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Maximum Storm Surge Elevations in the Tuktoyaktuk Region of the Canadian Beaufort Sea

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ABSTRACT. Storm surges are a significant concern in the siting and design of structures along the Beaufort Sea coast in that the coastal relief is low and the magnitude of surges in this region is large. Coastal storm surge elevations along the southern Canadian Beaufort Sea coast were documented by surveying log debris lines in the Kugmallit Bay/Tuktoyaktuk region. Careful attention to site selection and survey technique resulted in estimated errors in surge elevation measurements of less than ± 0.3 m. The data indicate a local surge maximum has occurred at Tuktoyaktuk at approximately 2.4 m above mean sea level (MSL); lower maximum surge elevations (2 m above MSL) were documented to the north and west of Tuktoyaktuk. There is no evidence that higher surges have occurred during the last 100 years. A surge that occurred in August 1986 measured approximately 1.6 m above MSL at Tuktoyaktuk and decreased to approximately 1.4 m above MSL 20 km to the north and west of Tuktoyaktuk. These surge elevation data provide a basis for the calibration of numerical models of surge and can be used directly in siting and design analysis of coastal structures.

Key words: Beaufort Sea coast, storm surges, Kugmallit Bay, Tuktoyaktuk

RÉSUMÉ. La houle des tempêtes est une préoccupation importante dans le choix de l'emplacement et dans le plan des constructions le long de la côte de la mer de Beaufort, du fait du relief côtier peu prononcé et de l'amplitude très grande de la houle des tempêtes dans cette région. On a recueilli des données sur le niveau côtier de la houle des tempêtes le long de la côte sud de la mer de Beaufort au Canada, en faisant le levé des lignes de débris de bois flottés dans la région de Tuktoyaktuk et de la baie de Kugmallit. En raison du soin apporté au choix des sites et à la technique de mesure, on estime que l'erreur dans les mesures du niveau de la houle ne dépasse pas 0,3 m. Les données indiquent que la houle a atteint un maximum d'environ 2,4 m au-dessus du niveau moyen de la mer (n.m.m) à Tuktoyaktuk; des niveaux maximaux un peu moins élevés (2 m au-dessus du n.m.m) ont été relevés au nord et à l'ouest de Tuktoyaktuk. Il n'y a pas de signes indiquant que des houles plus élevées auraient eu lieu au cours des cent dernières années. En août 1986, à Tuktoyaktuk, une houle a atteint environ 1,6 m au-dessus du n.m.m. et, à 20 km au nord et à l'ouest de Tuktoyaktuk, a été moins élevée, avec une hauteur de 1,4 m. Ces données sur le niveau de la houle constituent une base de références pour calibrer les modèles numériques de la houle, et elles peuvent être utilisées directement pour choisir l'emplacement des constructions sur la côte et en dresser les plans.

Mots clés: côte de la mer de Beaufort, houle des tempêtes, baie de Kugmallit, Tuktoyaktuk

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INTRODUCTION

Storm surges occur as the result of strong wind stress on the water surface that creates a strong net displacement of water; they are seen as either a rise (positive surge) or fall (negative surge) of the water surface. Surges have been recorded during the ice-covered winter period but are not as large as those surges that occur during the open-water season. These wind-driven water-level changes tend to be accentuated in shallow water areas and along shorelines. The generally low nearshore gradients and low coastal relief of the Tuktoyaktuk area of the Canadian Beaufort Sea make this coast particularly susceptible to impacts from positive surges.

Episodic storm surges in the Beaufort Sea have previously been identified as a potential hazard to coastal structures (Department of Public Works, 1971; Henry, 1975; Henry and Heaps, 1976; Reimnitz and Maurer, 1978, 1979). These surges may reach elevations in the order of 2-3 m above mean sea level (MSL) and, as such, inundate substantial areas of low-lying coastal tundra. The surges occur during late summer and fall storms and are usually driven by strong northwesterly winds associated with storms. As part of the planning process associated with coastal development in the region, it is necessary to quantify risk associated with storm surges to provide a guide for development, particularly in the Tuktoyaktuk region.

