

Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska

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ABSTRACT

A new quantitative coastal land gained-and-lost method uses image analysis of topographic maps and Landsat thematic mapper short-wave infrared data to document accelerated coastal land loss and thermokarst lake expansion and drainage. The data span 1955–2005 along the Beaufort Sea coast north of Teshekpuk Lake in the National Petroleum Reserve in Alaska. Some areas have undergone as much as 0.9 km of coastal erosion in the past 50 yr. Land loss attributed to coastal erosion more than doubled, from 0.48 km² yr⁻¹ during 1955–1985 to 1.08 km² yr⁻¹ during 1985–2005. Coastal erosion has breached thermokarst lakes, causing initial draining of the lakes followed by marine flooding. Although inland thermokarst lakes show some uniform expansion, lakes breached by coastal erosion display lake expansion several orders of magnitude greater than inland lakes.

Keywords: remote sensing, Landsat thematic mapper, Teshekpuk Lake, coastal erosion, permafrost, Alaska, Arctic, National Petroleum Reserve, erosion.

INTRODUCTION

The low-lying Arctic coastal plain north of Teshekpuk Lake (Fig. 1) in the National Petroleum Reserve in Alaska (NPPRA) hosts endangered and threatened species of waterfowl (Bollinger and Derksen, 1996), is the calving grounds for large herds of caribou (Kelleyhouse, 2001), and contains potentially significant petroleum resources (Bird and Houseknecht, 2002) (Fig. 1). Faced with managing the competing demands on this sensitive area, land and resource managers must consider the natural effects of a 30 yr warming trend that has resulted in ice-pack shrinkage and deterioration of permafrost (Hinzman et al., 2005; Belchansky et al., 2004; Osterkamp, 2003, 2005; Solomon et al., 1994), as well as the potential impacts of proposed human activity. A regional rapid quantitative assessment of

the area is critical for timely and accurate land-management decisions. The objective of this study is to quantitatively document rates of coastal land loss during the past 50 yr and describe the influence of coastal erosion on thermokarst lake evolution using Landsat thematic mapper short-wave infrared (TM SWIR) and topographic map data. The results contribute to an enhanced understanding of the dynamic and interactive processes that shape this landscape and help focus limited resources for further detailed study along a remote coastline.

The 2000 km² coastal plain north of Teshekpuk Lake has 130 km of coastline (Fig. 1). The study area is bordered to the east by Harrison Bay, to the west by Smith Bay, to the north by the Beaufort Sea, and to the south by Teshekpuk Lake (Fig. 1). The coastal-plain sediment, deposited during Quaternary sea-level highstands, includes narrow, low relief sandy beach ridges separated by broader areas of lower lying silty and muddy marine deposits (Fig. 1; Carter and Galloway, 2005). Much of the coastal plain is covered by thermokarst depressions, which contain a thin veneer of mostly muddy lake deposits underlain by either sandy beach-ridge or silty-muddy marine deposits (Fig. 1). The area is mantled by tundra that includes sedges, lichens, mosses, and dwarf willows (Mars et al., 2005). Permafrost generally is >250 m thick (Clow, 1998), extends to within 30–50 cm of the surface, and comprises as much as 75% ice and 25% sediment in the upper 5 m (Reimnitz et al., 1985).

An earlier study using National Ocean Survey charts (vintage 1950 and 1980) demonstrated that the area has some of the highest rates of coastal erosion in the region, locally exceeding 20 m yr⁻¹ of shoreline retreat (Reimnitz et al., 1985, 1988). Although the prevailing wind direction along the coast is from the northeast, westerly winds associated with major storms contribute significantly to coastal erosion; the tidal range is <1 m (Reimnitz et al., 1985). The shoreline consists primarily of 2–6-m-high permafrost bluffs, and the primary process of coastal erosion is wave undercutting and permafrost block collapse (Fig. 2; Reimnitz et al., 1985). Beaches are absent or poorly developed along most of the

