Coastal Permafrost Erosion

DOI: 10.25923/e47w-dw52

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Highlights

- Since the early 2000s, erosion of permafrost coasts in the Arctic has increased at 13 of 14 sites with observational data that extend back to ca. 1960 and ca. 1980, coinciding with warming temperatures, sea ice reduction, and permafrost thaw.
- Permafrost coasts along the US and Canadian Beaufort Sea experienced the largest increase in erosion rates in the Arctic, ranging from +80 to +160%, when comparing average rates from the last two decades of the 20th century with the first two decades of the 21st century.
- The initiation of several national and international research networks in recent years has enabled closer coordination and collaboration of measurements and a better understanding of pan-Arctic permafrost coastal dynamics.

Introduction

Permafrost coasts in the Arctic make up more than 30% of Earth's coastlines (Fig. 1; Lantuit et al. 2012) and they are sensitive to Arctic Ocean/permafrost-influenced land linkages (Nielsen et al. 2020). The changes currently taking place along these coasts are both indicators and integrators of changes occurring in the global climate system. Reductions in sea ice extent and increases in the duration of the open water period (see essay *Sea Ice*), rising air (see essay *Surface Air Temperature*) and sea surface temperatures (see essay *Sea Surface Temperature*), absolute and relative sea-level rise (see essay *Greenland Ice Sheet*), warming permafrost (Biskaborn et al. 2019), subsiding permafrost landscapes (Lim et al. 2020), and increased storminess and wave heights (Casas-Prat and Wang, 2020) all interact to amplify coastal permafrost erosion (Forbes, 2011). Recent changes in these conditions have increased the vulnerability of permafrost coasts to erosion and altered coastal morphologies (Farquharson et al. 2018), ecosystems (Fritz et al. 2017), carbon export to oceans (Tanski et al. 2019), infrastructure (Fritz et al. 2017), and human subsistence lifestyles (Irrgang et al. 2018).