Frequency and magnitude of storm surge occurrence is normally documented through the analysis of long-term tidal records and the return periods of particular surge elevations identified. However, tidal records for Tuktoyaktuk extend back only to 1961, with some significant gaps, and the largest known surges, in 1944 and 1970, were not recorded. As a result, an insufficient number of large surges have been recorded to accurately estimate return periods of potentially destructive surges. An alternative approach is to use numerical storm-surge models with surface wind stresses and pressure gradients as the driving inputs, but information on extreme winds over the Beaufort Sea is limited (Henry, 1984), and some field observations of extreme surge height are essential to establish confidence in the computations.

This study presents results from a systematic survey of log debris deposited on the tundra at the surge limit (Fig. 1), along the coastline in the Kugmallit Bay and Tuktoyaktuk region (Fig. 2). The objectives of the study were to (1) document the maximum surge levels, (2) document the spatial variation of surge levels and (3) estimate the frequency of occurrence of storm-surge events.

The survey technique was developed and refined during a 1985 field program near Tuktoyaktuk (Harper, 1985). A more extensive survey was conducted around Kugmallit Bay during 1986 (Harper, 1987).

BACKGROUND

There are two large surges listed in the historical record of the southern Canadian Beaufort Sea (Department of Public Works, 1971): one in 1944 estimated from interviews with local residents to be about 3 m above MSL and the other of similar magnitude in 1970. These surges are the highest that have occurred in the memory of the oldest residents of the region.

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FIG. 1. Oblique aerial photograph of typical pattern of log debris in the study area (Tuktoyaktuk Harbour, September 1986).

Forbes (1981) provides a discussion of storm log lines in the Babbage River estuary on the Yukon coast, 150 km to the west of the study area. Using sequential aerial photography, he noted that logs identified on 1944 photos (collected a few days prior to the 1944 surge) showed little evidence of movement in 1952 photos but had significantly changed in distribution prior to 1970 (photos collected a few days prior to the 1970 surge). Either the 1944 surge was relatively low in the Babbage River area or a major surge occurred there between 1952 and 1970. Since such a large surge is unlikely to have gone unnoticed at Tuktoyaktuk during this period, these observations demonstrate how surge elevations vary with locality. A survey by Forbes and Frobel (1985) along the Canadian Beaufort Sea coast documented log debris elevations in excess of 2 m above MSL, although many of the survey sites were in exposed locations subject to storm wave run-up.

Field observations from the Alaskan Beaufort Sea coast were well documented by Reimnitz and Maurer (1978, 1979), indicating that water levels may exceed 3 m above MSL during surges. Log line elevations were surveyed and used as an index of surge height. In some cases, historical data were used in conjunction with log line elevations to estimate the probable return period of the 1970 storm surge. The authors concluded that this surge (up to 3 m above MSL) represented a surge height "not equaled during the previous 90-100 years and may not have been exceeded in several hundred years" (Reimnitz and Maurer, 1979: 342). An interesting result of this study was that surges appeared to vary significantly in elevation over very short distances (1 m over a few kilometres distance). In consequence of these results, considerable care was taken in the present study to eliminate wind-wave effects of selecting well-sheltered sites, where large waves and associated swash are not likely to deposit driftwood material above the actual mean surge elevation.

METHODS

Site Selection

Methods used to document storm-surge elevations along the coast are discussed in terms of site selection and survey techniques. Proper site selection is critical to the success of this technique. In that we wanted to document *surge elevations* as opposed to surge-plus-swash elevations, sheltered embayment sites were preferred over exposed, open-coast sites. Most of our survey sites were in small embayments and rivers that have connections to the sea and restricted wave fetches (less than 1 km fetch). Potential sites were identified prior to the field surveys from vertical aerial photographs and oblique aerial videotapes. Final site selection was conducted during a low altitude overflight immediately prior to landing (Fig. 1).