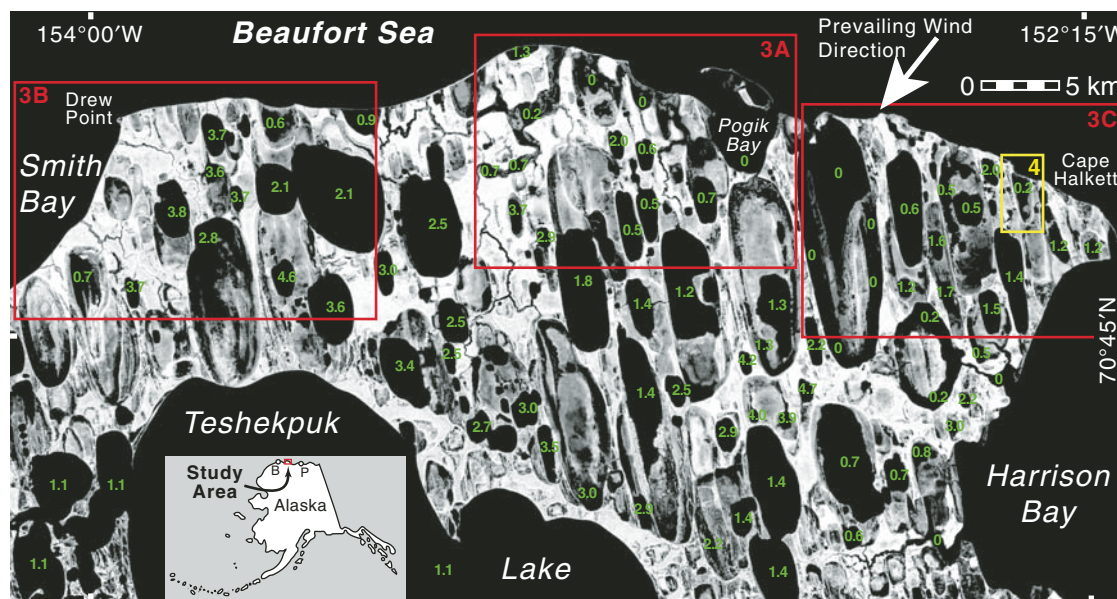


Figure 1. Landsat thematic mapper image (band 5) of study area, acquired in June of 2005. Gray areas in image are dry land and areas in black are water. Locations of areas in Figure 3 are highlighted in red. Location of area in Figure 4 is highlighted in yellow. Green numbers on lakes indicate lake elevation (in meters). Outline of study area on location map in lower left of figure is located between Barrow, Alaska (B) and Prudhoe Bay, Alaska (P).



Figure 2. Coastal erosion of mud-rich permafrost along Beaufort Sea coastline. Cliff height is ~3–4 m. Waves undercut permafrost and cause block slumping (center of photo). Photograph depicts no sand beach present to protect permafrost. (Photo courtesy of Gary Clow, U.S. Geological Survey.)

study area coast because of the predominance of permafrost comprising muddy coastal plain sediment. Thus, wave energy is dissipated on the permafrost bluffs, and undercut permafrost blocks fall directly into the sea (Fig. 2). Mud-rich permafrost blocks rapidly melt in seawater due to convective heat loss, and wave action suspends and transports muddy sediment offshore (Reimnitz et al., 1985; Kobayashi et al., 1999). Similar erosional processes have been described at Herschel Island, Canada (Harper, 1990). Sandy beaches, barrier islands, and spits are locally present where sand-rich permafrost bluffs are exposed at the shoreline, and those sandy beaches protect the permafrost bluffs from wave action (Reimnitz et al., 1985; Kobayashi et al., 1999). Reimnitz et al. (1985) found that coastal plain sediment type was the primary control on rates of coastal erosion. Average coastal erosion rates of 5.4 yr^{-1} and 1.4 m yr^{-1} were estimated in areas of permafrost comprising muddy deposits and sandy to gravelly deposits, respectively (Reimnitz et al., 1985).