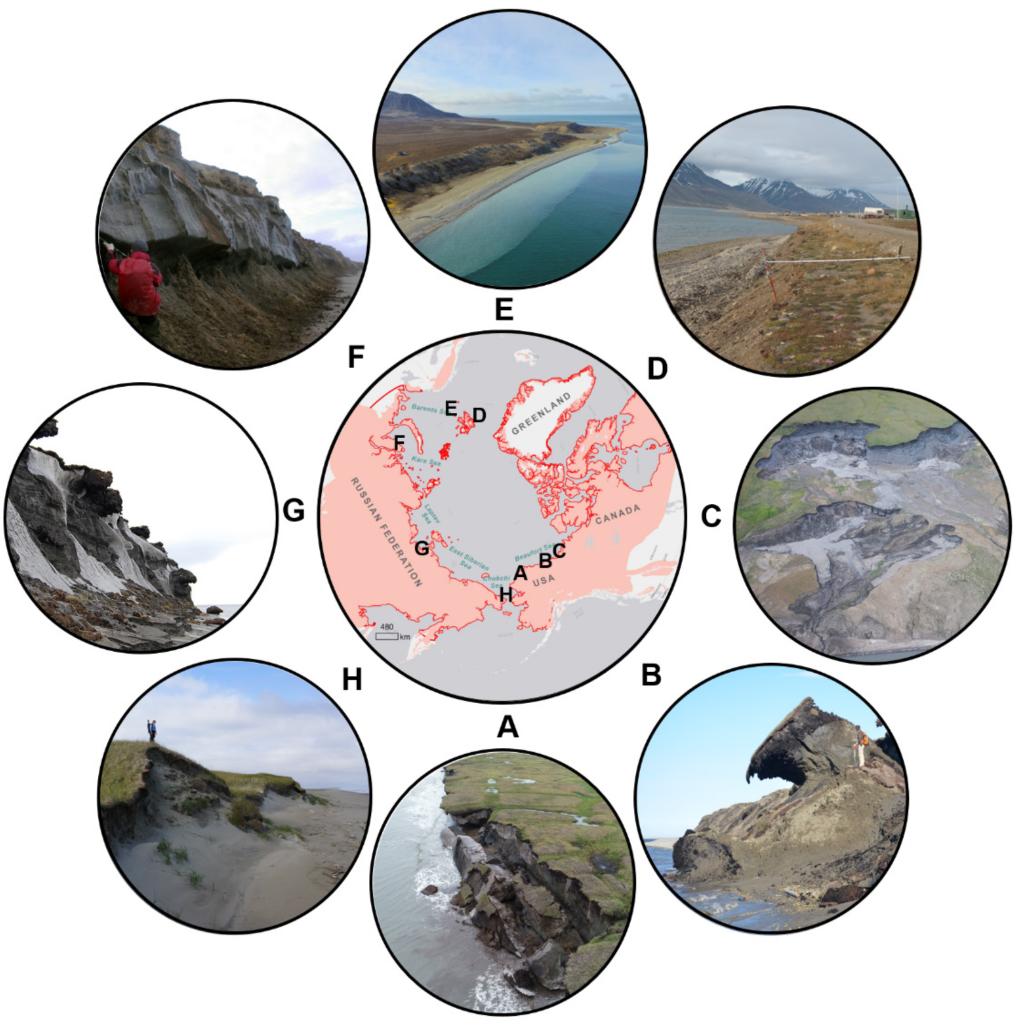

Fig. 1. Arctic permafrost region (red region in central figure) and the distribution of and variability in permafrost coasts (bold red line in central figure). (A) Ice-rich exposed permafrost bluffs at Drew Point, Alaska (photo: B. M. Jones); (B) Ice-rich and ice-poor exposed permafrost coastal bluffs at Barter Island, Alaska (photo: B. M. Jones); (C)

Permafrost-preserved buried glacial ice and retrogressive thaw slumps exposed at Herschel Island, Canada (photo: G. Vieira); (D) Mixed-type permafrost coast exposed at Adventfjorden, Svalbard (photo: E. Guégan); (E) Ice-poor permafrost coast at Calypsostranda, southern Svalbard (photo: P. Zagórski); (F) Ice-rich permafrost overlying fluvial sands with a thermo-erosional niche in the Kara Sea, Siberia (photo: A. Baranskaya); (G) Ice-rich, ice-complex deposits exposed at Muostakh Island, Siberia (photo: T. Opel); and (H) Ice-poor dune and barrier permafrost system at Cape Espenberg, Seward Peninsula, Alaska (photo: L. Farquharson).

Changes in permafrost coasts are primarily due to erosion (Lantuit et al. 2012). However, coastal change rates have high temporal and spatial variability, which is driven largely by diversity in internal and external factors. For example, sediment composition, permafrost properties, and coastline exposure contribute to the spatial variability in coastline change, while changing hydrometeorological and ocean forcing conditions determine the temporal evolution of coastline change (Shabanova et al. 2018). The highest erosion rates occur in unconsolidated sediment deposits that represent 65% of permafrost coasts in the Arctic (Lantuit et al. 2012). The remaining 35% of permafrost coasts are classified as rocky or consolidated material that exhibit more stability. In unconsolidated permafrost coasts, the presence of ice-rich permafrost is a weak but statistically significant contributor to higher coastal erosion rates (Lantuit et al. 2012). The primary drivers of erosion of ice-rich permafrost coasts are summer warmth and solar radiation (thermo-denudation) and wave action (thermo-abrasion) (Aré 1988).

Historic and contemporary decadal-scale changes

Baseline measurements of both historic and contemporary permafrost coastal change were established through the collaborative international efforts of the Arctic Coastal Dynamics program in the late 1990s and early to mid-2000s (Brown and Solomon 2000; Rachold et al. 2005). Historical benchmarks of permafrost coastal change typically integrate observations collected between the 1950s and the 1980s, with those acquired in the early to mid-2000s (Fig. 2; Lantuit et al. 2012). Data were synthesized from field observations and remote sensing-based coastline datasets. Information was compiled on measures of erosion and accumulation occurring in a specific area, and the aggregate mean was reported.