The site was further investigated on foot to assure that the log debris was, in fact, deposited by storm surge and not by ice push or human activities. The area landward of the maximum visible log line was examined closely to assure that the maximum log

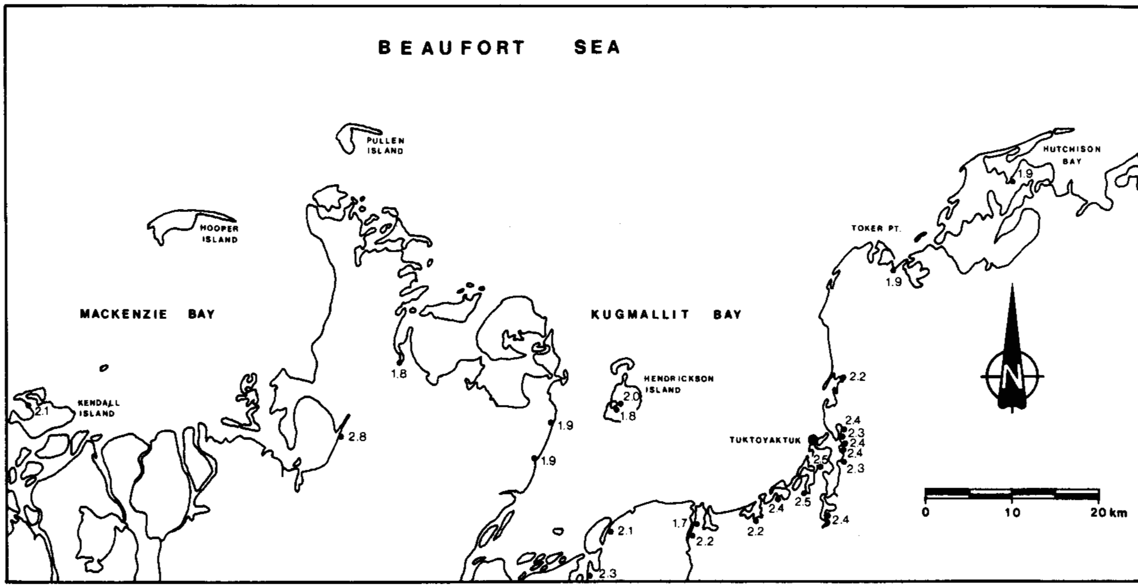

FIG. 2. Maximum storm surge elevations in metres above MSL in the Kugmallit Bay/Tuktoyaktuk area.

debris line was documented. Log lines were examined closely for the presence of cultural debris (e.g., flotsam, such as cans, bottles, plastics, lumber) that could be used to estimate the age of the log line.

Survey Technique

Critical aspects of the survey were to establish a common reference datum at all sites and to relate this to an absolute datum (e.g., MSL). Important components of the technique included: (1) the assumption that the still-water level at the time of the survey was the same as that of the tide gauge at Tuktoyaktuk and (2) the assumption that measurement of small wood chips in the log debris, usually found landward of the large logs, would be more likely to represent the maximum surge elevation than would large logs, which may ground below the maximum surge elevation.

In practice, a stadia rod was placed at the water's edge (at the still-water level), the time was noted and the elevation of the uppermost line of small wood debris was measured against this rod by use of a self-leveling surveyor's level. By measuring only the small log debris and eliminating the large logs, the scatter in measured elevation data was significantly reduced.

Following the field survey, elevations of all surveyed log lines were referenced to a common datum (MSL) using the measured tidal record from Tuktoyaktuk.

Accuracy

Several potential sources of error are associated with the survey technique. These include: (1) anomalies in site characteristics that make the site unrepresentative of the surge in the area, (2) leveling errors, (3) water-level transfer errors and (4) errors associated with estimating the log debris "limit."

