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Temporal and spatial variability in coastline response to declining sea-ice in northwest Alaska

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ABSTRACT

Arctic sea-ice is declining in extent, leaving coastlines exposed to more storm-wave events. There is an urgent need to understand how these changes affect geomorphic processes along Arctic coasts. Here we describe spatial and temporal patterns of shoreline changes along two geomorphologically distinct, storm-wave dominated reaches of the Chukchi Sea coastline over the last 64 years. One study area encompasses the west- to southwest-facing, coarse-clastic shoreline and ice-rich bluffs of Cape Krusenstern (CAKR). The other covers the north-facing, sandy shorelines on barrier islands, ice-rich bluffs, and the Cape Espenberg spit in the Bering Land Bridge National Park (BELA). Both study areas lie within the zone of continuous permafrost, which exists both on and offshore and outcrops as ice-rich bluffs along the BELA coast. We mapped changes in coastal geomorphology over three observation periods: 1950–1980, 1980–2003, and 2003–2014 using aerial and satellite imagery. We then compared these geomorphic changes to changes in sea-ice coverage, which declined ~10 days per decade between 1979 and 2016 in the southern Chukchi Sea. Changes in coastal geomorphology in both BELA and CAKR exhibited high spatial variability over the study period. Between 2003 and 2014, shorelines of barrier islands in BELA exhibited the highest mean rates of change, $-1.5\,\mathrm{m\,yr^{-1}}$, while coarse, clastic barrier beaches in CAKR showed only minimal change. Overall, shorelines in both BELA and CAKR became more dynamic (increasing erosion or increasing accumulation) after ca. 2003, with spatial variability in shoreline changes roughly doubling between the first period of observation (1950–1980) and the last (2003–2014). This increase in coastal dynamism may signal a transitional period leading to new state of geomorphic equilibria along these ice-affected coastlines.

1. Introduction

Approximately 34% of Earth's coastlines border Arctic seas above 60°N (AMAP, 2012; Lantuit et al., 2012). Despite being protected from wave action by the presence of sea-ice for 8 to 9 months of the year (Belchansky et al., 2004), some Arctic shorelines are markedly dynamic (Barnhart et al., 2014a; Jones et al., 2009). Warming climate, loss of permafrost, shifts in sediment supply, a decline in sea-ice cover and an increase in storms during the lengthening open water season (Lawrence and Slater, 2005; Stocker et al., 2014; Wang and Overland, 2009) threaten to trigger rapid and possibly drastic changes in coastal erosion and accretion in the Arctic over the coming century. Yet because of the cryosphere's nonlinear responses to climate change (Cohen et al., 2014; Miller et al., 2010; Serreze and Barry, 2011), and because of the nonlinear responses of coastlines to changing wave regimes (Komar, 1998; Stive et al., 2002), it is poorly understood how Arctic coastlines will respond to ongoing climate changes.

Sea-ice extent and duration, and onshore and offshore permafrost strongly influence Arctic coastal dynamics in space and time, specifically with respect to changing climate. Sea-ice is an important moderator of wave fetch and water temperature, and it shields coastlines from wave action, often for considerable portions of the year. The duration of sea-ice cover in the Arctic has declined by ~13% per decade since satellite observations began in 1979 (www.nsidc.org). Over the last ca. 40 years, the duration of landfast ice (ice seasonally frozen to the shoreface) in the Chukchi sea has declined one week per decade (Mahoney et al., 2014). The impact of sea-ice decline has already been observed through an increase in wave fetch, height, and swell size in

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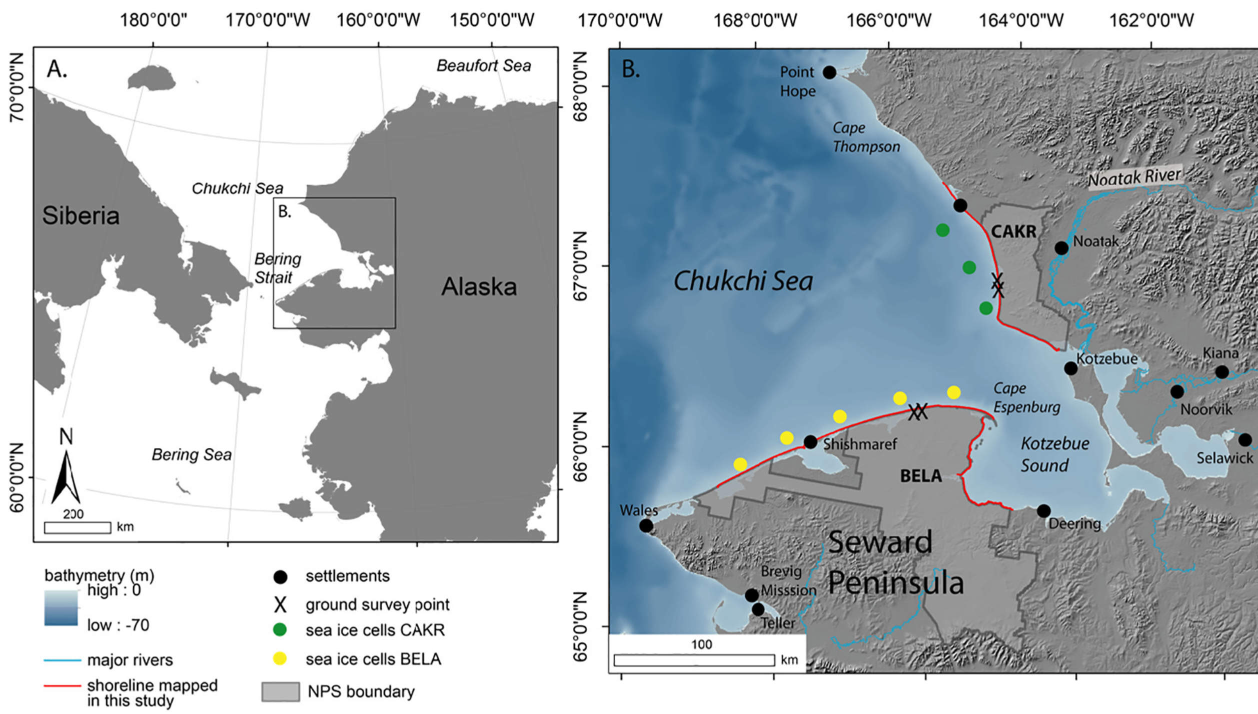

