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STORM SURGES IN THE ALASKAN BEAUFORT SEA

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Storm surges in the Alaskan Beaufort Sea

by

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Introduction

A large percentage of the world's population is concentrated on low coastal plains and deltas fringing the oceans. Thus, extreme storms, tidal waves, and floods have produced a long record of major catastrophes for man in terms of lost lives and property. The North Slope of Alaska fringes the Beaufort Sea and consists of a very low, tundra-covered coastal plain with numerous low deltas, allowing storm surges to inundate extensive areas. Until recently, the North Slope was an undeveloped area, therefore, no long term written record exists which might document catastrophes in this region. Since the nation is now looking at the North Slope and the adjacent continental shelf as a source for future energy, we should be aware of the consequences of potential catastrophes in this area.

In the Fall of 1970, westerly gale force winds occurred in the Canadian and Alaskan Beaufort Sea resulting in a surge reported to have been up to 3 m high (Anon., 1971a; Reimnitz, et al., 1972; Lewis and Forbes, 1975; Dygas and Burrell, 1976b). This is an order of magnitude higher than normal flood tide. Recurrence intervals for similar events range from 25 to 50 years (Anon., 1971a). The first author observed considerable amounts of driftwood afloat during the storm, while in transit on a small vessel from Point Barrow to Prudhoe Bay. Much of this driftwood was deposited on land and formed a rim that roughly marks the storm surge level. This rim can still be seen from low-flying aircraft.

During August, 1977, a reconnaissance survey was conducted by helicopter during 1.5 days to study the configuration and elevation of this driftwood line from Cape Halkett to the Canning River (Fig. 1). In this report the results of this survey are presented together with observations related to the 1970 storm surge and other surges. We will also briefly discuss the marine geological consequences of storm surges in the Beaufort Sea.

Field methods and their limitations

The driftwood line was sketched from an altitude of 500 feet on 1:63,360 scale topographic sheets, wherever it was adequately defined. Color photographs (35 m) were taken at the same time and later used to resolve some uncertainties in the sketch of the driftwood line. In some areas one pass with the aircraft was not sufficient to produce an accurate sketch. For this reason the lines in maps 1 through 5 contain local errors but provide a general configuration of the driftwood line. In addition, we used color IR photography to enhance differences in vegetation between the low-lying terrain, which had been inundated by salt water in 1970, and the higher terrain.

The flight was interrupted at a number of places to inspect material contained in the driftwood line and to measure the elevation of the line above sea level. In general we chose sites where the driftwood line was well defined within 200-300 m of the open ocean.This limit was dictated by the pole-and-horizon method (Emery, 1961), used for elevation measurements. In view of other limitations to the approach, the technique is sufficiently accurate ($\pm$ 10 cm). No tide gauge was in operation nearby during the period of the survey (August 14 and 15,

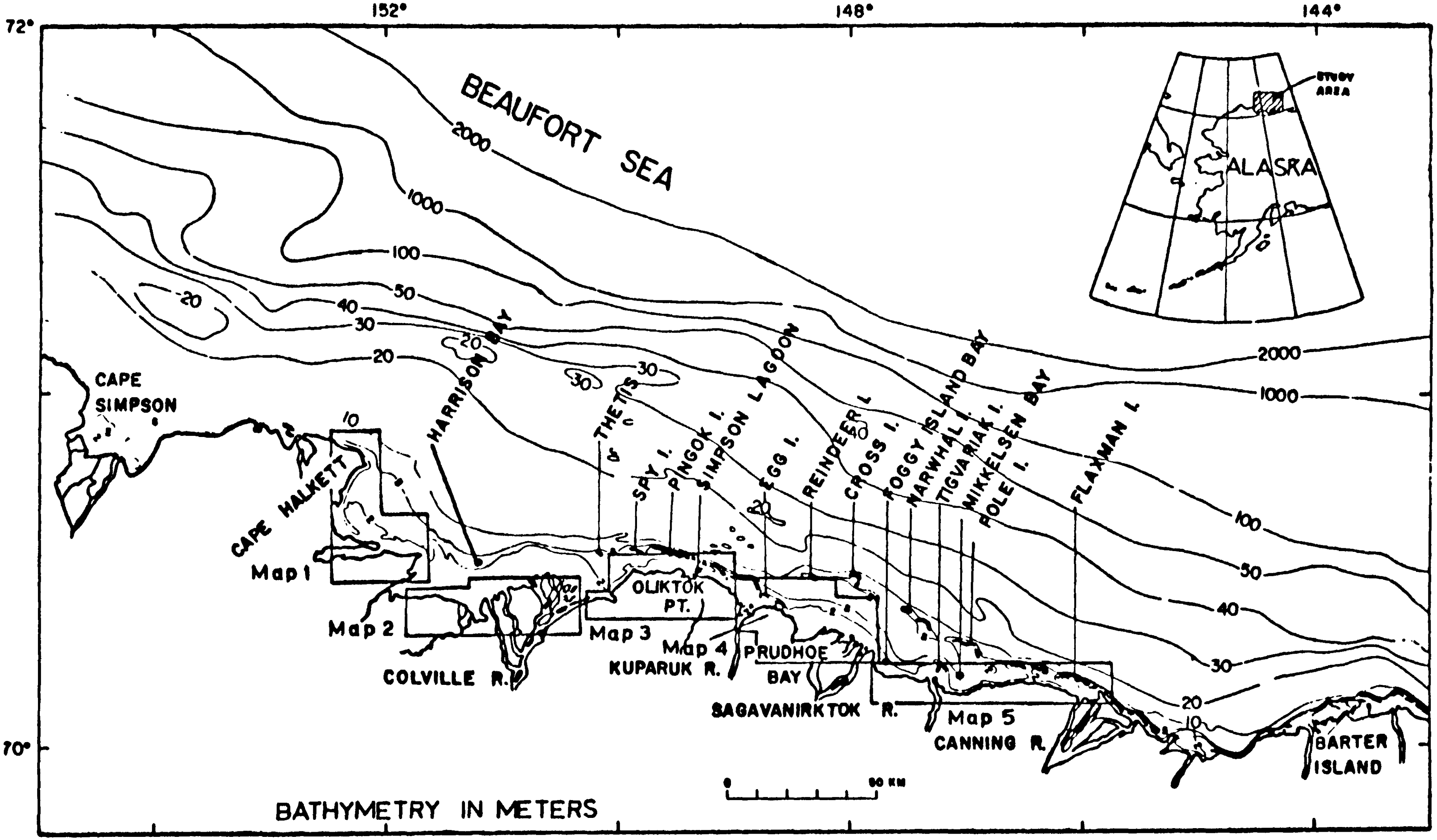


Figure 1.- Location map showing regional bathymetry and delineating map areas 1 through 5.

1977), but the weather was very calm and steady. We believe sea level was within 20 cm of its mean. Beach features related to the sea-level were noted at each site so that we could monitor the onset of any anomalous events.

Driftwood, in fact, does not mark the highest water level of a surge. It may lie higher or lower than the storm surge level, and we will briefly consider the two extremes.

1) On a steeply sloping land surface, oriented normal to deep water wave orthogonals, and with deep water close by, there is a considerable wave run-up. Here the driftwood comes to rest at an elevation representing the sum of storm surge height and maximum wave height. Due to the shallowness of the inner shelf in the study area, and due to the presence of ice which reduces the fetch, we estimate that the driftwood was not more than .5 m above the storm surge level at the sites studied.

2)On a gently sloping land surface with shallow water offshore, there is essentially no wave run-up. Here the largest trees, often with branches and other irregularities, may have .5 m or more draft. They therefore run aground far short of the extreme landward position of the water line and act as fences for smaller debris, which causes formation of a distinct driftwood line.

