Geo-Mar Lett (2005) 25: 127–137
DOI 10.1007/s00367-004-0194-x

ORIGINAL

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Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, northwest territories, Canada

Received: 16 December 2003 / Accepted: 29 April 2004 / Published online: 15 December 2004

Abstract Aerial photographs from 1972, 1985 and 2000 were analyzed to obtain measurements of coastal change in the Mackenzie Delta region of the Beaufort Sea. Changes from 1972 to 2000 are dominated by retreat of the shoreline with average annual retreat rates of -0.6 m a^{-1}, but ranging as high as -22.5 m a^{-1}. Rates vary significantly both between and within zones of similar exposure, morphology and coastal geology with the highest average rates located in areas that are most exposed to northwest winds. In general, decadal-scale rates of change have remained constant during the 28 years encompassed by this study.

Introduction

The Canadian Beaufort Sea coast is characterized by rapid rates of erosion and accretion forced by long-term sea level rise and periodic storms. Much of the coastline is known to be eroding at long-term rates of 1–2 m a^{-1} but can be in excess of 20 m a^{-1} in selected areas (MacKay 1963; Forbes and Frobel 1985; Harper 1990). Recent exploration for hydrocarbons in the region along with observations of climate change impacts on air temperatures and sea ice duration prompted a re-examination of the rates of coastal change. This paper reports on the results of a study of coastal change based on aerial photography from 1972, 1985 and 2000. It was undertaken to update existing compilations of coastal change measurements based on earlier photography (Harper et al. 1985; Harper 1990). The resulting database of coastlines and coastal change measurements can be used to identify hazard zones (e.g. Solomon and Gareau 2003), assess sediment budgets and to provide input for resolution of boundary delineation issues. The analysis of the data in conjunction with coastal material and morphological mapping provides a basis for explaining aspects of spatial and, to some extent, temporal variability in coastal responses in the region.

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Background

In contrast to temperate environments, coastal changes along the Beaufort Sea occur during an abbreviated 3–4-month-long open-water season. Impacts of late fall and winter storms are mitigated by the presence of a complete sea ice cover from mid-October through June. The presence of sea ice in various concentrations during the short open-water season also constrains the development of storm waves and associated coastal impacts. Coastal change rates in the region are also known to be highly variable both temporally and spatially (Harper et al. 1985; Solomon and Covill 1995; Solomon et al. 1994). Temporal variation is likely to be largely driven by interannual and decadal-scale fluctuations in atmospheric and hydrodynamic forcing which affects storminess and sea ice distribution. Spatial variability is largely a function of geological, cryological (ground ice and permafrost) and geomorphological (including exposure) conditions which control the erodability of coastal materials and the littoral sediment supply.

The presence of ground ice is a factor which is unique to high latitude coastal systems and its volume both subaerially and subaqueously is thought to be an important component of the sediment budget and of nearshore morphological response (e.g. Kolberg and Shah 1976; Mackay 1986; Wolfe et al. 1998; Dallimore et al. 1996). The relative roles of hydrodynamically induced erosion and thermally mediated erosion (erosion induced by thawing of permafrost and ground ice and associated consolidation—also known as thermal abrasion) were first discussed at length in the English literature by Are (1988). The role played by ground ice was further demonstrated in the course of the development of a numerical model of combined thermal and hydrodynamic erosion (Nairn et al. 1998).

The short open-water season implies that compared with other ocean basins the meterologically forced oceanographic regime in the Beaufort Sea is relatively mild, so other reasons have been sought to explain the high erosion rates. Héquette and Barnes (1991) investigated the statistical relations between retreat rates, coastal geology and oceanographic forcing and concluded that none of these could adequately explain the observed variability in retreat rates. They suggest that removal of material from the nearshore profile by ice-keel scour must play a significant role in coastal retreat. Entrainment of nearshore sediment in the sea ice canopy and its subsequent transport offshore during spring break-up is considered to be an important process along the Alaskan sector of the Beaufort Sea (Reimnitz and Barnes 1987), although the process has not been documented in the Canadian sector. Our understanding of the relative role of sea ice processes in this region remains rudimentary at this time

Study area

The study area is in the northwestern region of Canada at the mouth of the Mackenzie River and includes most of its delta front (Fig. 1). The boundaries of the study area were constrained by the extent of the 2000 aerial photography. The coastal zone within the study area includes the principal port in the region (the Hamlet of Tuktoyaktuk) and provides habitat for enormous numbers of waterfowl, caribou, fish, and whales (notably beluga). The total length of the coastline studied is in excess of 2,000 km (at an approximate scale of 1:5,000).The interface between the land and the sea is a lowland composed of Holocene to Pleistocene sediments underlain by thick permafrost. Generally, the coastline of the Canadian Beaufort Sea is composed of unconsolidated but ice-bonded sediments, including mud, sand, gravel, and glacial diamict (Rampton 1982, 1988).

The western portion of the study area is dominated very low (1–2 m above mean sea level) coastal bluffs and plains of the Mackenzie Delta. Delta sediments are dominated by very fine sand and silt alluvium with abundant terrestrially derived detrital organic material (Rampton 1988). East of the delta, the land surface is a honeycomb of thaw (thermokarst) lakes, pingos and low to moderate relief (up to about 30 m) tundra uplands. Surface sediments on Richards Island are largely composed of morainal deposits several metres thick which overlie the fine sands of the Kittigazuit Formation (Rampton 1988). Massive ground ice is typically found at the interface between the underlying sands and overlying impermeable diamicts (Rampton and Mackay 1971; Rampton 1988). East of Richards Island (on the Tuktoyaktuk Peninsula), large portions of the coastal plain are characterized by lacustrine deposits (silt, sand and peat) interfingering with coarser sandy outwash deposits (Rampton 1988). Narrow ice wedge polygons are prominent features of the lacustrine deposits, which also host many large pingos. Ice wedges are also common in diamicts. Rampton (1988) reports that peat and fine-grained materials (e.g. deltaic and lacustrine deposits) commonly have moderate to high ice contents.