METHODS

The observed rates of coastal erosion suggest that moderate resolution satellite data (30–50 m) can be used quantitatively to determine coastal land loss on a regional scale. Landsat TM data contain four 30-m-resolution visible near infrared (VNIR) bands in the 0.45–0.90 μm region, two 30 m SWIR bands in the 1.55–2.35 μm region, and one 120-m-resolution thermal infrared (TIR) band that extends from 10.4 μm to 12.5 μm (National Aeronautics and Space Administration [NASA], 2006). The satellite also has a large acquisition area of 180 km $\times$ 180 km per scene (NASA, 2006) and has been operational since 1985. The VNIR-SWIR spatial resolution, large orbital swath coverage, and period of operation of Landsat TM allow for assessment of coastal erosion along the Arctic coast of Alaska using a minimal number of scenes.

Ice and sediment-laden water typically have reflectance values similar to dry land in the VNIR region and can cause problems in defining shoreline (Mars et al., 2005). Landsat TM band 5 SWIR radiance data (band center at 1.65 μm) were used for mapping shoreline due to the high reflectance of dry land and relatively low reflectance of ice and turbid water exhibited in the SWIR region (Mars et al., 2005).

Over a 20 yr period, coastal retreat of 400 m at 20 m yr^{-1} represents 13.34, 30 m Landsat TM pixels. Average coastal erosion rates of 5 m yr^{-1} (Reimnitz et al., 1985) during the same time span represent 3.34, 30 m Landsat TM pixels. Thus, 30 m spatial resolution of the Landsat data was determined to be sufficient for change detection on 20 yr and 30 yr time scales based on observed rates of erosion (Reimnitz et al., 1985).

Image analysis of coastal erosion was compiled from U.S. Geological Survey (USGS) 1:63,360 topographic maps compiled from 1955 aerial photographs and Landsat TM data collected 22 July 1985 and 13 July 2005. The topographic maps and Landsat TM data provide 30 yr (1955–1985) and 20 yr (1985–2005) time increments for comparison. These three spatial images were registered and analyzed to produce net-change, derivative, color-coded images that reflect land loss and land gain during each time increment (Fig. 3).

Image-to-image linking was performed to determine that image-to-image registration error is $\pm 30 \text{ m}$ (1 pixel) between the 1985 and 2000 Landsat TM scenes. Image subsetting was performed to produce paired subscene images having exactly the same coverage and dimensions. A threshold was performed on each Landsat TM band 5 image to discriminate between dry land and ice plus water to produce a dry land and ice-and-water mask. Each mask is a byte image of 0 (ice and water) and 1 (dry land) digital number values. To produce a land-lost and land-gained map, the 2005 mask was then subtracted from the 1985 mask to produce an image in which the value -1 represents accreted land, the value 0 represents no land or no land change, and the value 1 represents eroded or submerged land.

The 1955 topographic maps illustrate shoreline at mean high water; the maps were scanned at 600 dots per inch and georegistered using a second-order polynomial warp registration algorithm. At least 9 ground control points were used for each digital topographic map, which produced root mean square (RMS) errors of <2.4 (6.1 m). The shoreline was vectorized from the georegistered topographic maps and rasterized to produce a 1955 shoreline byte image mask. The mask was subtracted from the 1985 mask to produce a land-lost and land-gained map. A mask of the coastline was used in conjunction with the 1955–1985 and 1985–2005 derivative land-lost and land-gained data sets to separately quantify the coastal erosion areas, 1985–2005 lake expansion areas, and Pogik barrier island areas. There is an estimated error of $\pm 10\%$ for erosion rates calculated from map and image data due to pixel size, geometric inaccuracies of the TM and topographic map data, and threshold misclassification.

To evaluate lake expansion from 1955 to 1985, the scanned, georegistered, 1955 topographic map image was coregistered to the 1985 Landsat TM data using image-to-image registration. Image-to-image linking of the coregistered 1955 map and 1985 Landsat TM images was performed to visually assess lake expansion. Lake elevations were determined from interferometric synthetic aperture radar data (IFSAR) acquired in the summer of 2002 (Intermap Technologies, 2006). The IFSAR data have 5 m horizontal resolution and 0.1 m vertical resolution.