The latter conditions applied to much of the driftwood on the mainland (Fig.2). Here the measured surge elevations generally underestimated the true surge height. The barrier islands were entirely awash during the storm. Therefore the driftwood came to rest during surge recession and values for surge height may also be too low. It is important to keep these limitations in mind in planning for coastal

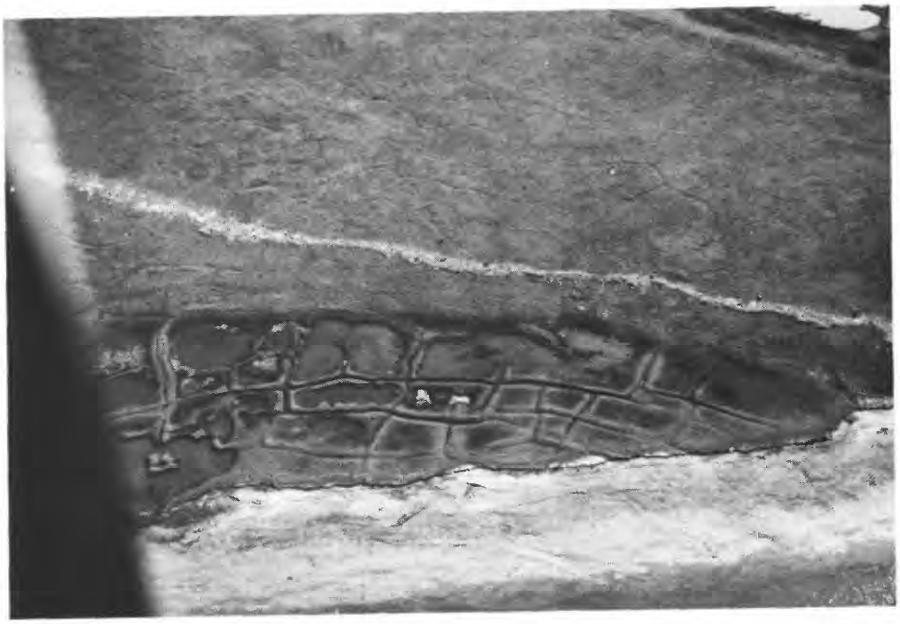


Figure 2.- Aerial view of well defined driftwood line on tundra surface with imperceptible slope. Distance across photograph is about 100 m.

Figure 3. - Large peices of sea ice driven onto islands by storm surge of September 1970, with keels deeply imbedded into island surface.

installations. Some discrepancies between the surge height as measured and the surge heights as inferred from other observations will be discussed later.

Background Information

The shelf of the Beaufort Sea in the study area (Fig. 1) is shallow, with the 20 m isobath about 30 to 35 km from the mainland shore and gentle relief (Carsola, 1954; Barnes and Reimnitz, 1974; Reimnitz and Barnes, 1974). The shelf has a nearly complete sea ice cover for nine months of the year. Astronomical tides have an average range of only 15 cm, and on a day-to-day basis they are overshadowed by the effects of wind. Easterly wind is most common, causing low water levels, while westerly wind causes a rise in water level (Short, 1973). The most severe storms bring westerly winds which generally occur during September or October.

Coastal navigators are well aware of the simple relationship between wind direction and water level and therefore read the wind rather than the tide tables. Ice is also moved onshore by westerlies and offshore by easterlies.

The sea level fluctuates with the tides regardless of the presence of an ice cover. Only within the shallow areas of the bottom-fast ice zone landward of the tidal cracks does the sea level remain constant under most conditions (Reimnitz, et al., in press). It has been noted, but is not well understood, that meteorologic tides, even surges, can occur in the middle of the winter in the presence of a nearly complete ice cover (Zubov, 1945; Henry, 1975; and Brian Mathews, personal commun.)

The September 13, 1970 storm reached its peak during the afternoon when northwesterly winds of 80 km/hr were observed at the Oliktok DEW-line site. According to Dygas and Burrell (1976b) the winds were gusting to almost 130 km/hr. At Deadhorse, some distance inland, peak wind velocities reached only 46 km/hr. (U.S. Dept. of Commerce). This discrepancy could be expected, because in the presence of a surface cold front, winds over the water may be two to four times stronger than those reported inland (Burns, 1973). In the area off Cape Halkett the senior author estimated westerly winds at 130 km/hr (70 knots), and wave heights of about 3 m. The waves were relatively small due to the presence of scattered bergy bits along the coast and due to the fact that 1/10 to 6/10 of the sea surface 20 km seaward was covered by sea ice (Atmospheric Environment Service, Canada). The Canadian ice chart for the Beaufort Sea on 24 September, 1970, showed that, probably as a result of the storm, pack ice had replaced most of the water of the inner shelf (A.E.S., Canada).

Spy Island (Fig. 1), observed through binoculars from Oliktok (Dygas, personal commun.), was marked be a line of foam from breaking waves, and large chunks of ice could be heard pounding the island which is 5 km from the observation point.

After the storm subsided all the islands between Oliktok and Prudhoe Bay were marked by large ice chunks (Fig. 3). The tundra surface around the Okiktok DEW-line site had been inundated, but the roads, pads, and runway remained above water. Two members of a shore navigation station camped east of Oliktok Point, almost lost their lives trying to wade across the flooded land to higher ground. Coastal erosion along the west side of the Point endangered the fuel storage tanks at the Point and waves and currents removed several hundred meters of road leading across the tundra. The land area around Bud Helmericks' settlement on the Colville Delta was entirely submerged. Only the pads on which the living quarters and hangar are built remained above water (B. Helmericks, pers. commun.). According to Helmericks, the flood level was 1.5 m above the river level. Due to the high water, the lake which provides the settlement's fresh water supply, turned to unusable salt water. A cabin built by Helmericks on the highest part of Thetis Island in Harrison Bay (Fig. 1), and all materials lying around the cabin, were washed away. Only one plank was found again. The following evidence from cross Island (Fig. 1) is pertinent to later discussion of the recurrence interval of high storm surges. An Eskimo cabin on the island wasdamaged by flood waters during the 1970 storm. According to Helmericks the cabin was built around the turn of the century. Luci Ahvakana and Abraham Stein, natives from the shores of Simpson Lagoon, give different dates for construction of the cabin, i.e. 1918/1919 and 1930, respectively. Some planks known to have been part of the cabin are now lying east of the cabin at a relatively low level. The cross after which Stockton (1890) named the island is still standing and the year 1889 is carved on it. According to Helmericks, wood chips from the construction and carving were lying around the base of the cross before the 1970 storm, but the wood chips were carried away and the island surface was reshaped by currents during the storm. The settlement at Beechy Point in Simpson Lagoon was awash during the flood, and some small boats were carried away. A large barge broke loose in the Prudhoe Bay area and came to rest nearly 1 m above sea level at the eastern part of the Sagavanirktok Delta. Some of the lighter barges used in Prudhoe Bay, which were secured for the winter next to the causeway, were set on top of the causeway (personal commun., James Lowe, Supt. of the Sealift operation). These barges require four feet of water to float and the causeway is six to seven feet above sea level, therefore, the minimum surge height required to lift the barges onto the causeway would have to be ten to eleven feet (± 3 m). Along the open coast the height of the storm surge was estimated to be approximately 3 m (Reimnitz, et al., 1972; Dygas and Burrell, 1976).

In the Canadian sector of the Beaufort Sea, where the pack ice front at the time of the storm was more than 150 km from the coast, nearly optimum conditions for the generation of a surge and waves existed (Anon., 1971b). A rise in water level was observed at Herschel Island more than five hours prior to the storm. At Shingle Point the winds were only 8-15 km/hr (5-10 mph) from the southwest. Five minutes later they were gusting in excess of 110 km/hr (70 mph) from the northwest (Anon., 1971b). The observed surge height was 2.4 m (Anon., 1971b), but locally it might have been up to 3 m (Lewis and Forbes, 1975). Deep water waves of up to 9 m were noted. Pack ice, including many remnants of multi-year floes and one ice is land were driven into Babbage Bight. The ice island grounded at 11 m water depth with its surface up to 12 m above sea level (Kovacs and Mellor, 1971), suggesting considerable surge height and driving forces. Damage reported from the Canadian coast was considerable, including bluff erosion (up to 12 m) at Tuktoyaktuk (Anon., 1971b).