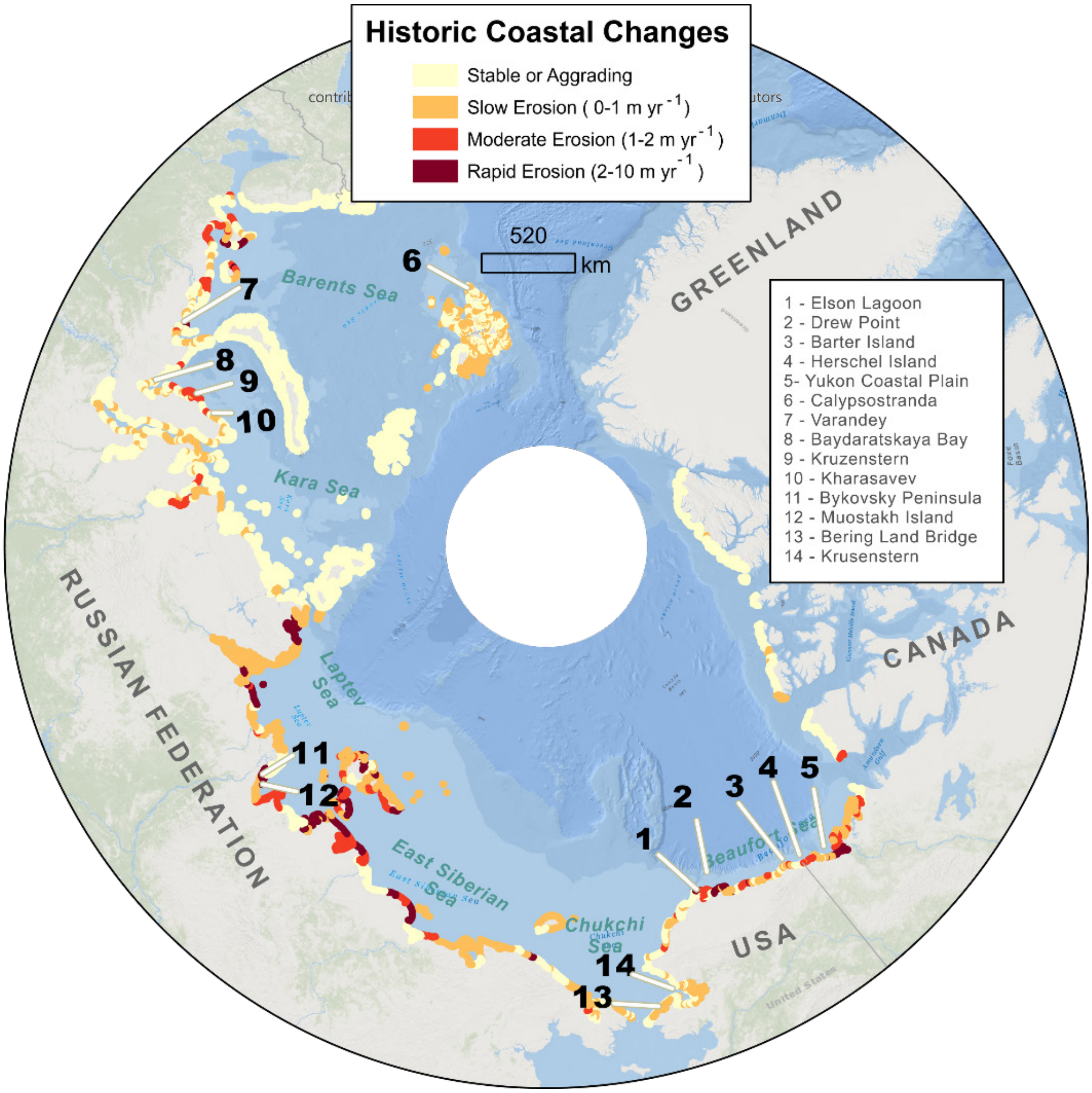

Fig. 2. Historic decadal-scale coastal change observations for permafrost coasts in the Arctic (Lantuit et al. 2012). Data are from the Arctic Coastal Dynamics database (https://doi.pangaea.de/10.1594/PANGAEA.919573) and are based on field observations and coastline change data collected between the 1950s and the 1980s, with updated positions acquired in the early to mid-2000s. The 14 sites mentioned in the essay where contemporary, decadal-scale coastal change rates exist are indicated with numbers in the map and referenced in the upper right text box. More detailed information on relative changes in erosion rates in the 21st century relative to measurements from the latter half of the 20th century are provided in Table 1.

Over the period ~1950 to ~2000, the mean Arctic-wide coastal permafrost change rate was -0.5 m yr^{-1} (where negative values indicate erosion), with substantial variability within and among different regions (Lantuit et al. 2012). According to the primary subdivisions of the Arctic Ocean, change rates have historically been highest along permafrost coasts along the US and Canadian Beaufort Sea (-1.1 m yr^{-1}), East Siberian Sea (-0.9 m yr^{-1}), Laptev Sea (-0.7 m yr^{-1}), and Kara Sea (-0.7 m yr^{-1}). Sites that were historically at or below the mean Arctic-wide coastal permafrost change rate were the Russian (-0.3 m yr^{-1}) and US (-0.5 m yr^{-1}) Chukchi Seas, Barents Sea (-0.4 m yr^{-1}), Canadian Archipelago (0.0 m yr^{-1}), and Svalbard (-0.02 m yr^{-1}) (Lantuit et al. 2012).

