Long-term rates of coastal erosion and carbon input, Elson Lagoon, Barrow, Alaska

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**ABSTRACT:** Low bluffs along Elson Lagoon (71°19′N, 156°35′W) consist of ice-rich, fine-grained sediments, surface and buried peats, and ice-wedges. A time series of erosion rates from 1949 to 2000 along the 10.8-km long reach of lagoon coast was determined by georeferencing aerial and high-resolution satellite imagery. Erosion rates for the period 1979–2000 were 47% higher (0.86 m/yr) than 1948–1979 (0.56 m/yr) and 23% higher than the 51-year average (0.68 m/yr). A total of 28 hectares of land was lost between 1979 and 2000. A sustained shift of storm winds at Barrow appears to correspond to the trend of increased erosion along the shores of Elson Lagoon. Water depths adjacent to the most rapidly eroding section (2.75 m/yr) are relatively deep; an indication of active submarine erosion associated with greater fetch and higher wave energy. Initial estimates of annual sediment input are $1.6 \times 10^3$ m$^3$/km for mineral sediment and 63,500 kg soil carbon/km for this section of Elson Lagoon. These observations of erosion, sediment fluxes and transport are a contribution to the Arctic Coastal Dynamics (ACD) project.

1 INTRODUCTION

Although erosion is limited to 3–4 months of ice-free water, extreme rates in excess of 10 m/yr are documented along many arctic shorelines; average rates between 2 and 6 m/yr are common. Erosion and accretion of the circumarctic coastline are the focus of the international Arctic Coastal Dynamics (ACD) program (Rachold et al. 2000, 2002). The ACD emphases are on the contributions of coastal erosion to the sediment budget of the inner continental shelf, and on assessing the sources, transfer and fate of organic carbon. How these processes and rates are affected by climate change, related storm events and sea level rise, and their impacts on local communities and coastal infrastructure, are all questions of concern for our research. Long-term ACD observational key sites have been established in northern Alaska at Barrow (this paper; Peckham et al. 2002), along Beaufort Lagoon (Jorgenson et al. 2002) in the Arctic National Wildlife Refuge, and the southeast Chukchi Sea coast (Jordon and Mason 1999). This report presents results of historical and recent observations of erosion and initial estimates of sediment and organic carbon inputs at the Elson Lagoon site.

Observations of erosion rates and beach processes at Barrow began in the late 1940s (MacCarthy 1953) and continued into the early 1980s (Harper 1978, Hume & Schalk 1967, Hume et al. 1972, Lewellen 1972, 1973, Walker 1991). For the Elson Lagoon coast southward to Dease Inlet (approximately 30 km), Lewellen determined erosion rates using 1948/49 and 1962/64 aerial photography, and found rates typically in the range of 1–3 m/yr, but some rates as high as 10 m/yr. Along the Chukchi Sea coast, Harper (1978) reported a mean rate of 0.31 m/yr between 1949 and 1976 for the 75-km coastline from Barrow to Peard Bay. The Outer Continental Shelf Environmental Assessment Program (OCSEAP) produced several map-based reports that compared 1951 and 1983 navigation charts for almost all of the ~1800 km Beaufort Sea coast (Reimnitz et al. 1988, Barnes et al. 1992). The western third of the area, which is comprised of fine-grained deposits, had substantially higher erosion rates (5.4 m/yr) than did the remainder of the study area (1.4 m/yr), which has sandy to gravelly deposits (see also Naidu et al. 1984).

2 SITE CHARACTERISTICS

The Barrow peninsula (71°19′N, 156°35′W) is bounded on the west by the Chukchi Sea and on the east by the Beaufort Sea and a long chain of offshore islands (Plover Islands) that form the eastern boundary of Elson Lagoon (Figure 1). The two ACD key sections for the Barrow Peninsula are: (1) the 10.8 km section along Elson Lagoon (this study) and (2) the 20-km section along the Chukchi Sea (Peckham et al. 2002) which includes the 4.4-km Segment E of the present report.