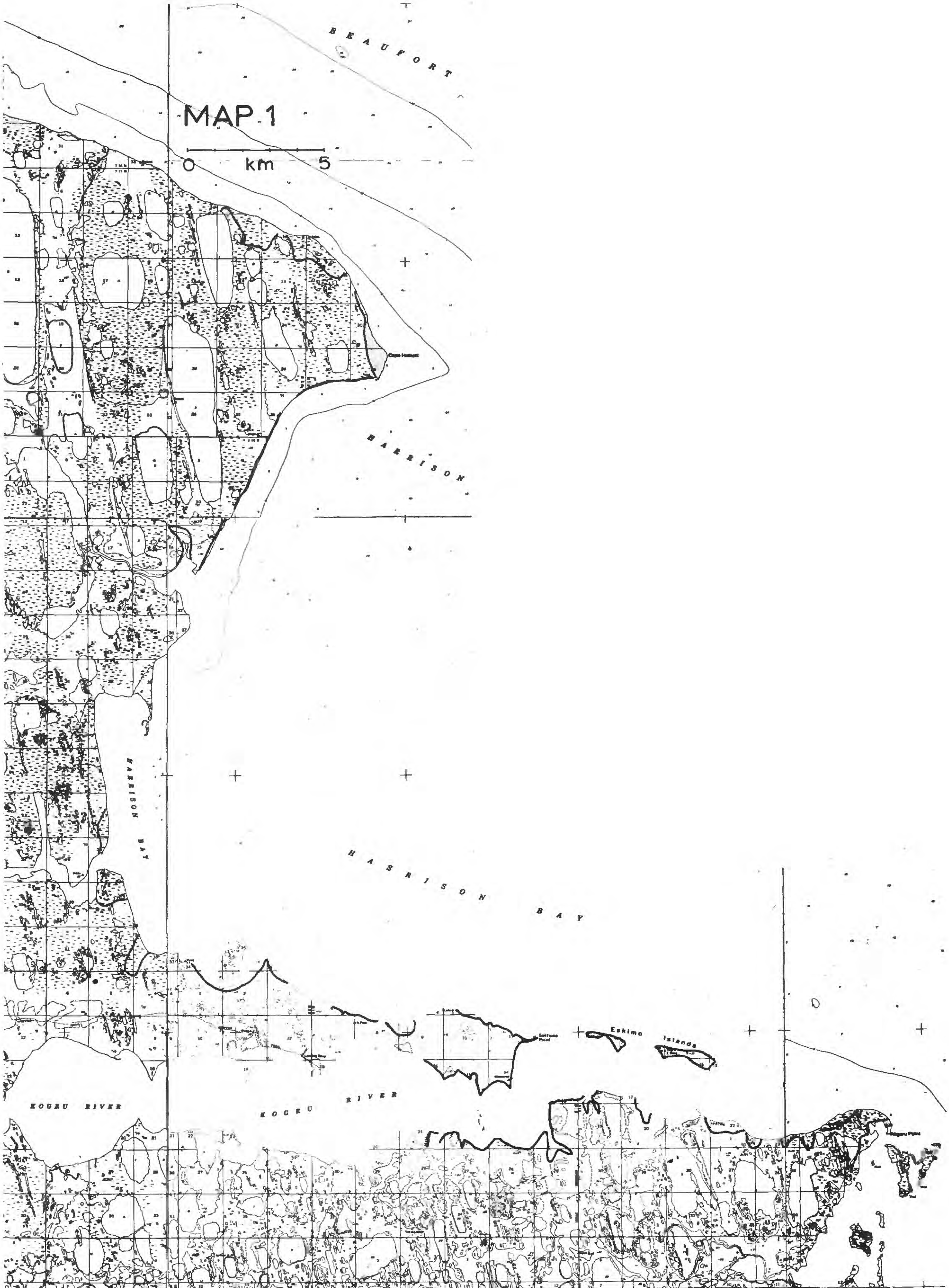
Observations of interest to the sedimentologist are the large amounts of sediment which were in suspension in the shallow waters. For example, the tugboat Radium Dew, anchored behind Escape Reef near Shingle Point, reported waves breaking over the wheelhouse coating the tug with mud. Buildings at Tuktoyaktuk, 200 to 30 m from shore were coated in frozen mud (Anon., 1971b). The entire sandspit at Nicholson Peninsula DEW-line site was awash and marked by 1 m breakers. As a result of the washover, the spit was 30 m narrower after the storm.

Some information on storm surges is available for the Chukchi Sea, mainly from observations and recordings at Barrow (Hume and Schalk, 1967). But the setting at Barrow is very different from that of the Beaufort Sea coast in general, and surges recorded at Barrow do not appear on the records at Oliktok or in Canada (Mathews, pers. commun., 1978). Thus the Beaufort Sea surge of 1970 was not an unusual event at Barrow, and the Barrow storm surge of October 1963, which flooded much of the Naval Arctic Research Laboratory area (Hume and Schalk, 1967), was about .5 m below the level of the 1970 surge on the Colville Delta (Helmericks, pers. commun., 1978) and was comparable to the normal spring flood stage of the Colville River.

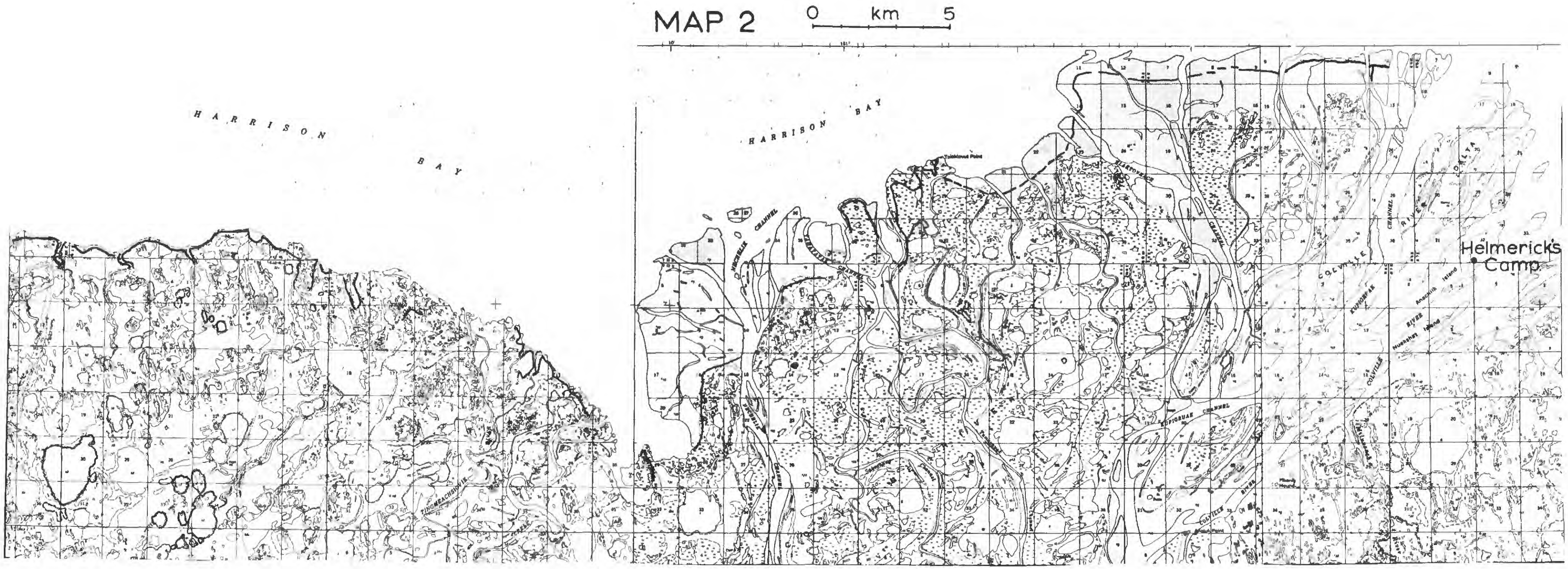
Results

Configuration of driftwood line.- The driftwood line, where it could be easily mapped from the air, is shown on maps 1 through 5. These maps are keyed to boxes on Figure 1. The elevation of the tundra surface, as shown on these U.S.G.S. topographic sheets, is in error, especially along Simpson Lagoon, where discrepancies of up to 4 m are found (Lewellen, 1977). Thus the elevation of the driftwood line cannot be read directly from the maps.