RESULTS

Results are displayed as color-coded, time-incremented, land-lost and land-gained areas on a Landsat TM grayscale image (Fig. 3). The land-lost category includes areas of coastal erosion (tidal effects were assumed to be negligible because of low tidal range and the presence of sea bluffs that are generally higher than tidal range) along the shores of the Beaufort Sea, Smith Bay, and Harrison Bay, as well as thermokarst depressions in which the area covered by water increased. The land-gained category includes areas of spit and barrier island growth, areas of deltaic filling of lakes and bays, and areas of thermokarst lakes that partly or completely drained.

The spatial patterns of coastal erosion for the two time increments are generally similar (Fig. 3). However, results indicate a significant increase in the rate of erosion with time. For the entire study area, land loss

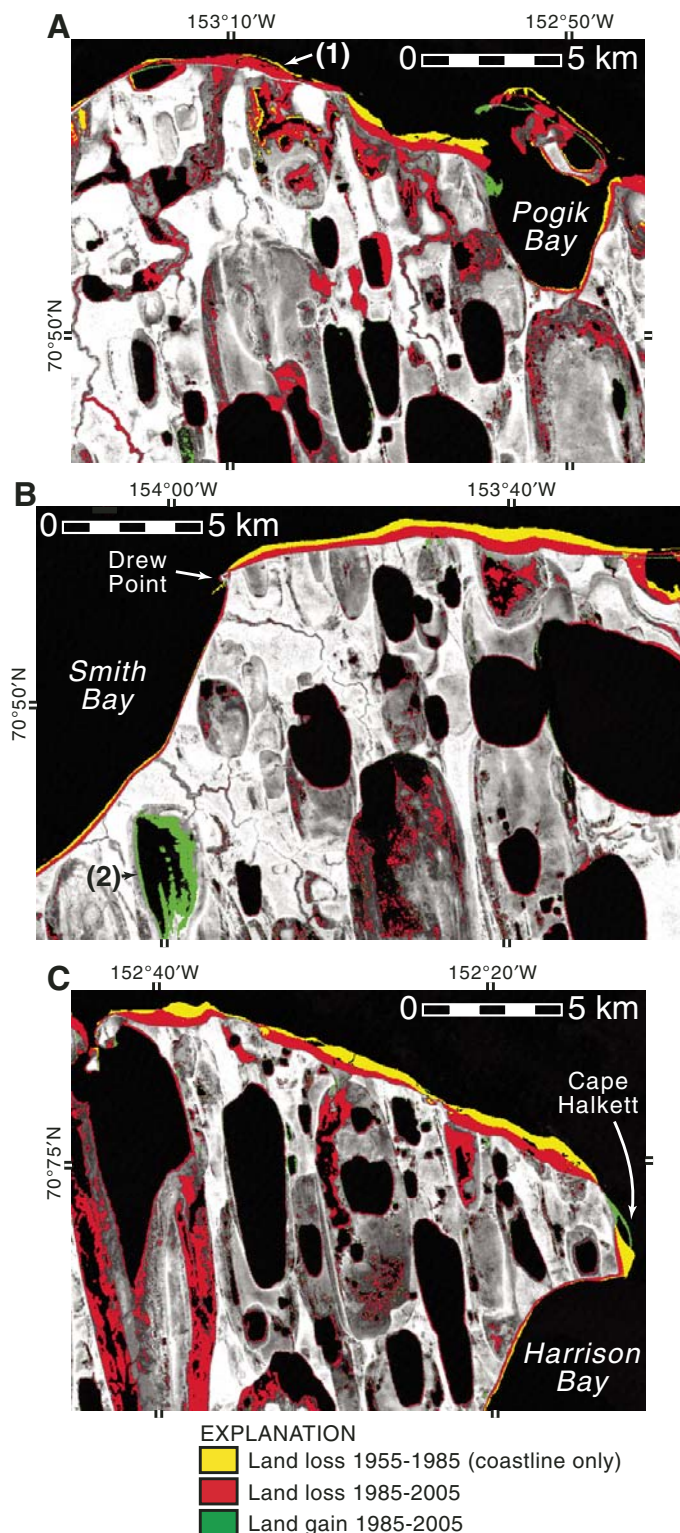


Figure 3. Coastal land lost and gained illustrations for (A) north-central part of study area including Pogik Bay, (B) western part of study area including Drew Point, and (C) eastern part of study area including Cape Halkett. Base images for A, B, and C are Landsat thematic mapper band 5 acquired in 2005. Areas in gray are dry land and areas in black are water. Location 1 in A is site of barrier island present in 1955 and absent in 1985–2005 data set. Location 2 in B is site of thermokarst lake that partially drained between 1985 and 2005.

attributed to coastal erosion during 1955–1985 is 14.3 km² compared to 21.6 km² during 1985–2005 (these numbers exclude barrier island migration north of Pogik Bay, where net change was minimal; Fig. 3A). Thus, average rates of land loss attributed to coastal erosion increased from 0.48 km² yr⁻¹ during 1955–1985 to 1.08 km² yr⁻¹ during 1985–2005.