Coastal landforms include low-angle tundra slopes gradually being drowned by the encroaching sea, deltas, tidal flats, supratidal marshes, beaches and barriers, lagoons, and complex embayments formed by breaching of thermokarst lake basins (Harper 1990; Lewis and Forbes 1976; Forbes and Frobel 1985; Hill et al. 1990; Ruz et al. 1992; Solomon and Forbes 1993; Hill and Solomon 1999; Solomon and Gareau 2003). Cliffs are the dominant backshore coastal landform (Harper et al. 1985; Harper 1990). Cliff morphology ranges from temporarily stable vegetated slopes to nearly vertical wave-washed cliffs, rising in some places to more than 30 m, although cliff heights of less than 10 m are more common. Cliff erosion processes include gullying, basal wave-cut notch development, shallow sloughing (i.e. active layer detachment slides), block failures, and retrogressive thaw failures (RTF). RTF occurs where

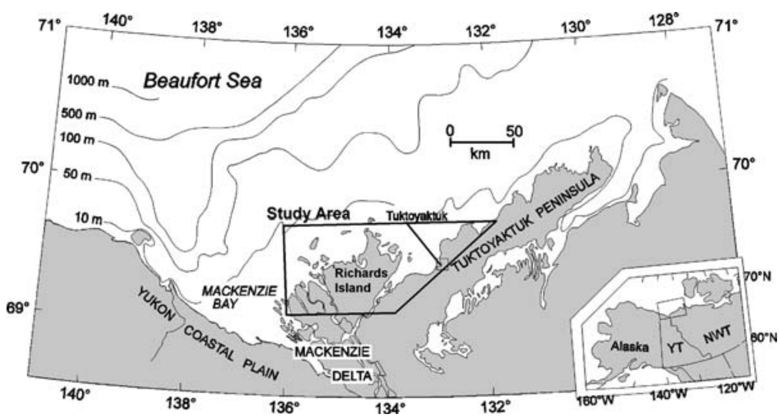


Fig. 1 The study area encompasses the coastal change measurement dataset for the period from 1972 to 2000

massive ice in the form of instratal sills or wedges is exposed in retreating headwalls. They develop amphitheatre basins with associated mudflows that transport sediment downslope from the headwall source to the shore. These features are concentrated along parts of the coast of Richards Island, and in the vicinity of Tuktoyaktuk (see Harper et al. 1985). They show a tendency for cyclical development, with stabilization and reactivation on time scales of about 10 years (Forbes and Frobel 1985).

The coastal areas of the Beaufort Sea are ice-covered for 8 to 9 months of the year. Freeze-up typically begins in October and break-up in June. The ice is often frozen to the seabed in water depths less than 1.5 m. Floating landfast ice extends offshore to a shear zone at the edge of the mobile polar pack. Pressure ridges, which develop in the shear zone, cause widespread scouring of the seabed in water depths greater than 8 m. The landfast ice zone is most extensive (>40 km wide in typical years) in the Mackenzie Delta region (Beaufort Sea Environmental Atlas).

During the open-water season, ice-free fetches of more than 100 km are common (based on data from the Canadian Ice Service weekly ice charts). Storm winds, which become increasingly frequent in late August and September, come predominantly out of the west and northwest, with a secondary mode from the east (Hill et al. 1990). Winds blowing over open coastal waters generate significant wave heights greater than 4 m with peak periods up to 10 s (Pinchin et al. 1985). The range of astronomical spring tides is no more than 0.5 m, but winds can generate positive and negative storm surges (Henry 1975). The maximum storm surge limit in the Tuktoyaktuk area is about 2.5 m above mean water level (based on surveys of driftwood lines—Forbes and Frobel 1985; Harper et al. 1988). Water level changes during surges occur over a few hours and can generate significant currents (>0.5 m s^{-1}) within restricted embayments (Solomon and Forbes 1993) and on the shoreface (Héquette et al. 2001). Storm surges occur during storms with northwest winds; these also allow larger waves to reach the shore and increase the limit of wave run-up.

Methods

Aerial photography was acquired by a private company (Tarin Resource Services Ltd) at 1:58,000 scale during August 2000. As described on the company website (http://www.tarinresource.com/), airborne kinematic GPS was used to provide control for the photography. The colour film was scanned in 24-bit colour at a resolution of 1,220 dpi resulting in a pixel size of 1.25 m. A soft-copy photogrammetric system was used to perform the aerial triangulation. The resulting image coordinate files that were measured during this process were checked, processed, and integrated with the triangulated data through a bundle adjustment program. Digital orthophotos were created using the orientation parameters for each photograph and georeferenced files for all points read within each photograph. The company estimates that the absolute horizontal accuracy of these data (the relationship of the data to itself rather than benchmarks) is in the range of 2 m. Investigations using existing ground control at Tuktoyaktuk and North Head show that the Tarin imagery is accurate to within about ±5 m of the correct geographic position. The imagery was purchased by special arrangement between the company and a consortium of government agencies.

The 1985 imagery was acquired in August; the 1972 imagery during the months of July and August. The 1:60,000 scale (1985) and 1:54,000 scale (1972), black and white aerial photos were purchased from the National Air Photo Library. Air photos from 1985 and 1972 surveys were scanned at 600 dpi, rectified and georeferenced using the Tarin orthoimagery as a base. Procedures in the Geographic Resources Analysis Support System (GRASS) were used to perform the rectification and georeferencing. The rectification procedure involved importing the scanned imagery into GRASS and assigning each image to an "imagery group". The GRASS procedure "i.points3" was then used to assign geographic control points (based on the 2000 imagery). The number of points ranged from 10 to 25 (a minimum of seven are required for a 2nd-order polynomial rectification). The proportion of the image which consisted of land controlled the number of points used (i.e. more land present in the image, the more points selected). The average root mean square (RMS) error for the selected points was kept below 5.0 m based on a 2nd-order polynomial rectification.

