PROGRESS IN ARCTIC COASTAL GEOMORPHOLOGICAL RESEARCH IN TIMES OF RAPID CLIMATE WARMING

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Abstract: Recognising the degree of climate transformations in the Arctic becomes vital, especially in times of rapid global climate change. The 21st century has seen a renaissance in Arctic coastal research. Here, we aim to present this recent progress. Moving from the European Arctic through the Siberian part and ending with the Canadian Arctic Archipelago (CAA), we describe how the region's coasts have transformed. This work is mostly focussed on progress in coastal geomorphology, geohazards, and reconstructions of the paleoarchives, although we also address the future research challenges of cold region coastal environments.

Key words: coastal evolution, cold region geomorphology, climatic changes, coastal geohazards, Arctic

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Introduction

The Arctic responds to ongoing climate change faster than any other region on our planet (Serreze, Barry 2011, Osborne et al. 2018), which is called polar (Arctic) amplification (Masson-Delmotte et al. 2012, Lee 2014, Park et al. 2019, Irrgang et al. 2022, Rantanen et al. 2022, Ziaja, Haska 2023). Recent studies show that in the last four decades, the Arctic has been warming up to four times faster than the rest of the globe (Rantanen et al. 2022). Moreover, Ballinger et al. (2020) report that the decade 2010–2020 proved the warmest since 1900 with an average surface air temperature rise of over 1°C.

Rising air and water temperatures carry enormous consequences reflected in the accelerated recession of glaciers (e.g. Kochtitzky, Copland 2022), permafrost thawing (e.g. Hjort et al. 2018), sea ice decline (e.g. Isaksen et al. 2016) resulting in variations in meteorological marine forcings (e.g. Zagórski et al. 2015, Wojtysiak et al. 2018), increased geohazards frequency (e.g. Long et al. 2015) and changes in relative sea-level (RSL) (e.g. Pattyn, Morlighem 2020). Apart from direct temperature rise consequences, coastline changes are controlled by sediment supply from terrigenous and marine sources (e.g. Zagórski 2011, Zagórski et al. 2012, Strzelecki et al. 2015, 2017a, Bourriquen et al. 2018) as well as postglacial changes in glacial isostatic adjustment (GIA).

Determinants of recent Arctic coastal development have been the subject of extensive research efforts, including numerous findings from the last