The Elson Lagoon site consists of four distinct segments separated by several shallow estuaries or embayments. The lagoon coastline forms the eastern land boundary of the Barrow Environmental Observatory (BEO); a protected research area of 3021 hectares (7,466 acres) established in 1992 by the local native land owners (Ukpeagvik Inupiat Corporation,
UIC). A section (E) of the previously studied Chukchi Sea coast is included in this report to illustrate the differences between the two coastal regimes.

Maximum permafrost thickness in the Barrow region is about 400 m. The shallow active layer in these peaty and fine-grained, reworked lake sediments averages less than 30 cm as measured in 2002 along 11 transects. The dominant soil is the meadow tundra soil (Typic Aquiturbels) with an average carbon content of 50 kg/m³ in the upper one meter of soil and permafrost (Drew 1957, Bockheim et al. 1999). Massive peat inclusions are common in the uppermost permafrost. Ages of these buried peats range from several thousand years to 11,000 years (Brown 1965). Ice-wedge polygons as classified by Drew (1957) are manifested in a variety of surface morphologies that range from young, flat-topped polygons with narrow troughs, to depressed centers with raised rims, to high-centered polygons (HCP). The HCP occur along drainages and shorelines and reflect the melting of the underlying network of ice wedges. The ice contents of the sandy and silty sediments in the upper 3–4 m of permafrost decrease from 70% to 45% and are underlain by late Quaternary deposits (Brown 1968, Sellmann & Brown 1975, Sellmann et al. 1975).

3 METHODS

To assess the rates of coastal erosion, coastlines were mapped using high-resolution (1 m) IKONOS satellite imagery acquired on 16 July and 16 August 2000. A time series of older black and white aerial photography for 1949 (1:10,000), 1962 (1:18,700), 1964 (1:2400), and 1979 (1:63,360 color infrared) and 1997 (1:24,000 color) were scanned. For rectification, the August IKONOS image was used as the base map to obtain geodetic control points, and the photographs (tiff images) from the various years were rectified to the satellite image using ERDAS Imagine software. Rectification accuracy (relative to the 2000 image) ranged from 0.69 m RMS (root-mean-square) for the 1964 photography to 2.56 m RMS for the 1962 photography.

After the photography was rectified, the coastline (water’s edge) was digitised on screen. When compared to erosion rates measured over a long period, the effect of measurement error is relatively small (e.g., up to 0.1 m/yr for a 20-yr period). Estimated accuracy of the coastline boundary delineation is ~1–2 m. The coastlines then were used to determine the area of land lost for each period by closing adjacent coastlines into polygons. Average width of land lost per period was calculated as the area lost divided by the length the coastline segment.

A total of 14 permanent transects were established for measurement of elevations, thaw depths, and future bluff retreat (Table 1). A number of these transects are located at U.S. Geological Survey monuments (MacCarthy 1953). A hydrographic survey was conducted in August 2001 using a Ross 950 hydrographic survey kit. Figure 1 shows location of the seven off-shore bottom profiles.
4 RESULTS AND DISCUSSION

4.1 Erosion rates

The four segments differ in length, orientation, elevation, soils and polygon types and are collectively representative of this outermost section of the Arctic Coastal Plain. (Table 1, Figure 1). Mean elevations of the four segments range between 1.8 m (D) and 3.3 m (B) with maximum elevations of 4.4 m in the latter segment. Photogrammetric analysis reveals high spatial variation in rates of coastal retreat; erosion rates among the four segments ranged from 0.69 m/yr to 2.75 m/yr for the period 1979–2000, with an overall erosion rate of 1.27 m/yr (Table 1). Total loss for the entire Elson Lagoon study area between 1979 and 2000 was 28 ha. Over the 50-year period of record, Segment A lost 8.6 ha (21.3 acres) of coast. Even within a short segment there are large differences in erosion rates; for example, within Segment A, the maximum rate was 2.2 m/yr at the northernmost section, and the minimum rate was 0.1 m/yr for the 1948–2000 period. Major differences in spatial variation between segments are illustrated for the period 1948–2000; 120.8 m (2.32 m/yr) for Segment D (Figure 2) vs. 35.5 m (0.68 m/yr) for Segment A.