After the points were selected, the image was rectified using the GRASS procedure "i.rectify3". Initially, a 2nd-order polynomial rectification was used. If the results were not satisfactory, a 3rd-order polynomial rectification was used. The average output resolution of the rectified images was 2.5 m. The final rectified image was then inspected for accuracy against the original control points. If the result was not satisfactory, new points were selected and old points dropped until a satisfactory result was obtained. The imagery was also compared to surrounding rectified images for accuracy and to determine the overlay order in the final photo mosaic. Comparisons between the georeferenced images and existing ground control at Tuktoyaktuk indicate that the image to image horizontal accuracy is less than ±10 m.

For each aerial photo dataset, the shorelines were digitized by hand and the wet-dry line was used as a proxy for the high tide line. For the 2000 imagery, this took the form of a dark line or scarp since the photography occurred within weeks of a severe storm surge event. The line was more obscure in the 1985 and 1972 photography. Mapping the shorelines was performed by a single operator to maintain consistency. In the vicinity of the modern delta, very low, nearly vertical coastal bluffs are characterized by narrow to virtually nonexistent beaches. In these cases the shoreline was mapped based on the position of the bluff-edge or waterline at the time of the survey. Problems areas were encountered where vegetation extends to the waterline, where coastlines were shaded (e.g. low sun angles) and in areas of poor image contrast. The degree of horizontal accuracy in positioning the line adds an additional uncertainty to the measurements of approximately ±10 m, although under unfavourable conditions, the positioning error could be greater.

The 1972, 1985 and 2000 shorelines were used as a basis for making measurements of coastal change during the 13 (1972–1985), 15 (1985–2000) and 28 (1972–2000) year periods which intervened. An automated procedure was developed to insert an orthogonal line between the two shorelines and the length of the line was inserted into a text file along with its bearing. The measurements were checked by an operator to determine whether erosion or accretion occurred (i.e. whether the change in position was negative or positive). Measurements of coastal change were made for the 1972–2000 and 1985–2000 intervals every 200 m and were assigned a geographic point coincident with the 2000 shoreline. Coastal change from 1972 to 1985 was calculated by subtracting the change between 1985 and 2000 from the change between 1972 and 2000. The rate of retreat was calculated for each point by dividing the total amount of retreat by the number of years between each photo survey.

Following the automated procedures, the data was rechecked and obvious erroneous points were found and removed. These points were in error because the automated orthogonal line generation created problems where the ends of shorelines were not exactly coincident. Measurement points were also removed where checking revealed problems with the identification of the shoreline. This was especially apparent on wide, low gradient beaches. For this reason, measurements on spits were excluded in most cases. The remaining measurements should have an uncertainty of less than ±20 m. However, comparisons between these digitized shorelines and those derived from high resolution (1:5,000–1:10,000) aerial photos taken in the same years reveal maximum differences of less than 10 m in selected locations (Tuktoyaktuk and North Head). Therefore, while individual retreat rates of ±0.7 m a^{-1} (1972–2000) and ±1.3–1.5 m a^{-1} (1972–85 and 1985–2000) are within the error bounds of the measurements, we consider that errors for most individual retreat rate measurements are likely to be less than ±1 m a^{-1}. Measurements of coastal reaches that are based on the average of many measurements will have smaller statistical errors than the individual measurements.

Results

Measurements of coastal change were analyzed to determine the degree of variability within and between different time intervals and in different regions within the study area. Based on previous work (e.g. Harper 1990; Solomon et al. 1994) we know that there are potential differences in coastal stability between regions based on backshore morphology, elevation and material type and the degree of exposure to northwest winds. Morphology, elevation and material type were identified using data from the Geological Survey of Canada's Coastal Information System for the Beaufort Sea (Solomon and Gareau 2003). Degree of exposure to NW winds was assessed on the basis of generalized facing direction of the coastal reaches and the degree to which the coastal segment is sheltered by offshore islands. Five zones were defined based on variations in these factors (Fig. 2 and Table 1).

Summary statistics (Table 2) were evaluated for each zone and the combined dataset. The mean change rate for the set of measurements at exposed locations as well as for each zone is negative, in keeping with observations that the coast is largely erosional. For the entire exposed dataset, there is a decrease in the mean rate of retreat of 15% over the period 1985–2000 as compared to 1972–1985; the decrease in the means is statistically significant (>90%). The spatial distribution of change

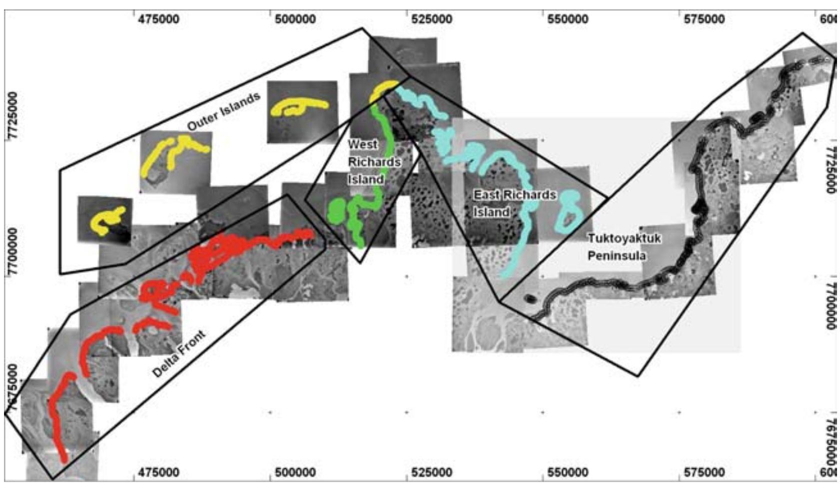


Fig. 2 Subsets of zones with differing coastal attributes and stability. See Table 1 and text for descriptions of the zones. Note: *grid tick* marks are 25 km apart