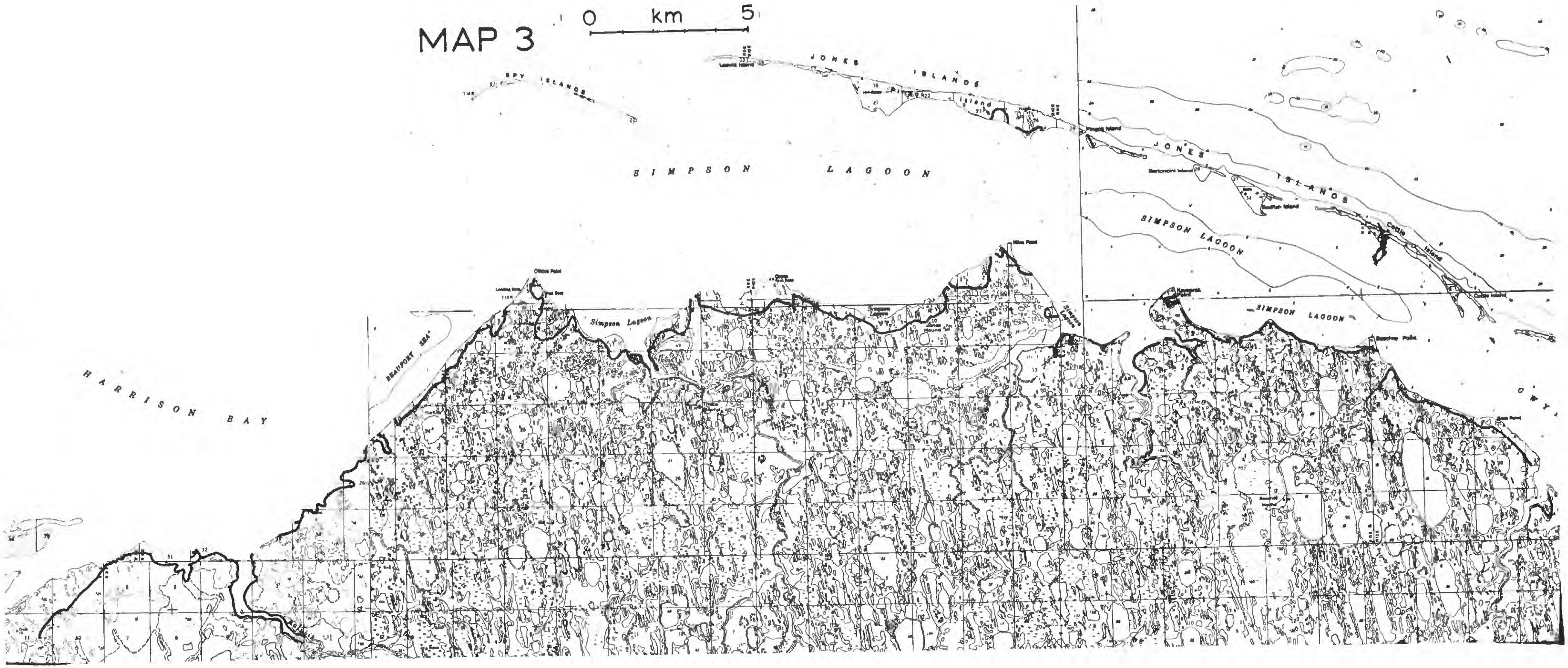
The distance of the driftwood line from the shore varies from 20 m to about 5000 m on the Kuparok and Colville Deltas. But on the deltas