When comparing temporal differences along Segment A, there is a three-fold difference in rates among the more discrete time periods. Mean annual erosion rates were remarkably similar among the earlier three periods for 1948–1964 (0.58 m/yr), 1964–1979 (0.59 m/yr), and 1979–1997 (0.69 m/yr), but were much higher for 1997–July 2000 (1.47 m/yr). The recent 1.5-m storm-surge that occurred during 10–14 August 2000 along the Chukchi coast may have contributed to the average measured 1.15 m of erosion along Section A. Erosion rates at Segment A and D over longer periods were substantially higher during 1979–2000 than 1948–1979. The more recent period of 1979–2000 (0.86 m/yr) is 47% higher than the period of 1949–1979 (0.56 m/yr), and 23% higher than the 51-year average (0.68 m/yr). In contrast to these erosion rates, analysis of the 1979 and 2000 imagery for the 4.4-km, Segment E along the Chukchi Sea revealed that this gravel coast aggraded by an average 0.5 m/yr. Both erosional and aggradational coasts were observed on the imagery.

4.2 Environmental factors

The process of shoreline retreat is enhanced by the undercutting of the coastal bluffs (thermo-erosion notches; Walker 1991), and removal by wave action of the slumped and thawed materials that protects the coast from additional retreat. The frequency, intensity and duration of storms, and high water events affect
seasonal to multi-decadal rates of retreat, whereas local spatial differences in erosion are attributed to the spatial variations in bluff elevation, ice and organic contents of exposed sediments, water depth and fetch. Diurnal tidal movements at Barrow are limited to about 0.3 m (Beal 1968, Matthews 1970) and are not considered a major agent of erosion. Erosion ceases as bluffs freeze and the lagoon becomes ice covered commonly during the last half of October.

Hydrographic surveys in the offshore Segments A, B, and C confirmed the persistence of a submerged shoal at about 1-m depth parallel to the coast and approximately 2 km offshore, and the relatively deep 2.5-m trough between the crest of the shoal and the mainland (Figure 2). The shoal corresponds to bathymetric trends that appear on the early U.S. Coast and Geodetic Survey maps and as discussed by Lewellen (1973). A truncated bench extends 500 meters offshore of segment D; the same distance reported by Lewellen for 1964; although erosion has advanced over 100 meters inland, suggesting active submarine erosion. Furthermore, deeper water nearshore and longer fetches for Segment D allow more wave energy to reach further inshore. These observations and the lower elevations are consistent with the larger erosion rates along Segment D.

The observed increase in erosion rates between 1979 and 2000, for instance from 1.95 to 2.75 m/yr for Segment D (Table 1), may be attributed to an increase in the frequency and intensity of storms. Late summer and fall storms produce winds from the southwest and are observed to exert major erosion on the Chukchi coast (Hume & Schalk 1967, Walker 1991). There are few observations of erosion along the Elson Lagoon coast during these southwesterly storms, when water levels would be at maximum height. Major storm surges such as the October 1963 storm have breached the Barrow spit in the vicinity of Segment E (Brown & Sellmann 1966, Hume & Schalk 1967). Other major storms have occurred over the past half century; notably the storms of October 1954, 1956, 1977, 1993, 1998, September 1986, August 2000, and July 1993. Large quantities of sediments are redistributed in the lagoon during these extreme or extended wind events.

Analysis of the Barrow National Weather Service wind data from 1948–1999 reveals increases in wind-speeds from the east-northeast and west for the period 1984–1999 as compared to 1948–1984 (Figure 3). Winds from the easterly sector during the predominantly ice-free period generate waves that directly impact the site. This increase in windiness during the predominantly ice-free period appears to correspond to the observed increase in erosion rates along the Elson Lagoon coast. Future studies will document the relationships of wind duration and direction and water level as related to erosion.