Table 1 Description of shore zones used to define variations in coastal change behaviour

Zone	Backshore form	Foreshore material	Exposure
Outer Delta	Very low bluffs (< 2 m)	Silt to fine sand	Mostly exposed to NW winds
Outer Islands	Low to high bluffs (2–30 m)	Sand and gravel	Exposed to NW winds
West side of Richards Island	Low to moderate bluffs (2–15 m)	Sand and gravel	Protected behind extensive shoals
East side of Richards Island	Low to moderate bluffs (2–15 m)	Sand and gravel	Protected from NW winds
Tuktoyaktuk Peninsula	Low to high bluffs (2–30 m)	Sand and gravel	Exposed to NW winds

Table 2 Summary statistics (in metres per year) for the exposed dataset and each regional subset (Fig. 3) for all three time intervals

Zone	*N*	Mean	Minimum	Maximum	Median	Standard deviation	Standard error
All 1972–2000	2697	−0.94	−15.33	3.84	−0.51	1.53	0.03
All 1972–1985	2697	−1.02	−16.86	7.31	−0.68	1.92	0.04
All 1985–2000	2697	−0.87	−22.50	6.57	−0.47	1.86	0.04
Outer Delta 1972–2000	717	−1.77	−10.67	2.66	−1.27	1.82	0.07
Outer Delta 1972–1985	717	−1.77	−16.86	5.48	−1.21	2.29	0.09
Outer Delta 1985–2000	717	−1.77	−11.75	6.57	−1.34	1.99	0.07
East Richards Island 1972–2000	571	−0.40	−4.65	1.95	−0.28	0.62	0.03
East Richards Island 1972–1985	571	−0.58	−6.24	3.19	−0.47	1.08	0.05
East Richards Island 1985–2000	571	−0.25	−5.09	4.84	−0.24	0.87	0.04
Outer Islands 1972–2000	196	−1.51	−15.33	2.86	−0.91	2.79	0.20
Outer Islands 1972–1985	196	−1.29	−11.58	5.29	−0.93	2.20	0.16
Outer Islands 1985–2000	196	−1.70	−22.50	5.59	−0.74	3.95	0.28
West Richards Island 1972–2000	251	−0.46	−4.99	1.05	−0.30	0.79	0.05
West Richards Island 1972–1985	251	−0.60	−7.58	4.65	−0.49	1.35	0.09
West Richards Island 1985–2000	251	−0.34	−6.48	2.97	−0.22	1.19	0.08
Tuktoyaktuk Peninsula 1972–2000	466	−0.75	−6.84	2.04	−0.44	1.28	0.06
Tuktoyaktuk Peninsula 1972–1985	466	−0.84	−10.95	4.68	−0.51	2.00	0.09
Tuktoyaktuk Peninsula 1985–2000	466	−0.67	−9.00	4.44	−0.34	1.48	0.07

rates over the period from 1972–2000 is illustrated in Fig. 3.

Outer Delta zone

Some of the most rapid rates of retreat (mean of -1.8 m a^{-1}) are associated with the exposed delta-front bluffs in the Outer Delta zone. Maximum retreat rates approach -20 m a^{-1} and there is no change in the rate between the time intervals. Harper et al. (1985) calculated mean retreat rates in this area of -2.4 to 2.5 m a^{-1} for the period 1952–1973. While there appears to be a decrease from the earlier interval to the more recent, Harper et al. base their average rate on a considerably smaller number of samples (37) measured only along the

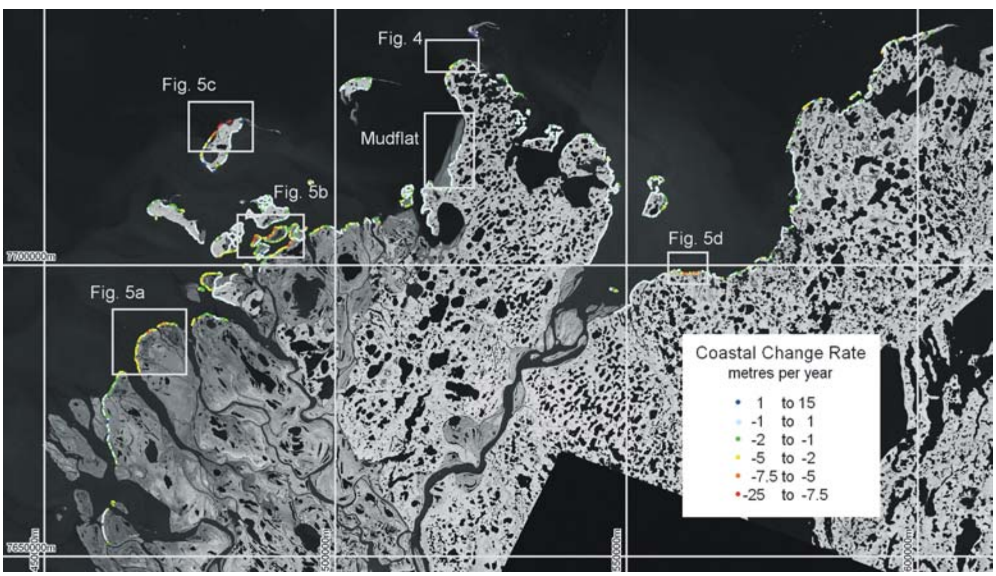


Fig. 3 Coastal change at all the exposed sites shows a distinctive zonation, with the highest rates of retreat associated with the Outer Islands and Delta Front. However, there is considerable variability within those zones as well. The net change from 1972 to 2000 is illustrated overlain on a Landsat image mosaic 1998–1999 (provided by Environment Canada). A high density of lakes characterizes the more ice-rich tundra to the east of the modern Mackenzie River delta. *Boxes* show the location of figures. *Grid lines* are 50 km apart

most exposed parts of this zone. Choosing only those points in the same region as the Harper et al data for the 1972–2000 period yields a rate of -2.6 m a^{-1}, similar to that found for the earlier period. Variability is also high within the zone with localized retreat rates ranging from -17 m a^{-1} and progradation rates up to nearly 7 m a^{-1}. The stable or accretional coastlines tend to be located at the southwestern end of the zone, in the lee of newly accreted shoals and islands at the mouth of an active distributary channel (Jenner and Hill 1998). Rapid retreat is centred on sections of coast that are exposed to the west and northwest as well as in locations which appear to be quite sheltered (along channels between the modern delta and coastal islands composed of older terrain). This spatial pattern of retreat and accretion is consistent between the two observation periods.