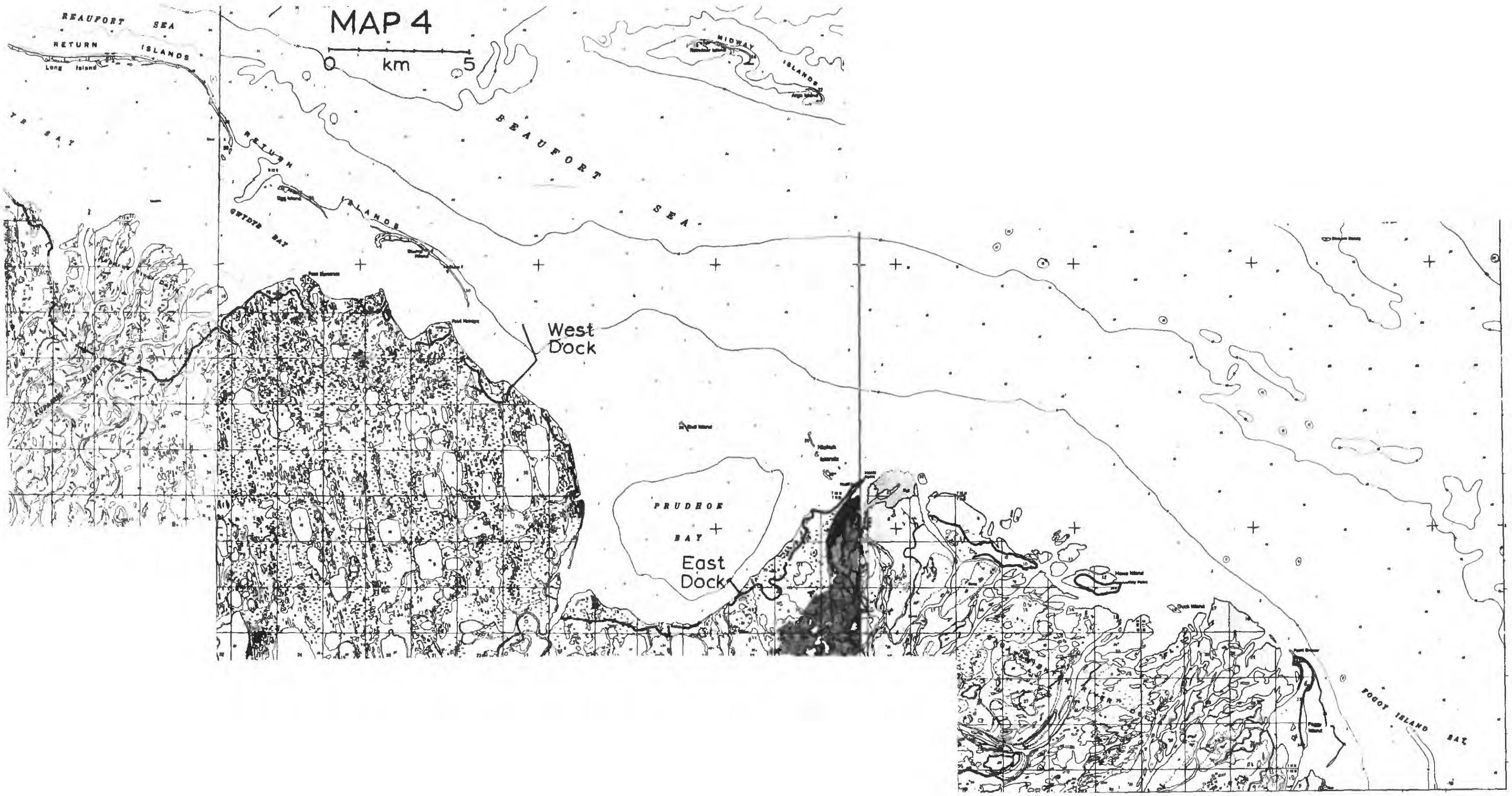

MAP 1
0 km 5
BEAUFORT
HARRISON
HARRISON BAY
HARRISON BAY
KOGRU RIVER
KOGRU RIVER
Eskimo Islands

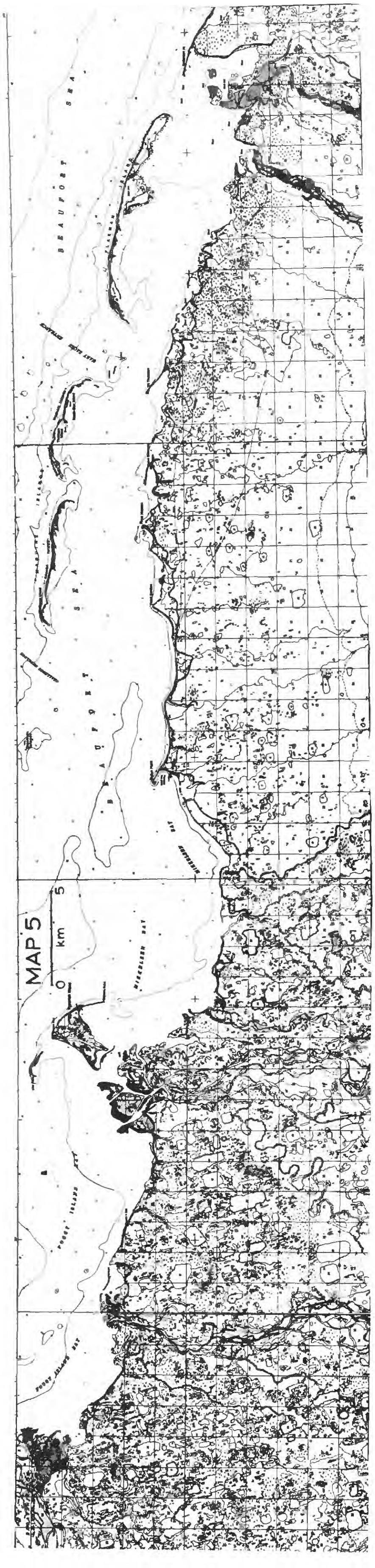
MAP 2


0 km 5
HARRISON BAY
HARRISON BAY
Helmericks Camp
COLVILLE
CHANNEL
RIVER

MAP 3


0 km 5
SPY ISLANDS
JONES ISLANDS
SIMPSON LAGOON
Simpson Lagoon
HARRISON BAY
BEAUFORT SEA


MAP 4
0 km 5
BEAUFORT SEA
RETURN ISLANDS
Long Island
GWYDYR BAY
MIDWAY ISLANDS
West Dock
East Dock
PRUDHOE BAY
FOGGY ISLAND BAY


MAP 5
0 km 5

the lines are difficult to trace, because a well defined shoreline is so far away and the driftwood is scattered about widely. Storm surges also interact with river floods mixing wood freshly brought down from the interior with wood from the sea. The driftwood line on the delta plains therefore is dashed. In many localities two or even three distinct driftwood lines could be identified from the air (Fig. 4). The second highest line could, in some cases, be related to a westerly storm of August 1975, but no attempt was made to map this event. It was .7 to 1.2 m lower than the 1970 surge. Materials set adrift during positive storm surges are moving eastward along the coast. Therefore westward facing slopes, often oriented at right angles to the general trend of the coast, intercept more wood than land surfaces sloping northward toward the open sea (Fig. 5). Coastal depressions which open westward to the sea, as the creek valley in Figure 4, often have well defined driftwood lines on opposing slopes and generally catch abnormally large amounts of flotsam.

Elevation of driftwood line.-The elevation of the highest driftwood line shows large variations, ranging from about 1.4 m to 3.4 m above sea level.These measured values were plotted and the height above mean water level is shown by the contours in Figure 6. We were able to read the elevation of the flotsam above sea level to the nearest centimeter, but have rounded the values off to the nearest decimeter. At a number of stations we have doubts about the elevation readings given in Figure 6, due to discrepancies between our measurements and other information on surge height. We will discuss these problems, proceeding along the coast from west to east.

The value of 1.4 m at the Colville River delta is probably too low

Figure 4. - Two driftwood lines at different elevations, paralleling a westward-opening drainage. The higher line records the 1970 storm surge, and about 1 m lower is an accumulation dating a 1975 storm.

Figure 5. - Driftwood line on westerly slope, facing into the surface drift of the 1970 storm surge. Opposite side of estuary lacks driftwood. White driftwood line parallels linear relief feature, separating surfaces with differing morphologies.

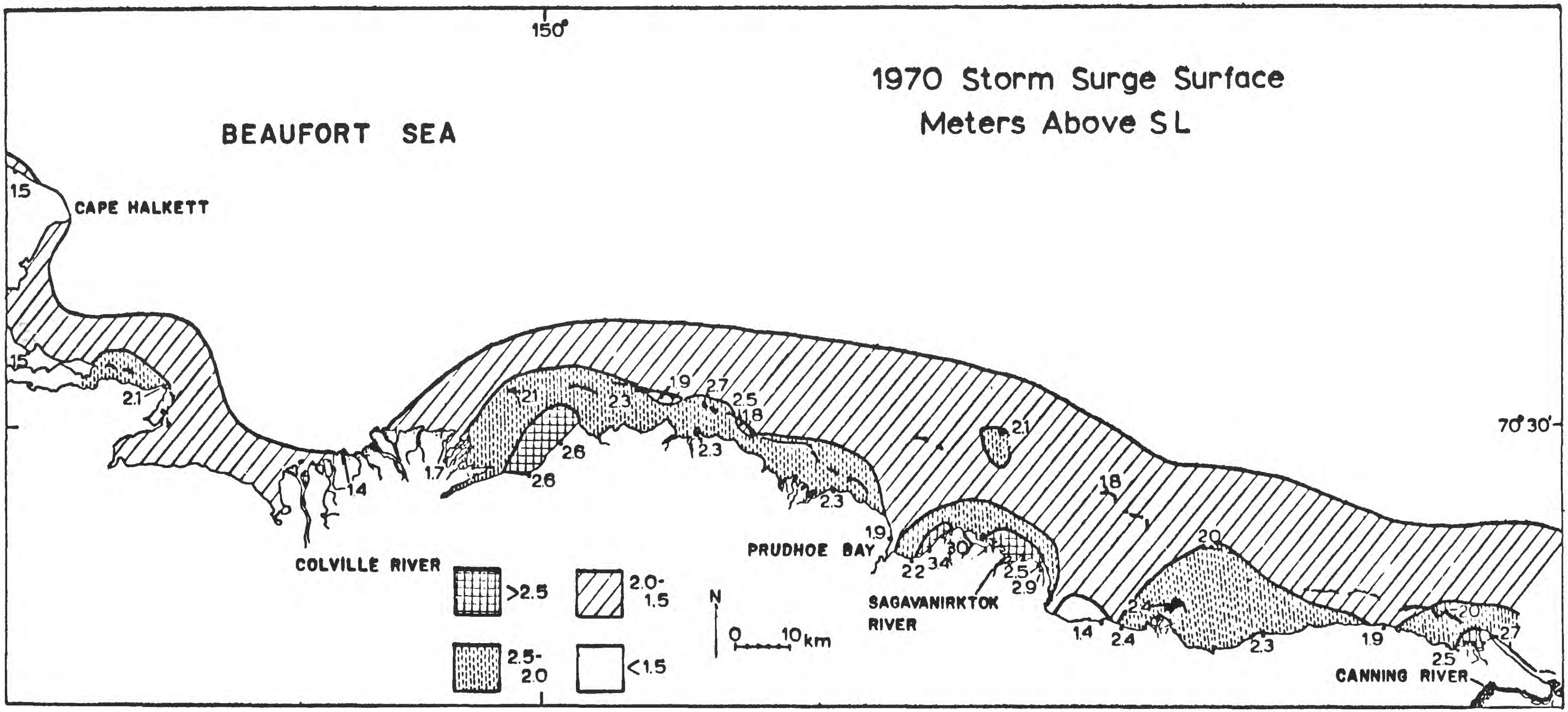


Figure 6.- Height of 1970 storm surge above mean sea level, as measured from the elevation of driftwood found on the mainland and islands. Note pile-up of water on the east side of shallow embayments and the lagoon near the Canning River.