Since the early 2000s, observations from 14 coastal permafrost sites have been updated, providing a synopsis of how changes in the Arctic system are intensifying the dynamics of permafrost coasts in the 21st century (Table 1; Fig. 2). Observations from all but 1 of the 14 coastal permafrost sites around the Arctic indicate that decadal-scale erosion rates are increasing. The US and Canadian Beaufort Sea coasts have experienced the largest increases in erosion rates since the early 2000s. The mean annual erosion rate in these regions has increased by 80 to 160% at the five sites with available data, with sites in the Canadian Beaufort Sea experiencing the largest relative increase. The sole available site in the Greenland Sea, on southern Svalbard, indicates an increase in mean annual erosion rates by 66% since 2000, due primarily to a reduction in nearshore sediment supply from glacial recession. At the six sites along the Barents, Kara, and Laptev Seas in Siberia, mean annual erosion rates increased between 33 and 97% since the early to mid-2000s. The only site to experience a decrease in mean annual erosion (-40%) was located in the Chukchi Sea in Alaska. Interestingly, the other site in the Chukchi Sea experienced one of the highest increases in mean annual erosion (+160%) over the same period. In general, a considerable increase in the variability of erosion and deposition intensity was also observed along most of the sites.

Table 1. Synthesis of historic and contemporary decadal-scale coastal change rates from 14 coastal permafrost sites in the Arctic. The map site number and site location are linked to information provided in Fig. 2.

Map Site Number	Site Location	Historic Decadal-Scale Change		Contemporary Decadal-Scale Change		Change in Rate	References
		Rate (m yr^{-1})	Time Period	Rate (m yr^{-1})	Time Period	Percent (%)	
Beaufort Sea							
1	Elson Lagoon	-0.90	1979 to 2000	-2.10	2000 to 2018	+133	Brown et al. 2003; Tweedie personal communication
2	Drew Point	-8.70	1979 to 2002	-17.20	2002 to 2019	+98	Jones et al. 2018; Jones personal communication
3	Barter Island	-1.50	1979 to 2000	-2.70	2000 to 2020	+80	Gibbs et al. 2020
4	Herschel Island	-0.50	1979 to 2000	-1.30	2000 to 2017	+160	Radosavljevic et al., 2016; Cunliffe et al. 2019
5	Yukon Coastal Plain	-0.60	1970 to 1990	-1.30	1990 to 2011	+117	Irrgang et al. 2018
Greenland Sea							
6	Calypsostranda	-0.06	1960 to 2005	-0.10	2005 to 2017	+66	Zagórski et al. 2020

Map Site Number	Site Location	Historic Decadal-Scale Change		Contemporary Decadal-Scale Change		Change in Rate	References
		Rate (m yr^{-1})	Time Period	Rate (m yr^{-1})	Time Period	Percent (%)	
Barents Sea							
7	Varandey	-1.60	1961 to 1998	-2.40	1998 to 2012	+50	Sinitsyn et al. 2020
Kara Sea							
8	Baydaratskaya Bay	-0.61	1964 to 2005	-1.20	2005 to 2016	+97	Novikova et al. 2018
9	Kruzenstern	-0.50	1964 to 2010	-0.90	2010 to 2019	+80	Baranskaya personal communication
10	Kharasavey	-0.90	1988 to 2006	-1.20	2006 to 2016	+33	Belova et al. 2020
Laptev Sea							
11	Bykovsky Peninsula	-3.70	1982 to 2000	-5.30	2000 to 2018	+43	Grigoriev, 2019
12	Muostakh Island	-5.40	1982 to 2000	-9.50	2000 to 2018	+76	Grigoriev, 2019
Chukchi Sea							
13	Bering Land Bridge	-0.26	1980 to 2003	-0.68	2003 to 2014	+160	Farquharson et al. 2018
14	Cape Kruzenstern	-0.22	1980 to 2003	-0.13	2003 to 2014	-40	Farquharson et al. 2018

There is overwhelming evidence that erosion at ice-rich and ice-poor unconsolidated permafrost coasts is increasing in the Arctic since the early to mid-2000s when compared to decadal-scale measurements taken between ca. 1960 and ca. 1980. Higher and more fluctuating erosion rates reflect increasing coastal dynamics associated with intensified environmental changes. These larger-scale environmental changes include increases in summer air temperature, permafrost thaw and land subsidence, rising sea levels, reductions in sea ice cover and the resulting increase in open water period, and increasingly impactful storms. Combined, these changes have led to an increase in the effect of thermo-denudation and thermo-abrasion on permafrost coasts and document the cumulative effects of climate change on the Arctic System.