Outer Island zone

Relatively high mean rates of retreat (-1.3 to -1.7 m a^{-1}) are also associated with exposed fringing tundra islands and headlands found in the Outer Island zone. The highest individual measured retreat rates (up to -22.5 m a^{-1}) in the region are found in this zone. The slight apparent increase in mean rate in the 1985–2000 interval for the exposed parts of this zone is not statistically significant. The cliffs in this zone range from 5–30 m and are composed of sand and gravel with locally high ice content. Lower elevation, drained lake bluffs that are characterized by finer sediments are also found in the zone; these are where the highest retreat rates are found. However, in general, there is little difference between retreat rates of ice-rich tundra and drained lake shores. Lower rates of retreat are found along south and east-facing shorelines. There are notable gradients in local retreat rates that are related to well-defined littoral cells. As an example, at North Point (Fig. 4), retreat rates decline downdrift from the western end of the coastal reach (from -3.7 m a^{-1} to less than -1 m a^{-1}).

This zone is directly exposed to the high winds and associated storm surge and waves from the NW. Water depths in the nearshore increase fairly rapidly, allowing larger waves to impact directly on coastal bluffs during high water events. Less intense events with lower associated water levels may have less impact than infrequent more intense storms (Dallimore et al. 1996). Gradients in rate are related to variations in exposure and to updrift sediment supply. In the latter case, lower retreat rates in some downdrift locations are a result of buffering and protection by sediment deposition on the beaches and nearshore.

West Richards Island

Relatively low mean rates of shoreline retreat (-0.3 to -0.6 m a^{-1}) are associated with the west-facing coast of Richards Island. The decrease in mean rate from 1972–85 to 1985–2000 is statistically significant at 90%. Most of this zone is backed by low to moderate elevation tundra cliffs and vegetated slopes that are mapped as mostly or partially stabilized. The West Richards Island zone is sheltered from northwesterly storms by extensive sand and mud-flats and multiple nearshore bar systems deposited just off the coast and by the outer fringing islands to some extent. The shoals and bars are indicative of high sediment supply to this zone. The sediment source is a combination of erosion products from updrift sources (e.g. the outer islands) and suspended sediments from the Mackenzie River. These depositional features also act to dissipate waves that accompany

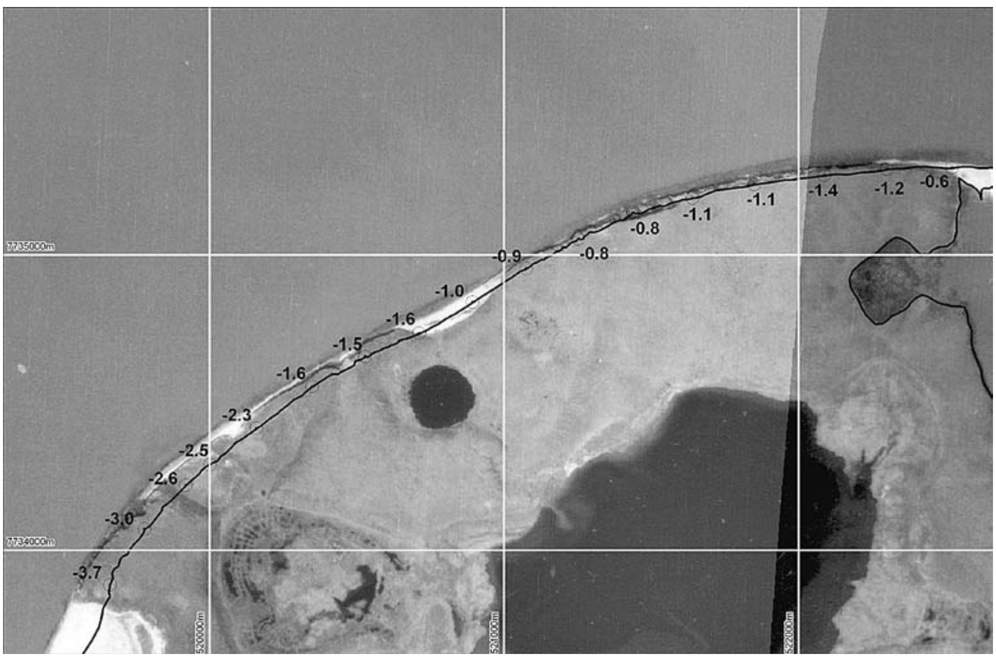


Fig. 4 The North Point littoral cell is characterized by a downdrift gradient in erosion rate that is coincident with deposition of eroded material from higher rates in the updrift area. The airphoto is from 1972 with the 2000 shoreline shown in black. Erosion rates vary from -3.7 m a^{-1} in the west to the -0.6 m a^{-1} in the east. See Fig. 3 for the location. Note: *grid lines* are 1,000 m apart

higher water levels and thereby limit the erosional impacts.

East Richards Island

Mean shoreline retreat rates along the east-facing, East Richards Island coast range from −0.2 (1985–2000) to −0.5 m a^{-1} (1972–85). The decrease in retreat rate in the 1985–2000 interval is statistically significant (at 90% level). The highest rates of retreat are found in the northern part of the zone, where waves propagating from the NW refract into the area during storm surges. Some localized areas of higher shoreline retreat are associated with active retrogressive thaw failure. Generally, the sheltered shoreline close to the mouth of East Channel (Fig. 1) is stable. Harper et al. (1985) measured mean retreat rates that are similar to those measured in this study (−0.3 m a^{-1}). The east side of Richards Island is composed of cliffs and slopes that are protected from northwesterly windstorms by their facing direction. While strong winds do occur from the east and south, fetch for the development of large waves is limited and these wind directions are associated with lower than normal water levels (negative storm surge) which tend to limit their impacts on coastal bluffs.