because it was referenced to an elevated sea surface from the dnamic and steric contribution (fresh water) of the river. The 2.1 m value for Thetis Island is also too low because the cabin of Helmericks, located on ground equally as high as that on which the highest driftwood was found, was washed away in 1970. Furthermore, for neighboring Spy Island, Reimnitz et al. (1972) reported an elevation slightly above 3 m. This estimate was made by referencing the flotation line of stranded bergy bits to sea level and allowing for the effects of a seaway during the grounding. This was probably compensated for largely by the fact that up to 1.5 m of ice keels were buried in the island surface. A surge height of 3 m for this area would also be in line with an eye witness estimate (Dygas and Burrell, 1976). On the tundra-capped part of Cottle Island we made one stop for elevation measurements. There a well-developed driftwood line on the seaward side was less than 100 m distant from an equally pronounced accumulaton on the lagoon side. The elevations were 2.5 and 1.8 m, respectively. The difference is due either to high wave run-up on the seaward side and protection on the lagoon side, or to a later time of deposition of the materials on the lagoon side. On Cross Island we measured the height of a natural accumulation of driftwood at 2.05 m, but a still higher accumulation is present which we suspect has been piled up by man. In any case, the small Eskimo hut (40 to 70 years old) on the island, which was severely damaged during the storm, would have been submerged at least .8 to .9 m. None of the lumber found as far as 1 km distant from the hut, and clearly identifiable as a part of it, now lies more than 1.2 m above normal sea level. We do not have a good explanation for this. On the east side of Prudhoe Bay we found the highest driftwood, 3.4 m. We were doubtful about this reading because the wood was found only a few meters inland from the edge of a near vertical, westward-facing bluff. However, this elevation measurement is supported by eye witness accounts from personnel of Arctic Marine Freighters at the East Dock nearby (about 3 m). Driftwood found on Narwhal Island was measured at heights up to 1.8 m above sea level. Viewed from the air, the highest part of the island, at 2.5 m, shows traces of what appear to be current-produced bedforms. Therefore we believe that the island may have been overtopped during the 1970 storm. Also, the 2 m value measured on the highest part of Pole Island, may well be conservative. Lastly, a reading of 1.85 m was obtained on a driftwood line on the mainland coast near the west tip of Flaxman Island, where a gravel storm berm on the present beach is up to .3 m higher.

Configuration of sea surface during the 1970 surge.- The elevation of the sea surface during the 1970 storm surge was contoured in Figure 6, based on our measurements on land and on the islands. Along the shores this surface may be .5 to 1 m in error. These errors are inherent in the driftwood line and its relationship to mean sea level, as previously discussed. The offshore extent of the surface higher than 1.5 m is arbitrary, but it is known that storm surge amplitudes decrease rapidly with distance from the coast (Henry, 1975).

Vegetation patterns related to the driftwood line.- Summer ground observations made locally during the first three seasons after the storm suggested that the tundra vegetaton was killed as far inland as the driftwood line. Locally there are patches of vegetation with different color intensities near the shore than those landward of the driftwood lines, as for example in Figure 7. But today, eight years after tundra

Figure 7. - Black-and-white print of color infra-red photo showing faint driftwood line trending from the left lake to lower left of photo. Region with dark patches of vegetation does not coincide with area indundated by saltwater in 1970. Tire tracks on beach give scale.

Figure 8. - Close-up view of driftwood deposited by the 1970 storm surge. Note barrel for scale. Smooth well drained slope leading to higher ground on right lacks evidence of higher surges, and should preserve such records for at least 100 years, but probably 200 to 300 years.

vegetation was inundated by salt water, salt-burn patterns cannot be used to map the extent of inundation.

Composition of the driftwood line.- The wood in the highest driftwood line is generally sound, giving evidence for a slow rate of decay (Fig. 8). Most of the wood has probably gone through a number of cycles of drift and rest, and 95% of it appears to be fresh enough to be set adrift again. Logs up to 45 cm in diameter and 10 m long are mixed with small trunks, branches, and sticks (Fig. 8). Logs more than 15 cm in diameter do not originate in drainage basins of Alaska's North Slope because they do not grow at this latitude and elevation. We believe that most of this material comes from the drainiage basin of the Mackenzie River and not from the Yukon or other rivers draining to the Bering and Chukchi Seas. This opinion is based partly on findings by Giddings (1952), who studied driftwood in the Canadian Arctic and on the predominance of westerly coastal currents. Much of the large lumber on the beaches and in the high driftwood line has been notched or chipped with crude tools. We believe that most of these marks are more than thirty or forty years old, dating from the time when natives using such tools inhabited the coast. Along with the natural wood, the high driftwood line also contains varying amounts of milled lumber, pallets, treated pilings, and other debris. The ubiquitous oil drum is present in many places, but under favorable conditions it moves with a strong wind on flat terrain, and therefore is not a good indicator of the extent of flooding. Small amounts of glassware, jars, bottles, plastic, and light bulbs, are also found in the high driftwood line. Materials in direct contact with the tundra surface are slowly being incorporated into the vegetative mat. Rare tundra slabs were found incorporated into the driftwood line.

Older surges and the extreme event.-Old and rotten wood can also be be found within the areas flooded in 1970. The largest logs seem to last the longest, and thus we commonly found surfaces of old logs barely protruding above the tundra mat, so rotten that they no longer supported the weight of a man. Nowhere did we find such materials at elevations above those of the 1970 surge, but in some places rotten wood was found coincident with the 1970 driftwood line. It always is very distinct from the driftwood moved by the 1970 storm surge. In areas where much driftwood collects, very old events, with all components decomposed, might be expected to show up as linear accumulations of compost, perhaps marked by different vegetation. We found no such evidence.

In most places studied, the land slopes imperceptibly, and therefore evidence for an "extreme event" ranging up to 1 m higher than the 1970 surge, might be found over a very wide area. In such areas, evidence for still higher surges is difficult to obtain. We found one location where the detection of a very high surge was facilitated by a smooth, well-drained, relatively steep slope leading to higher ground a short distance from the beach (Fig. 8). This location is at the mouth of the Canning River (Fig. 6), where at 2.7 m elevation, the driftwood line is relatively high, and where much driftwood accumulates. This eastern end of the long lagoon system acts like a natural trap for driftwood, as would also have been true in the past, but we found no evidence for surges higher than the one of 1970.