Fig. 1. The study region with Bering Land Bridge National Park and Preserve (BELA) and Cape Krusenstern National Monument (CAKR) outlined in grey.

Arctic seas (Francis et al., 2011; Overeem et al., 2011; Thomson et al., 2016; Thomson and Rogers, 2014), and the lengthening open-water season has resulted in increasing wave energy available for coastal erosion and sediment transport (Overeem et al., 2011). Another important effect of the changing sea-ice regime is the increased probability that autumn storms will make landfall before the winter ice has re-formed (Forbes, 2011). Storms occurring during the ice-free season generate the most geomorphologically significant wave events along Arctic coastlines and hence strongly influence coastal processes (Barnhart et al., 2014b; Mason et al., 1996).

Permafrost in the coastal zone affects shoreline geomorphic processes that occur over multiple temporal scales. Rising air and water temperatures are accelerating the thaw of permafrost, which is destabilizing some Arctic coastlines (Barnhart et al., 2014a; Günther et al., 2015; Kasprzak et al., 2017). Long term permafrost monitoring sites onshore in northern Alaska show an increase in temperature at 20 m depth of between 0.21 °C and 0.66 °C decade^{-1} between 1995 and 2015 (Romanovsky et al., 2017). Mean annual, ground temperatures in the Bering Land Bridge National Park and Preserve (BELA) are projected to increase by up to 3 °C by 2050 (Panda et al., 2016). Warming is also evident offshore where the sea-surface temperature (SST) of the Chukchi Sea has risen by 0.5 °C per decade since1982 (Timmermans and Proshutinsky, 2015). Among the potential impacts of permafrost thaw are more rapid erosion of ice-rich bluffs, which in some regions is already occurring with great rapidity (Jones et al., 2009). Another possible impact is an increase in sediment supply due to permafrost degradation along streams that supply sediment to barrier beaches, foredunes, spits and barrier islands that may now be sediment-poor.

Here we use repeat aerial and satellite imagery to estimate rates of shoreline change between 1950 and 2014 along two geologically distinct coastlines in the southeastern Chukchi Sea. Each study area contains several, distinctly different geomorphological subunits, and together encompasses 480 km of sea-ice affected coastline. We address these questions: 1) How variable have erosion and accretion been along these permafrost coastlines over the last 64 years? 2) Have different types of coastal geomorphology responded to sea-ice decline differently? 3) If ongoing trends in climate continue, how will these coastlines change over the coming centuries? By addressing these questions we provide new insight into coastal dynamics in the Chukchi Sea, a region whose geomorphic responses to ongoing climate change have been little studied compared to the Beaufort Sea coast.

2. Previous studies

The coastal dynamics of permafrost-affected shorelines have been studied primarily along the Beaufort Sea coast (Hume and Schalk, 1967; Jones et al., 2009; Jorgenson and Brown, 2005; Mars and Houseknecht, 2007), the Beaufort Sea coast of Canada (Harper, 1990; Hequette and Barnes, 1990; Lantuit and Pollard, 2008; Radosavljevic et al., 2016; Solomon, 2005), and the Arctic seas of Siberia (Günther et al., 2015, 2013). Much of this research has focused on the often spectacular erosion of ice-rich permafrost bluffs (e.g., MacCarthy, 1953; Jones et al., 2009; Günther et al., 2015), and to a lesser extent on the dynamics of Arctic barrier-island systems (Gorokhovich and Leiserowitz, 2012; Harper, 1990; Hequette and Ruz, 1991). Only a few studies (including Hequette and Ruz, 1991 and Radosavljevic et al., 2016) have explored how permafrost-affected Arctic coastlines of mixed morphology and grain size respond to sea-ice decline and permafrost thaw.

Previous studies of coastal dynamics in the southeastern Chukchi Sea measured rates of coastal change between 1950 and 1980 using the "instantaneous water line." This is the position of the land–water interface when a remote-sensing image is acquired (Boak and Turner, 2005) and is used as an estimate of shoreline position (Manley et al., 2007). Mean rates of change in the instantaneous water line along the BELA and CAKR coastlines suggested an overall erosional trend between 1950 and 1980, followed by an overall accretional trend between 1980 and 2003 (Gorokhovich and Leiserowitz, 2012). Defining shoreline position based on instantaneous water lines is problematic in a place like the Chukchi Sea where relative sea level can change by > 1 m in response to short-lived storm surges. Despite the low tidal range of approximately 25 cm (tidesandcurrents.noaa.gov), we observed that the gently sloping beaches of BELA allow the water line to shift landward by several meters during an average diurnal cycle.