Tuktoyaktuk Peninsula

The Tuktoyaktuk Peninsula zone is characterized by mean coastal change rates of −0.7 to −0.8 m a^{-1}. The decrease from the 1972–1985 period to the 1985–2000 period is statistically significant. These rates are intermediate between the high rates of the Outer Islands and Outer Delta zones and the low rates of the more protected east and west coasts of Richards Islands. The highest rates of change are located in the southern part of the zone in association with low elevation, lacustrine deposits (Rampton 1988) that have been mapped as relatively ice-rich. In some locations, shoreline retreat rates vary rapidly alongshore with rapid erosion associated with retreat of headlands, especially those adjacent to drowned thermokarst lake embayments. However, not all headlands experience high rates of change and some have been remarkably stable over the 28 years of record. Mean change rate for this zone is −1.3 m a^{-1} for the period 1950–1973 (Harper et al. 1985, 107 measurements).

The Hamlet of Tuktoyaktuk is also within this zone. It has a long history of erosion problems partially associated with high ground ice content (e.g. Rampton and Bouchard 1975, Kolberg and Shah 1976; Shah 1978). Measurements at two locations (Harper et al. 1985) for the period 1950–1973 (prior to the initiation of shore protection works in 1975) range from −1.6 to −1.7 m a^{-1}. Based on the present study, parts of the coast without shore protection immediately adjacent to the Hamlet are retreating at rates of −1 to −2 m a^{-1} although unpublished data indicate that short-term rates can be much higher (i.e. 7–10 m of cliff retreat in a single storm event as a result of undercutting and block failure).

Aggradation

Aggradational zones are relatively rare along the coasts analyzed in this study. A total of 57 point locations (out of nearly 2,700) had measurements that exceeded +1 m a^{-1}. Most of these were isolated points, with occasional clusters of 4–5 locations (representing about 1 km of coast) in protected environments. An additional 381 locations had measurements between +0–1 m a^{-1} with a mean of +0.25 m a^{-1}. These locations were scattered throughout the region in both sheltered locations and where sediment supply was abundant (from river sources or eroding updrift coastal reaches).

Discussion

Highest rates of coastal change

The coastal change rates measured for this project generally corroborate the results of previous investigations (Harper et al. 1985) in their magnitude and in showing that local conditions affect their spatial distribution. While differences in the mean rates of coastal change between the zones in the region vary over factors of 2–5; individual local rates within zones vary by two orders of magnitude (0.2– 20 m a^{-1}). The highest individual change rates (−5 to −20 m a^{-1}) occur in 4 distinct clusters (Figs. 3, 5a–d). Three of these occur on the western side of Richards Island in the Outer Delta and Outer Island zones. The Ellice Island cluster (Fig. 5a) is found on a typical low, exposed modern delta shoreline that is exposed to the west. It is possible that the coastal morphology plays a role in that it is slightly promontory, which may result in somewhat higher wave energies reaching this location as compared with adjacent coastal segments. Subtle variations in local bathymetry and sediment delivery from the rivers may also play a role, but we do not have information with which to substantiate that hypothesis. The Whale Island cluster (Fig. 5b) consists of moderately protected very low delta islands composed of recent alluvial material. These coasts are relatively well protected behind other islands. However, the close proximity of other islands creates opportunities for channelization of either river or surge related flows which could have a localized impact.

The exposed west and north sides of Pelly Island (Fig. 5c) have experienced very high rates of retreat on barriers and the adjacent headlands. These systems are moving in concert with headland erosion contributing sediment to maintain the integrity of barriers as storm surge washover translates them southeastward. The headlands are a combination of low drained lake tundra