Discussion

Surge surface height.- The variations in the height of the surge surface are considerable. But they follow a predictable pattern based on model studies (Henry and Heaps, 1976). Shallow embayments open in the direction of the wind forcing the surge show maximum run-up. On the other hand, major promontories provide shelter and therefore show little surge run-up on their lee sides. In the study area (Fig. 6) a major pile-up of water occurred on the southeast corner of Harrison Bay, in the southeast corner of Prudhoe Bay, and at the eastern end of the long lagoon ending at the Canning River (Leffingwell Lagoon). The positive bulge off the eastern Sagavanirktok Delta may be explained in terms of water piling up against Point Brower, a high promontory east of the Delta. In the southwestern sectors of Harrison, Prudhoe- and Foggy Bays (east of the Sagavanirktok River), the water level remained relatively low. We expected to find evidence for a pile-up of water in the eastern end of Simpson Lagoon which apparently did not occur.

Recurrence of major surges.- Historical evidence suggests that storm surges of the magnitude of the 1970 event do not occur often. In the Mackenzie Delta area, the winds recorded during the September 1970 storm have a return period of 40 to 50 years (Anon., 1971a). Although this was the worst storm in the memory of even the oldest residents of Tuktoyaktuk, there was another severe storm on September 9, 1944 (Anon., 1971b). Luci Ahvakana, a native from Beechey Point near Prudhoe Bay, estimated that it had been 50 years since the last similar storm (personal commun., 1978). Bud Helmericks said that according to natives there was a similar storm in the early forties (pers. commun., 1978). R.F. Henry searched the historical records of the Mackenzie Bay area and found mention of two earlier surges: 1905 and 1929 (pers. commun., 1978). Thus, one could conclude that there has not been a surge of the 1970 amplitude since 1889, when the cross was erected.

Based on observations on weathering characteristics of wood used in native cabins, abandoned boats, day beacons, and other markers, and a comparison with driftwood found in the highest deposits, we estimate that the 1970 surge has not been exceeded for 50 to possibly 100 years.

Geologic effects of storm surges.- Shoreline erosion is a major contributon to the sediment budget of Arctic shelves, and this contributon may be larger than that of the rivers. Dygas and Burrell (1976a) show that along Simpson Lagoon the average yearly erosion rate is 1.4 m, but rates of up to 40 m have been documented in a single season (Short, 1973). The long-term averages generally are the result of short-term severe events (Dygas and Burrell, 1976a), when as much as 20 years of normal sediment transport can be affected (Hume and Schalk, 1967). Since bluff retreat is largely a result of thermal erosion of ice-bonded sediments, and this in turn requires an overtopping of the narrow beaches to bring the sea water in contact with the bluffs, a westerly wind is most efficient. A thermo-erosional niche (Fig. 9), extending as much as 10 m into the bluff is formed, triggering slumping and solifluction. During strong easterly winds, on the other hand, sea level is lowered, occasionally exposing 40 m or more of lagoon floor (Lewellen, 1977). At these times bluff erosion does not contribute to the sediment supply.

The reports of bluff retreat during the 1970 storm in the Canadian sector of the Beaufort Sea, the size reduction of a spit, and especially the mud coating of buildings far inland and of a tug at anchor (mentioned earlier), all point to the dynamic processes which occur during westerly storms. Thus it is not surprising to find that bluff erosion along Simpson Lagoon, where many data points are available

Figure 9. - Thermo-erosional niche resulting from minor surge in 1972. The sea overtopped the beach and undermined the coastal plain up to 5 m.

(Dygas and Burrell, 1976a), is higher on the west side of promontories than on their east side. There is ample evidence that the net longshore transport, and the direction of island migration is to the west (Short, 1973, Dygas and Burrell, 1976a). However, during the extreme events, when tremendous amounts of sediment are introduced into the sea and concentrations of suspended matter are extremely high near shore, the transport is in the opposite directon, to the east.

Ice gouging is very effective during westerly storms, bringing pack ice against the coast where it runs aground. This causes ice gouging and bulldozing of sediments toward the east, opposite to the general direction of ice drift (Reimnitz and Barnes 1974). The 1970 storm, which brought growlers and bergy bits up to the highest parts of the barrier islands (Fig. 3), produced gouges leading up to areas normally exposed above sea level (Reimnitz et al., 1972). Due to strong currents during these times, the gouges are being filled at the same rate at which they are produced (Reimnitz et al., 1972). Depressions up to 1.5 m deep, resulting from the melting of the ice above sea level, were found on the islands in following years (Short, 1973). These depressions attest to the depth of gouges made in shallow regions of the shelf. If the fetch and the resulting waves are large, as they were in Canada during the storm, long continuous gouges probably would not form because the ice is pounding in the sea and impacting the bottom at regular intervals. As the fetch decreases with the advancing pack ice front, the resulting gouges will become increasingly linear and regular. The process of ice gouging in a strong current results in winnowing and re-suspension of shelf sediment, as discussed by Reimnitz and Barnes (1974). Vibracores, which we obtained recently, show that periods of slow depositon of mud were interrupted by a number of severe events of current winnowing, when clean, ripple-bedded sand units of 10 or more centimeters in thickness formed, 20 or more kilometers from shore. Such sand units may represent storm surges of the 1970 magnitude.

Major changes in the size and configuration of barrier islands and bars seem to occur during the major storm surges. Argo and Reindeer Islands, charted in 1970 as single islands, now are double islands, probably breached during the storm. Gravel-filled drums which serve as foundations for a day beacon on Spy Island, seem to have originally been flush with the top of the island but they are now exposed up to 50 cm. This exposure, together with the extensive overwash deposits along the south side of the island, suggest that island migration occurs in steps related to major storms. Barnes et al., (1977) detected an anomalous seaward migration of the east end of Stump Island over a 20-year period and related this to the widening of the narrow funnel-like end of Simpson Lagoon during a westerly storm. The highest surfaces of all barrier islands in the area show the effects of current shaping.

Recent findings in the northern Bering Sea indicate that under otherwise similar conditions, a cold temperature storm surge may have very different effects on the coastline than a warm temperature surge (A. Sallenger, unpublished manuscript). The cold temperature storm surge was accompanied by beach accretion which Sallenger attributes to the possible effects of the formation of an icefoot during that time.

Storm Surge Scenario.- For the developer of offshore- and shoreline facilities required, for petroleum exploration and production, it would be useful to simulate the course of events that might be triggered by a major storm surge.

Open water conditions are a requisite for the generation of a major surge, since transmission of wind stress to the water is inhibited by the presence of shorefast ice. A severe westerly storm is the second requisite. A combination of these two factors restricts the time frame to the months of September and October. The pack ice edge during this time may be somewhere on the midshelf. There may be little or no warning of the storm, and wind velocity may increase from light to gale force within just minutes, as was reported from Canada. However, the water may start to rise before a change in local wind regime occurs. Maximum wave size will be reached within a few hours of the onset of the westerly storm, as the fetch is later restricted by the encroachment of pack ice on the the inner shelf regon. Swift easterly currents of 2 to 3 knots should be anticipated in the shallow regions of the shelf. Most positively buoyant items below the surge level will be picked up by the seas and moved eastward and onshore at a rapid rate. These items include boats, barges, fuel containers, lumber, and buildings, as well as driftwood. The greatest danger to artificial structures probably lies in the encroachment of pack ice. Solid fields of pack ice exert tremendous pressures, but even individual growlers, rolling and pounding with the waves, will act as huge battering rams exerting thousands of tons of force on any fixed structures. Such rams might impact the bottom to greater depths than the depths of incision of long, continuous ice gouges, and thereby endanger buried pipelines.

Major surges inundate rather extensive coastal regions. Because roads leading to causeways, and the causeways themselves, may be flooded, land-based relief and rescue operations using vessels such as small tugs, will be difficult. Vessels navigating in coastal waters generally rely on radar for positioning. A flooded coastline will be hard to recognize and navigation during the time of a surge will be difficult. Causeways at right angles to the force of the storms, such as the present West Dock, will probably be either breached or destroyed, just as the road at Oliktok Point was destroyed. The gravel fill of the West Dock might well plug the l-m deep entrance channel to Prudhoe Bay. Similar to the effects of major promontories, causeways would initially cause a pile-up of water, and therefore cause an abnormal inundation of the adjacent land.

