March to June 1974. Journal of Geophysical Research 81:4467-4476.

PAQUETTE, R.G. and BOURKE, R.H. 1974. Observations on the coastal current of Arctic Alaska. Journal of Marine Research 32(2):195-207.

______. 1979. Temperature finestructure near the sea-ice margin of the Chukchi Sea. Journal of Geophysical Research 84(C3):1155-1164.

______. 1981. Ocean circulation and fronts as related to ice melt-back in the Chukchi Sea. Journal of Geophysical Research 86:4215-4230.

ROYER, C. and MUENCH, R.D. 1977. On the ocean temperature distribution in the Gulf of Alaska, 1974-75. Journal of Physical Oceanography 7(1):92-99.

SOLOMON, H. and AHLNÄS, K. 1980. Ice spirals off Barrow as seen by satellite. Arctic 33(1):184-188.