Significant changes in coastal erosion rates influenced by the presence of a barrier island and the types of sediment eroded from the shoreline can be observed in the area west of Pogik Bay (location 1, Fig. 3A), where an 11-km-long barrier island was mapped in 1906 (Leffingwell, 1919). This barrier island is 75 m wide and 3 km long on the 1955 topographic map and it was reduced in area (presumably by erosion), migrated landward, and became welded to the coast (became a narrow beach) during 1955–1985 (location 1, Fig. 3A). From 1985 to 2005 the narrow beach persisted as the shoreline retreated as much as 400 m (location 1, Fig. 3A). The sandy barrier island documented by Leffingwell (1919) and visible on the 1955 topographic map apparently shielded the mud-rich permafrost bluff from direct wave action and erosion. Once the barrier was mostly eroded (by 1985), the predominantly mud-rich permafrost shoreline was more directly exposed to wave action, resulting in accelerated erosion from 1985 to 2005.

From 1955 to 2005 the shoreline retreated a maximum of 900 m along the broad headland that defines the northern shore of the study area. In contrast, a maximum of 300 m of shoreline retreat occurred during the same time interval in Pogik, Smith, and Harrison Bays (Fig. 3). These observations are consistent with those of Reimnitz et al. (1985), who concluded that rates of coastal erosion are greater on open-ocean shorelines than on partially closed shorelines such as those in bays and lagoons.

Excluding the land loss attributed directly to coastal erosion, an additional 90.0 km² of land loss occurred across the study area between 1985 and 2005. Most of this additional land loss is attributed to the breaching of thermokarst lakes by coastal erosion and the subsequent flooding of those thermokarst depressions by marine water, and a small proportion of this additional land loss is attributed to expansion of inland thermokarst lakes. The breaching and subsequent marine flooding of a thermokarst lake is illustrated in Figure 4. An intact lake in the 1955 topographic map image (Fig. 4A) has been breached by coastal erosion and mostly drained of fresh water in the 1985 Landsat TM image (Fig. 4B).