Natural hazards are one of the main causes of oil spills, and the likelihood of a spill is great during a storm surge. The oil could cover regions as extensive as those shown in maps 1 through 5. In any case, the intrusion of salt water would make the lakes within those areas useless to man. Up to five years is required to restore them to normal freshness.

Winter storm surges.- Major surges occur during open water conditions where 2 to 3/10 ice cover may be considered open water (Henry and Heaps, 1976). But, winter surges, which occur during times of complete ice cover, have also been reported. Zubov (1945) describes an unusual rise in water level to 1.25 m above normal at Cape Cheliuskin in late January (p. 253). He also describes a "roller" of 1 to 2 m height (p. 254), moving into a bay in January and breaking up the 1 m ice cover which was complete. Furthermore he reports that"wind-driven fluctuations of sea level on the Severnaya Dvina did not cease throughout the winter, while the entire sea was solidly covered with ice"(p. 335). Winter storm surges have not always shown a correlation with storms. Henry (1975) recorded two surges of about 1 m height in the Canadian sector of the

Beaufort Sea during the winter of 1973/1974; one in November and another in January. Only the November surge was associated with local strong westerly winds (Henry and Heaps, 1976). These winter surges were recorded on three tide gauges; two onshore, and one offshore. The observation that offshore levels seem to be comparable to onshore levels under the fast ice cover is of extreme interest (Henry and Heaps, 1976), as it suggests driving mechanisms other than wind for some of the reported winter surges.

Murphy Clark of CATCO Inc. at Prudhoe Bay (who has had ten years of winter experience on the fast ice regions working with Rolligons and other heavy equipment) noted that flooding of extensive areas of fast ice along the coast and in lagoons does occur occasionally (pers. commun. 1978). We must assume that this flooding affects only the bottom-fast ice, which is not free to lift off the sea floor immediately with a rising water level. This phenomenon is commonly observed during surface flooding of fast ice by rivers, where only the floating fast ice rises to the top of the flood waters.

Driftwood certainly would not be moved by such winter surges, and most other summer-surge related processes, such as bluff erosion, will not occur. But since winter sub-ice processes have been largely ignored, and their potential is even rejected by some, we will briefly discuss one aspect of winter surges that the sedimentologist should consider. Lack of documentation, however, makes this purely speculative.

In lagoon and bay entrances where an ice canopy restricts cross sections, high flow velocities might be anticipated during winter surges. Ice coring data obtained in May and June, 1969, when the fast ice thickness is still near its maximum, indicated that the ice in the entrance channel to Prudhoe Bay was abnormally thin due to turbulence, and that at the shoalest point there was over 40 cm of water below the ice (Barnes et al., 1976). This leads to the conclusion that surges should affect Prudhoe Bay throughout the winter.

Brian Mathews operated a bubbler-type tide gauge at Oliktok during the winter of 1973. Three surges were recorded during January and February with heights of 94 cm, 140 cm, and 69 cm. He provided us with the 140 cm surge record, which lasted from January 8 through January 10. The trace was truncated at 140 cm height and the surge may have peaked at 160 cm. The pressure rise to 140 cm occurred over an 18 hour period.

In attempting to calculate flow velocities in the Prudhoe Bay channel during the surge recorded at Oliktok, we proceeded as follows:

Based on an ice growth curve for the region (Schell, 1974), the ice thickness at that time was estimated to be approximately 1.1 m. The area lying within the 1.1 m isobath of Prudhoe Bay, determined from U.S. Coast and Geodetic Survey smooth sheet #7857, is 15.6×10^6 m^2. The channel crossection was calculated at 175 m^2 with a maximum under-ice depth of .5 m, from recent, unpublished survey data of Peter Barnes. We made the following assumptions:

1) The free-floating ice within the bay rises 1.4 m along a sharp boundary following tidal cracks along the 1.1 m isobath.

2) The volume of water added to the bay equals the area of free-floating ice x 1.4 m (surge height).

3) The rise in water level occurs over an 18-hour period.

4) The ice on the relatively narrow entrance channel remains at the normal level, unbroken and rigid.

Based on these assumptions, the flow rate in the entrance channel would be 3.9 m/sec (about 8 knots). Raising the 1.1 m thick ice as proposed would cause flooding of the bottom-fast ice fringing the bay. This would nearly double the amount of water moved through the channel. Such flooding apparently occurred during a storm surge at Babbage estuary in early January, 1974 (Lewis and Forbes, 1975). We did not account for such flooding, as there are many problems with this model. Changing assumption No. 4 above, and allowing the ice canopy above the channel axis to arch upward 1.4 m, would greatly increase flow crossection and thereby reduce flow velocity to 1 m/sec (about 2 knots). There are numerous other ways in which the ice canopy might behave under loading by such a surge. However, in all the reasonable models we considered, flow velocity through the channel should be considerable and should lead to bed erosion and deepening. We observed no pronounced deepening during the following summer. This could be explained by 1) channel infilling between the time of scour and the time of our observations in August, 2) ice canopy reacting in an unknown, or unpredictable manner, 3) presence of erosion-resistant anchor ice or ice-bonded sediments along the channel floor, among other possibilities.

Knowledge of how a solid ice canopy reacts during a surge with water forced through a narrow entrance into a bay is critical for determining channel flow velocities. Apparently such knowledge is not available. There is evidence that in restricted basins, under certain hydraulic conditions, hydraulic pressure increases to a level at which explosive rupture occurs causing ice ejection and water spouting. It is interesting that such observations are either old, or from natives, people living with nature. In spite of the greatly increased activity over the ice in modern times, the unusual events are unlikely to be noticed. The modern observer is preoccupied with his narrow objectives, his time is limited, the transit is rapid, he is overpowered by the noise of engines, he is not searching for distant landmarks, and he returns for the night to safe quarters on land. From late November through January there is nobody on the ice. One old report comes from Parry (1826) who observed that large pieces of ice were thrown hundreds of yards as a result of pressure build-up below the ice canopy of a bay. We found another observation on the same subject in E. de K. Leffingwell's field notebook from the period 1906 to 1914, where he recorded an eye witness report from the mouth of the Aichilik River. Pieces of ice were thrown 15 m high with subsequent water spouting to 9 m high for several hours (entry for Dec. 19, 1910).

The possible effects of winter surges remains an unsolved problem. Numerous attempts of our own to learn more about this problem using current- and tide-recording packages in shallow waters and tidal inlets below the fast ice have resulted in extensive damage to the equipment or its total loss.

Conclusions

The line of driftwood deposited by the 1970 storm surge ranges in height from about 1.5 to +3 m above mean sea level, and its proximity to the water line ranges from 20 m to 5000 m on low delta plains. The driftwood line today does not coincide with a vegetation boundary resulting from salt water intrusion. Variations in the height of the storm surge follow a predicted pattern, with greatest water pile-up at the end of shallow embayments opening into the direction of westerly wind.

Historical information suggests that storms of similar magnitude to that of 1970 occur at about 25-year intervals, but our findings indicate that the 1970 surge height was not equaled during the last 90 to 100 years and may not have been exceeded in several hundred years.

Large amounts of sediment are supplied to the shelf during such surges from thermo-erosion of the coastal plain. Over long periods of time, westward-facing bluffs of promontories show higher erosion rates than eastward-facing bluffs. This reflects the importance of the short term effects of the rare westerly storms compared to the effects of the dominating easterly winds and waves. Major modification of barrier islands also occurs during the surges. All barrier islands were submerged and under the influence of breakers and currents, and, during late stages, the islands were also affected by gouging and pounding of large ice blocks. The pack ice brought in against the coast during a surge results in intensive ice gouging. If a major surge were to occur during a period of offshore petroleum exploration or production, damage can be extensive.

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