It is possible that sites may not be representative of the local area due to variations in local "surge" levels or due to localized land elevation changes (e.g., subsidence or emergence that could occur around a pingo). Careful attention to site selection in this study minimized the potential for selecting unrepresentative sites. Survey data from nine sites in a very small geographic area (within a 5 km radius around Tuktoyaktuk) produced a mean standard deviation of ± 0.07 m among all nine surveyed sites and a maximum range of 0.23 m among the sites. As such, errors associated with "unrepresentative" sites appear to be less than ± 0.1 m at any site.

All level readings were verified in the field by a cross check with stadia readings. Level lines were not closed at all sites, but closure at several sites indicated a maximum 0.04 m closure error. At a location on Hendrickson Island, log debris lines in close proximity to each other were surveyed completely independently using a very complicated procedure of water-level transfer across lakes and were found to agree with each other within 0.14 m. Since these sites represented the most complicated surveys of the study (five separate tripod set-ups), it is estimated that errors associated with leveling other sites (one tripod set-up) are less than 0.1 m.

It is difficult to quantify error associated with water-level transfer, as the error may be due to poor estimation of the water level at the site or difference between water levels at the Tuktoyaktuk tide gauge and at the measurement site. The former error is estimated to be less than 0.02 m at any site because of the sheltered nature of these sites and the absence of waves. The latter error, due to difference in water levels between the reference and measurement sites, is also estimated to be very small (<0.02 m at any site). At one location near Tuktoyaktuk surveyed in both 1985 and 1986, the measured heights of the highest debris line were 2.37 ± 0.06 m and 2.37 ± 0.02 m above MSL respectively, supporting the assumption that water-level transfer errors were minimal.

There is potential error associated with estimation of the log debris limit at an individual site due to the scatter of logs. At least three measurements of the debris limit were made at each site and more where considerable variation was evident. The error associated with natural variance of the debris at a site can be estimated by averaging the standard deviations in elevation from all protected sites (n = 27) and is ±0.07 m (maximum standard deviation at a site is ±0.13 m).

The estimated errors of various survey components are summarized in Table 1. Assuming that all errors were introduced at a site and were the same sign, estimates of the log debris elevation could be in error as much as ±0.38 m. However, in practice, errors are likely to be offsetting, resulting in probable errors of less than ±0.10 m.

TABLE 1. Summary of estimated errors of survey techniques

Site anomaly errors	±0.10 m
Leveling errors	±0.10 m
Water-level transfer errors	±0.05 m
Error in estimation of log debris	±0.06 m (±0.13 m maximum)
Total	±0.31 m (±0.38 m maximum)

RESULTS AND DISCUSSION

The data indicate the regional variation in maximum surge elevations in the Tuktoyaktuk region (Fig. 2). Also of interest is a surge measured on the Tuktoyaktuk tide gauge on 23 August 1986, documented at a number of the survey sites (Fig. 3).

The survey measurements indicate that the maximum surge elevations in the Tuktoyaktuk area are approximately 2.4 m above MSL (Fig. 2). The measured surge elevation decreases to approximately 1.9 m above MSL, both to the north and west and along the western shore of Kugmallit Bay. This pattern of spatial variance in maximum surge elevation is consistent with numerical model results (Henry and Heaps, 1976), which indicate a local maximum at Tuktoyaktuk under northwesterly storm wind conditions. A similar pattern was observed by Reimnitz and Maurer (1978) along the Alaskan Beaufort Sea coast, where maximum surge and swash measurements were observed along northwesterly facing coasts.

The pattern of maximum surge limit is consistent with measurements of the surge limit due to a storm event on 23 August 1986 (Fig. 3). This surge peaked at 1.45 m above MSL (CHS tide gauge records), and debris associated with it was clearly distinguishable at the 1986 survey sites. The local maximum of approximately 1.6 m was at Tuktoyaktuk and decreased in both the northerly and westerly directions; along the west shore of Kugmallit Bay, this surge was 1.4 m above MSL.