The future of permafrost-affected coastal research

Ongoing coastal issues in the Arctic transcend borders. A high proportion of Arctic residents live in the coastal zone, and many derive their livelihood from terrestrial and nearshore marine resources (Forbes 2011). Industrial, commercial, tourist, and military presence in the Arctic is expanding. Each will need to grapple with coastal permafrost erosion and the related impacts on the dynamics of the nearshore zone. The socio-economic consequences of an increasingly dynamic system will become a recurring theme and have a profound impact across the Arctic, influencing human decision making and adaptation planning. For example, take the remote Yupik Village of Newtok, Alaska, located in a zone of discontinuous permafrost along the Bering Sea. Annual erosion rates as high as 22 m yr^{-1} along the low-lying bluffs of Newtok have reinforced its recent relocation efforts. In the Canadian Beaufort Sea, the natural deep-water harbor in the Hamlet of Tuktoyaktuk is protected by Tuktoyaktuk Island. This island is at risk of being breached in the next 20-25 years, exposing the harbor to larger waves and intensified erosion. With the increasingly rapid pace of environmental and social change, there is ever greater need for international collaboration between researchers and impacted local societies to focus on permafrost coasts in transition.

Fortunately, more accurate, frequent, and extensive mapping of permafrost coasts has been made possible by an increase in spatial and temporal earth observations from spaceborne and airborne platforms. Access to commercial high-resolution satellite imagery, available through national and international federally-funded research projects in the US, Europe, and Russia, has increased the number of observations by several orders of magnitude at specific key sites, relative to the previous 50 years. More readily available ancillary datasets on climate, sea ice, storms, and permafrost dynamics have increased our capacity to better model and predict future coastline positions and their impacts on infrastructure. The initiation of several national and international research networks, in recent years and in past decades, has enabled closer coordination and collaboration of measurements and a better understanding of permafrost coastal dynamics. Future efforts will focus on expanding the permafrost-affected coastal change knowledge base beyond the continuous permafrost region, to include vulnerable coasts located in the discontinuous permafrost zone as well as rocky permafrost coasts. Connections between researchers and Indigenous communities have increased beyond hub communities, which allows for a more informed dialogue and representation of key issues and the factors driving rapid changes along permafrost coasts. The formation of interdisciplinary research teams and increasing collaboration across knowledge systems, such as Western science and Indigenous knowledge, has increased the scope and breadth of studies being conducted along permafrost coasts as well as their societal relevance. Combined, these developments show great promise for understanding future changes in coastal permafrost dynamics and the potential impact on both the natural and built environments.

Acknowledgments

Benjamin Jones, Louise Farquharson, Craig Tweedie, Chris Maio, and Vladimir Romanovsky were supported by grants (OISE 1927553 and 1927137) from the US National Science Foundation Office of International Science and Engineering (OISE) and Office of Polar Programs (OPP). Anna Irrgang, Hugues Lantuit, Paul Overduin, and Gonçalo Vieira were funded by the EU project Nunataryuk (grant number

773421). Stanislav Ogorodov and Alexey Maslakov were funded by the Russian Science Foundation Project 16-17-00034 and the State Budget Theme AAAA-A16-116032810055-0. Alisa Baranskaya was funded by the Russian Foundation for Basic Research (RFBR) grant 20-35-70002. Ann Gibbs, U.S. Geological Survey, Coastal/Marine Hazards and Resources Program. Piotr Zagórski was supported from the project of the National Science Centre (Poland) No. 2013/09/B/ST10/04141, Matt Strzelecki was supported by NAWA Bekker Programme (PPN/BEK/2018/1/00306). Ingmar Nitze and Guido Grosse were funded by the ESA GlobPermafrost and ESA CCI+ Permafrost projects. Mette Bendixen is funded by The Danish Independent Research Council with grant number 8028-00008B.

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November 9, 2020