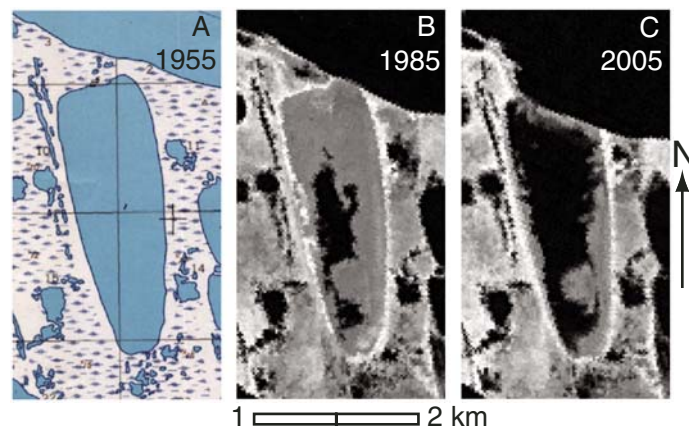


Figure 4. Topographic map and Landsat thematic mapper scenes illustrating coastal lake drainage and flooding of old lake bed to produce estuary or marine bay. A: 1955 topographic map depicts intact thermokarst lake (light blue represents water). B: Band 5 Landsat image from 1985 illustrates that coastal erosion has breached and drained thermokarst lake exposing ~70% of lake bed (black represents water). C: Band 5 Landsat image from 2005 illustrates that ~75% of lake bed has been flooded, forming new estuary or marine bay (black represents water).

The 2005 Landsat TM image (Fig. 4C) shows that the shoreline has continued to retreat landward and that ~70% of the former lake bed has been inundated, presumably by marine water. Continued coastal erosion and marine flooding likely will produce a more open estuary or marine bay similar to Pogik Bay (Fig. 3A). Marine flooding of thermokarst depressions and incised channels appears to be responsible for most of the 1985–2005 land loss near the shore (Fig. 3). Inland, away from any marine influence, most thermokarst lakes show small and uniform land-loss patterns that suggest a rise in lake level or uniform erosion of the lakeshore (Fig. 3). Visual assessment of temporal data sets suggests that thermokarst lake expansion was greater during 1985–2005 than during 1955–1985, and is probably due to regional permafrost warming (Osterkamp, 2003). Landsat TM data from 1985 and 2005 indicate that thermokarst depressions with marine connections (e.g., Pogik Bay) are laterally expanding more rapidly than inland thermokarst lakes, suggesting that flooding by marine water accelerates permafrost deterioration and thereby hastens land loss.

A relatively small amount (19.1 km²) of land gain is recorded in the study area between the 1985 and 2005 Landsat images (Fig. 3). This land gain resulted from spit formation down-drift from areas of coastal erosion (e.g., Cape Halkett, Fig. 3C) and from drainage of inland thermokarst lakes (e.g., location 2, Fig. 3B; Brewer et al., 1993). Many inland lakes have drained into other lakes or into the sea, evidently as the result of headward erosion of incised channels that are visible between and within drained lake beds (Figs. 1 and 3). Inland lake water levels, which are perched on permafrost, display significant local variation (Fig. 1) that creates natural elevation gradients along which headward channel erosion may occur. Deterioration of permafrost due to warming temperatures may accelerate this type of lake drainage by rendering the lakeshores more susceptible to erosion.

CONCLUSIONS

Analysis of topographic map and Landsat TM data indicates that coastal erosion has more than doubled along a segment of the Arctic Alaska coast during the past 50 yr, from an average rate of 0.48 km² yr⁻¹ during 1955–1985 to 1.08 km² yr⁻¹ during 1985–2005. Coastal erosion has breached numerous thermokarst lakes, causing initial draining of the lakes followed by progressive flooding by marine water. By this process, freshwater lakes evolve into marine bays over time. Landsat TM data are also useful for documenting historical drainage of inland thermokarst lakes, primarily by headward erosion of incised channels.

These results suggest that topographic map and moderate resolution satellite data can be used effectively to monitor short-term change in shoreline and coastal plain geomorphology in Arctic regions. Such observations may contribute to enhance understanding of recent and ongoing geologic processes and may provide a foundation to anticipate future change in dynamic settings. This information also provides a framework for scientifically sound land-management and policy decision making in sensitive Arctic areas.

Although the scope of this study did not include evaluation of specific factors that influence coastal erosion and thermokarst lake evolution, the results are consistent with climate change trends that have resulted in warming of permafrost and shrinking summer pack ice in the Arctic Ocean. The former would render permafrost coastal bluffs and inland lakeshores more susceptible to erosion by waves and headward erosion of ephemeral streams, respectively, and the latter would increase wave fetch and contribute to more intense summer storms. These suggested links represent hypotheses to be tested.

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