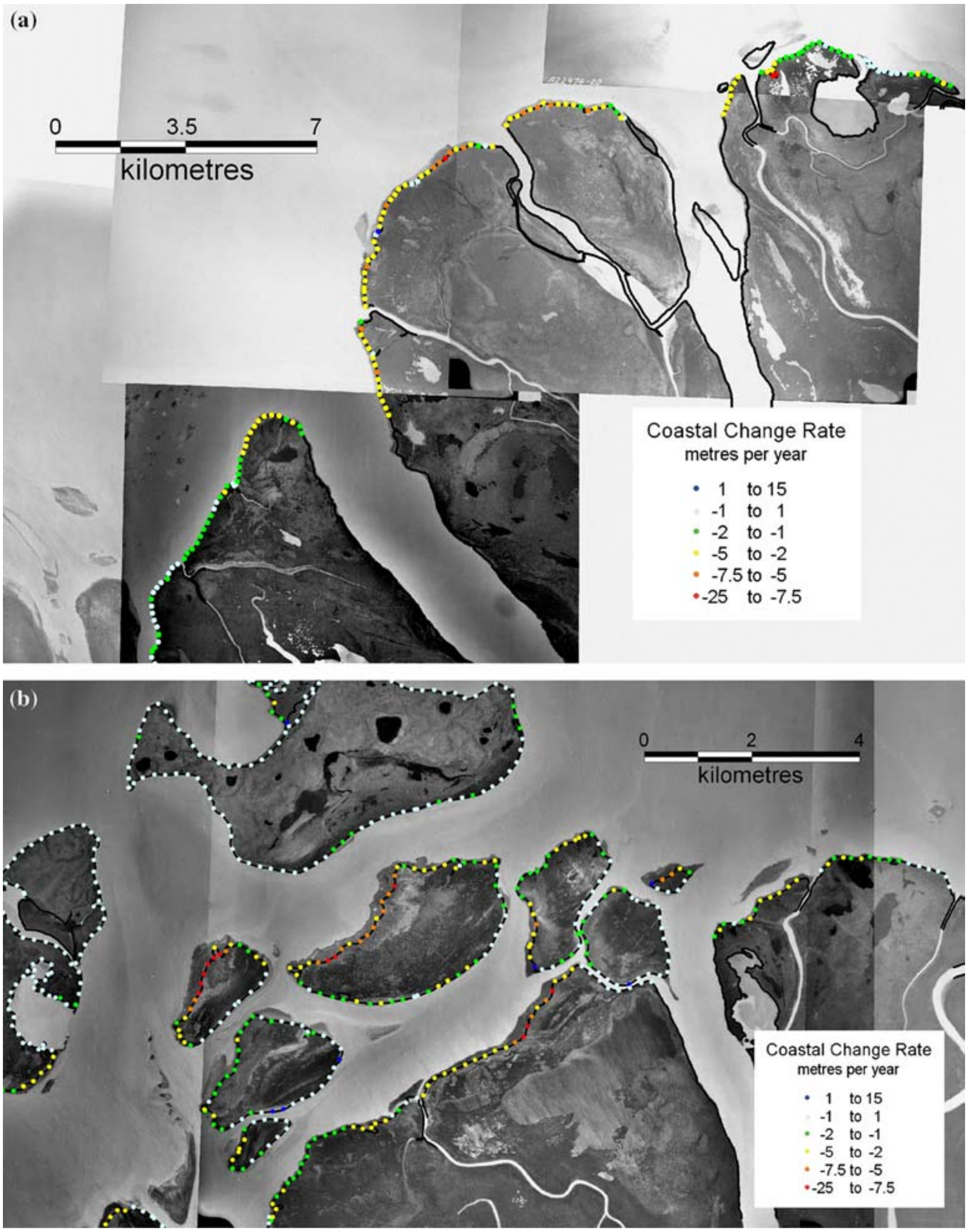


Fig. 5 Erosion rates of −5 to −20 m a^{-1} (1972–2000) are concentrated in exposed Outer Delta (**a** Ellice and **b** Whale), Outer Island environments (**c** Pelly) and in ice-rich semi-protected bluffs in Kugmallit Bay (**d**). **a** High rates of rates of retreat are associated with low (1–2 m) delta front bluff composed of organic silt and fine sand. The *black line* depicts the 2000 shoreline overlaid on the 1972 air photo. **b** High rates of coastal retreat in the relatively sheltered portion of the Mackenzie Delta may be caused in part by localized channeling of river distributaries. The *black line* depicts the 2000 shoreline overlaid on the 1972 air photo. **c** Extremely high (−8 to −16 m a^{-1}) erosion rates are associated with headlands adjacent to drowned lake basins which act as sediment sinks. The *black line* depicts the 2000 shoreline overlaid on the 1972 air photo. **d** Relatively rapid erosion is associated with low-lying, ice-rich terrain (*boxed area*) along the Tuktoyaktuk Peninsula. The *black line* depicts the 2000 shoreline overlaid on the 1972 air photo

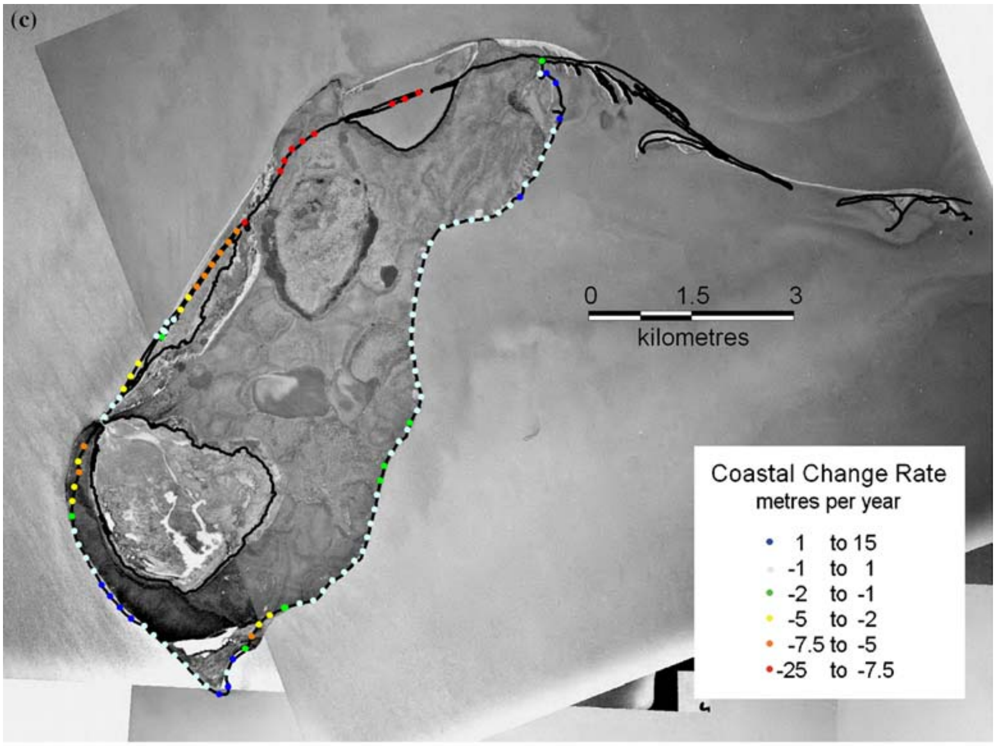
and higher more ice-rich hummocky terrain with the former exhibiting slightly higher rates of retreat than the latter. The Tuktoyaktuk Peninsula grouping (Fig. 5d) is centred on a 5-km-long, north-facing segment of very low, drained-lake tundra. This segment was mapped as more ice-rich than its neighbours based on the presence of pingos and abundant ice wedges in the backshore. The segment is well inside Kugmallit Bay and fronted by shallow water (2 m depth), but its north facing exposure may contribute to its relatively higher retreat rate. Likewise, the relative abundance of ice and lacustrine silt and organic material indicates that little of the eroded volume of material is available for building beaches which would act to protect the erodable tundra bluffs. Local thaw subsidence in the nearshore may also play a role.