The very slow deterioration of wood fragments under arctic conditions allows conclusions to be drawn about surge behavior over long periods of time. Observations of log debris throughout the study area suggest that the highest log debris lines are the result of the same surge event. Cultural debris was rare in the highest log line and consisted primarily of lumber pieces, which were not diagnostic in terms of age. However, at one well-documented location, a small plastic float was found within the log debris, and since plastic was relatively rare before 1944, we assume the log debris dates from the 1970 surge event. Based on the historical evidence of large surges in both 1944 and 1970 and on our observations of cultural material in the debris, we conclude that these surges were of approximately the same elevation. As such, the maximum log debris line at all sites probably contains a mixture of 1944 and 1970 log debris material, and all debris below this line was deposited after 1970. The lack of any debris above this line indicates that this 1944/1970 surge level was the highest in the area, at least within the last 100 years and probably within the last few hundred years.

The survey results produce a consistent and clear picture of storm surge in this part of the Beaufort Sea. The magnitude of the surges, up to 2.4 m above MSL, is of significant concern in the siting of coastal structures. In addition to the concerns about surges in the siting of structures, large waves associated with the surge-generating storms may elevate water heights as much as 1.75 m above the surge level in locations exposed to the northwest. As a result, siting analyses must assess not only the spatial variability in surge elevations within the region, but also the coastal exposure to northwesterly storm waves.

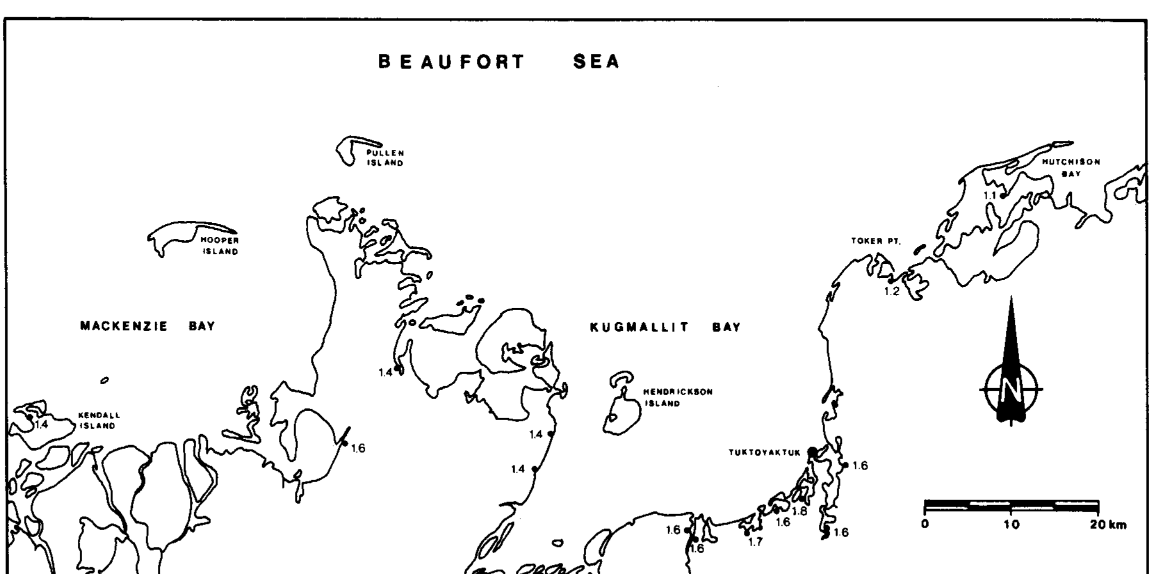

FIG. 3. Storm surge elevations in metres above MSL from a surge that occurred on 23 August 1986.

CONCLUSIONS

- The survey technique used to document storm surge elevations produced consistent results with an estimated accuracy of better than ±0.3 m.
- In the Kugmallit Bay area, a local maximum in surge elevation occurs at Tuktoyaktuk under northwesterly wind conditions.
- Maximum surge elevations at Tuktoyaktuk are approximately 2.4-2.5 m above MSL, whereas maximum surge elevations in coastal areas to the north and west are closer to 2.0 m above MSL.
- There is no evidence that higher surges have occurred during the past 100 years.

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