4.3 Sediment inputs

Ground ice was estimated from data developed at Barrow (Brown 1968, Sellmann et al. 1975), and employs the method for computing sediment input reported in Reimnitz, et al. 1988). For this report, and
based on the unknown variations in ice-wedge distribution and amount of excess ice, we simply applied an average ground-ice value of 50% for all sections above sea level, a mean elevation of 2.5 m, and average erosion rate of 1.27 m/yr \((2.5 \times 1.27 \times 0.5 = 1.6 \times 10^3 \text{m}^3/\text{km})\). This approximation of sediment input agrees with the Reimnitz et al. (1988) computation for the 344 km stretch of the western Beaufort Sea coast which had an average rate of erosion of 2.5 m/yr. Their values for sediment input were \(3.5 \times 10^3 \text{m}^3/\text{km}\) for bluff erosion, and \(3.8 \times 10^3 \text{m}^3/\text{km}\) for offshore (submarine) sections. For this report we did not compute the subaerial contribution of sediment input due to the limited information on offshore ground ice content, permafrost degradation and sediment transport (Lewellen 1973). As concluded by Reimnitz et al. (1988), these ranges of annual sediment inputs are conservatively seven times greater than those derived from the major river catchments of Arctic Alaska.

Estimates of soil organic carbon (SOC) are based on soil units presented on the 1957 soils map (Drew 1957) and SOC values for the upper one meter of soils and permafrost (Bockheim 1999, unpublished data). We assigned carbon values 50 kg/m³ for these tundra soils. For this report we did not consider the carbon that occurs below the one-meter depth since the majority of soil and buried peats are observed to occur in this upper one-meter section. Our first approximation of organic carbon input to the lagoon for the four lagoon segments vary from 32,500 to 137,500 kg C/km (Table 1). This range is a function of erosion rates with an average of 63,500 kg C/km \((1000 \times 1.27 \times 50)\).

4.4 Landscape evolution

Britton (1957) in his classic paper on tundra vegetation described the thaw-lake cycle as the reworking of landscapes by the expansion of ponds into lakes, subsequent drainage due to shoreline erosion or stream capture, and formation of a new tundra surface on the reworked lake sediments. The age of modern lake formation and drainage has been estimated from radiocarbon dating of strandlines and headward erosion rates (Carson 1962, Lewellen 1972), surface peats (Eisner & Peterson 1998), and buried frozen peats (Brown 1965). For Segment A Brown obtained several radiocarbon dates from frozen buried peats in the range of 2200 and 6700 years BP (I-2602 and I-2048, respectively). The drained-lake basin in Segments C and D to the east of East Twin Lakes provides additional insight into the relative age of coastline retreat, lake drainage and landscape evolution (Figure 4). The northern configuration of the lake before drainage would have extended about 150 meters into what is now the lagoon. Based on an average rate of erosion of 1 m/yr, we estimate that the lake drained within the last 100–150 years. The surface peat layer from this basin was sampled for radiocarbon dating and yielded a date of 80^{14}C yr BP ± 90 (CAMS 77861; W. R. Eisner, pers comm., Jan 10, 2002) and approximates the onset of peat accumulation. Our estimate for drainage of the lake and the age of peat formation are in general agreement. Based on similar estimates, East Twin Lake is expected to drain within the next 30–40 years, since both headward lake and lagoon erosion are advancing over the remaining 100 m of tundra surface at rates of >1 m/yr. Drainage resulting from shoreline erosion is likely to occur as an ice-wedge polygon trough is intercepted by the lagoon; thus renewing the lake to land cycle.

5 CONCLUSIONS

Photogrammetric analysis confirmed the high spatial and temporal variations in rates of retreat along the Elson Lagoon coast. Erosion rates ranged from 0.65 m/yr to 2.75 m/yr for the period 1979–2000, with an overall erosion rate of 1.27 m/yr, and a loss of 28.2 ha. Erosion rates during this period were 47% higher (0.86 m/yr) than 1948–979 (0.56 m/yr) and 23% higher than the 51-year average (0.68 m/yr). For Segment A, erosion rates of 1.47 m/yr during the most recent period (1997–2000) were double the rates during prior intervals. Starting in the mid 1980s Barrow wind data show a corresponding trend toward more erosive surge- and wave-generating conditions. Water depths adjacent to the most rapidly eroding Segment D (2.75 m/yr) are relatively deep; an indication of active submarine erosion associated with greater fetch and higher wave energy. Initial estimate of annual sediment input is \(1.6 \times 10^3 \text{m}^3/\text{km}\) of sediment, a value that is
in general agreement with other calculated sediment inputs along the Beaufort Sea coast. This estimate is at least seven times greater than for those derived from the major river catchments of Arctic Alaska. Initial estimate of organic carbon loss is 63,500 kg C/km.

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REFERENCES