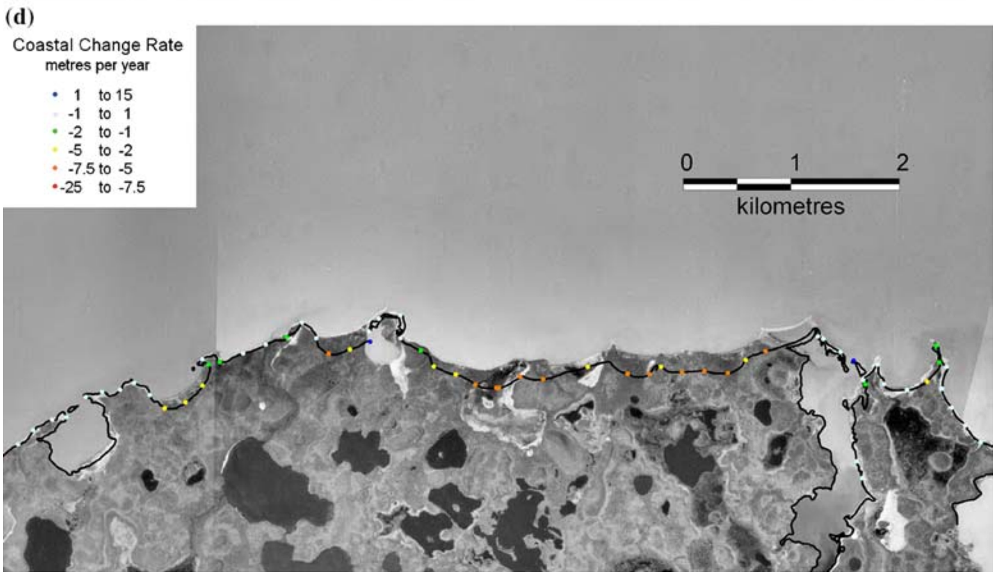
In summary, rates of coastal change are strongly influenced by exposure to northwest wind-driven waves and associated high water levels. Local geological and morphological conditions (e.g. cliff height, ice content, shoreface materials, sediment sources, nearshore bathymetry, etc) mediate and modify the effects of exposure.

Temporal variability

Data from East Richards Island, West Richards Island and the Tuktoyaktuk Peninsula zones and from the overall dataset (Table 2) suggests that there has been a 15% decrease in the mean rate of coastal change in the 1985–2000 interval compared to the 1972–1985 interval.

Fig. 5 (Contd.)





However, the zones with the highest rates of change (Outer Delta and Outer Islands) do not exhibit the decrease. It is possible that areas with lower rates of change (less exposed, greater sediment supply) are more sensitive to changes in forcing than zones with higher change rates. Sequences of small storms or the impacts of large storms in protected sites may cause armouring of coastal bluffs with sloughed materials. At exposed locations, wave energy may also be sufficient to remove sloughed materials quickly, whereas they may persist in protected zones. Analysis of the duration of total storm durations as well as sequences of storminess should be undertaken to see if there are differences between the coastal rate change periods.

Alternatively, the lack of a consistent difference in rates between the two time intervals investigated in this study may indicate that the mean environmental forcing (storm frequency and intensity and ice regime) in the region has not changed appreciably over the past three decades. It is known that year-to-year environmental variability is quite large, with some years experiencing intense storms and large amounts of open water and other years the opposite. Since the impacts of annual variability in environmental forcing on coastal change have been averaged over the 13–15 year time periods it is not possible to identify the effects of individual storms or sub-decadal stormier intervals. Results from Harper et al. (1985) provide a somewhat longer time-scale

(25 years), however, differences between this study and previous assessments are difficult to attribute because of the differences in methods used and choice of measurement locations. In particular, higher rates of change are found on the Tuktoyaktuk Peninsula by Harper et al. (1985) than by the present study. Climate records do not extend back beyond the early 1960s, so it is not possible to ascertain whether this change has a climatic origin.

Conclusions

Analysis of coastal change measurements based on a time series of moderate resolution aerial photographs show that:

1. Coastal change from 1972 to 2000 in the Mackenzie region of the Canadian Beaufort Sea is dominated by retreat of the shoreline with average annual retreat rates of $-0.6\ \mathrm{m\ a}^{-1}$, but ranging as high as $-22.5\ \mathrm{m\ a}^{-1}$.
2. Rates vary significantly both between and within zones of similar exposure, morphology and coastal geology.
   (a) The highest average rates are in areas that are most exposed to northwest winds. These winds, which are accompanied by elevated water levels, induce rapid episodic erosion. However, increased sediment supply can counter the effects of an exposed location by building protective bars and flats (i.e. West Coast of Richards Island).
   (b) Conversely, locations that are sheltered from the northwest winds (i.e. East Richards Island) are characterized by the lowest mean rates of change.
3. While there is some tendency towards a decrease in rate from 1972–1985 to 1985–2000 in areas with lower average retreat rates, that tendency is not reflected in the zones with higher retreat rates. In general, long-term (decadal-scale) rates have remained constant during the 1972–2000 period encompassed by this study.

Acknowledgements Adrienne Jones and Doug Matthews of the Government of the Northwest Territories provided funding and encouragement for the project. Scanning, registration, digitization and measurement of the coastal change were performed by Tekmap Consulting. Hans Arends and the Inuvialuit Land Administration managed the government purchase of the Tarin orthoimagery, which was facilitated by R. Pinel of Tarin Resources. Comments by Dr. W. Pollard and an anonymous reviewer improved the quality of the final paper. Geological Survey of Canada Contribution No. 2004013.z

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