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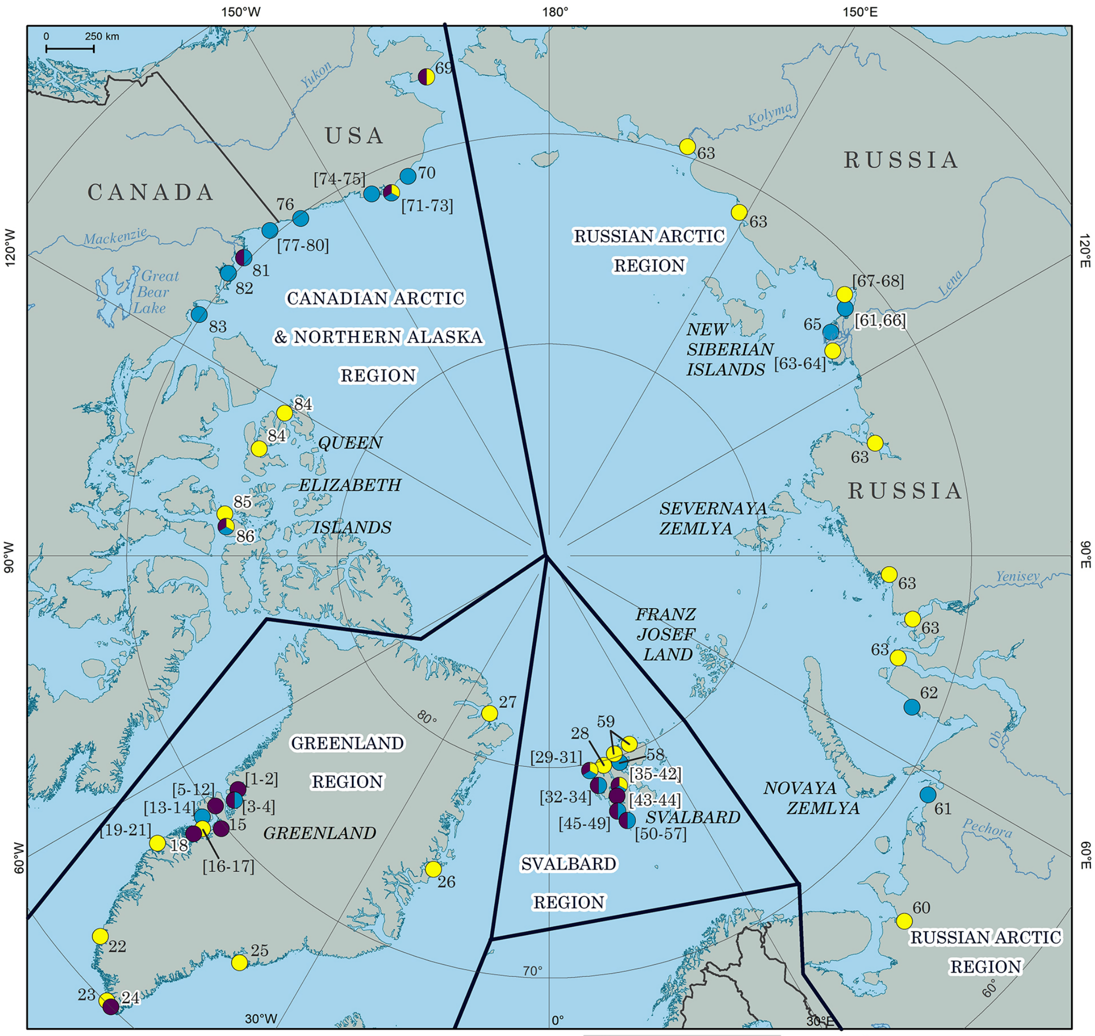
decade (Strzelecki et al. 2015, 2017b, 2018, 2020, Zagórski et al. 2015, Jaskólski et al. 2017, Jarosz et al. 2022). Here we report on the current state of knowledge of the processes shaping Arctic coastlines from the perspective of progressive climate warming in which anthropogenic forcing plays



Subject of the work

- paleodata
- coastal changes
- geohazards
- geohazards and paleodata
- geohazards and coastal changes
- geohazards, paleodata and coastal changes

Author of the publication:

1	Schiermeier, 2017
2	Gauthier et al., 2018
3	Svennevig et al., 2019
4	Strzelecki and Jaskólski, 2020
5	Pedersen et al., 2002
6	Dahl-Jensen et al., 2004
7	Buchwał et al., 2015
8	Rosser et al., 2015
9	Szczuciński et al., 2015
10	Benjamin et al., 2018
11	Korsgaard et al., 2023
12	Svennevig et al., 2023
13	Bendixen and Kroon, 2017
14	Luetzenburg et al., 2023
15	Wolper et al., 2021
16	Long et al., 2006
17	Long et al., 2011
18	Long et al., 2015
19	Long et al., 2009
20	Long et al., 2010
21	Bennike et al., 2011
22	Woodroffe et al., 2014
23	Sparrenbom et al., 2006
24	Steffen et al., 2020
25	Long et al., 2008
26	Pedersen et al., 2011
27	Funder et al., 2011
28	Brückner and Schellmann, 2003
29	de Wet et al., 2018
30	Wojtysiak et al., 2018
31	Wołoszyn et al., 2022
32	Mercier and Laffly, 2005
33	Bourriquen et al., 2018
34	Aga et al., 2023
35	Rachlewicz, 2009
36	Strzelecki, 2011
37	Long et al., 2012
38	Strzelecki et al., 2015
39	Sessford et al., 2015
40	Jaskólski et al., 2017
41	Strzelecki et al., 2018
42	Wieczorek et al., 2023
43	Isaksen et al., 2016
44	Jaskólski et al., 2018
45	Bogen and Bønsnes, 2003
46	Zagórski, 2011
47	Zagórski et al., 2012
48	Zagórski et al., 2020
49	Jarosz et al., 2022
50	Ziaja et al., 2009
51	Zagórski et al., 2015
52	Ziaja and Ostafin, 2015
53	Grabiec et al., 2017
54	Strzelecki et al., 2017
55	Strzelecki et al., 2020
56	Lim et al., 2020
57	Kavan et al., 2022
58	Ziaja and Haska, 2023
59	Hormes et al., 2011
60	Larsen et al., 2006
61	Ogorodov et al., 2020
62	Belova et al., 2019
63	Whitehouse et al., 2017
64	Bolshiyanov et al., 2015
65	Chan et al., 2023
66	Vonk et al., 2012
67	Sander et al., 2018
68	Sander et al., 2019
69	Mason et al., 1995
70	Hamilton et al., 2021
71	Gibbs and Richmond, 2017
72	Farquharson et al., 2018
73	Mason et al., 2020
74	Jones et al., 2018
75	Wang et al., 2022
76	Gibbs et al., 2021
77	Lantuit and Pollard, 2008
78	Lantiut et al., 2012
79	Obu et al., 2016
80	Irrgang et al., 2018
81	Berry et al., 2021
82	Manson et al., 2005
83	Tanguy et al., 2023
84	Nixon et al., 2014
85	St-Hilaire-Gravel et al., 2010
86	St-Hilaire-Gravel et al., 2011

Fig. 1. Schematic division of the Arctic corresponding to the chapters in the work and relevant publications on the Arctic coastal change research mentioned in this study.

a part. This review focusses on Arctic coastline change studies from the 21st century with particular emphasis on publications from the last decade, presented by regions (Fig. 1) and taking into account both developments in modern coastal morphodynamics, resilience to coastal geohazards as well as advances in paleo coastal research (Fig. 1). We also present future research challenges reported in the studies.

Data and methods

Despite the consensus that the Arctic coast is vulnerable to the effects of climate change, the availability of high-spatiotemporal-resolution data in many of its parts is limited (Irrgang et al. 2022). Remote sensing data used by researchers working on the Arctic coastlines include aerial and unmanned aerial vehicle (UAV) photos as well as satellite multispectral images (Zagórski 2011, Zagórski et al. 2015, 2020, Strzelecki et al. 2020, Geyman et al. 2022, Kavan et al. 2022, Kavan, Strzelecki 2023, Tanguy et al. 2023), out of which some are publicly available but usually with limited quality. Archival data (old maps, aerial photographs, field sketches) are also of great value, although they are often difficult to access. Recent methods, e.g. deep learning, automatization or visualization (Ziaja et al. 2009, Ziaja, Ostafin 2019, Urbański, Litwicka 2022, Ziaja, Haska 2023) and tools, e.g. Digital Shoreline Analysis System (DSAS) are used to observe and measure rates of coastal changes, as well as to forecast changes in the Arctic (e.g. Barnhart et al. 2016, Zagórski et al. 2020, Himmelstoss et al. 2021, Wołoszyn et al. 2022). However, high resolution data is still very limited in space and time and, as a result, detection of small and rapid changes remains a challenge.

Global forcing's of Arctic coastal changes

Recession of glaciers

Arctic regions can be generally divided into glaciated (Fig. 2A) and non-glaciated (Fig. 2B). Glaciated domain refers to Greenland, Canadian Arctic Archipelago (CAA), Svalbard, and Russian Arctic islands often supplemented by subarctic

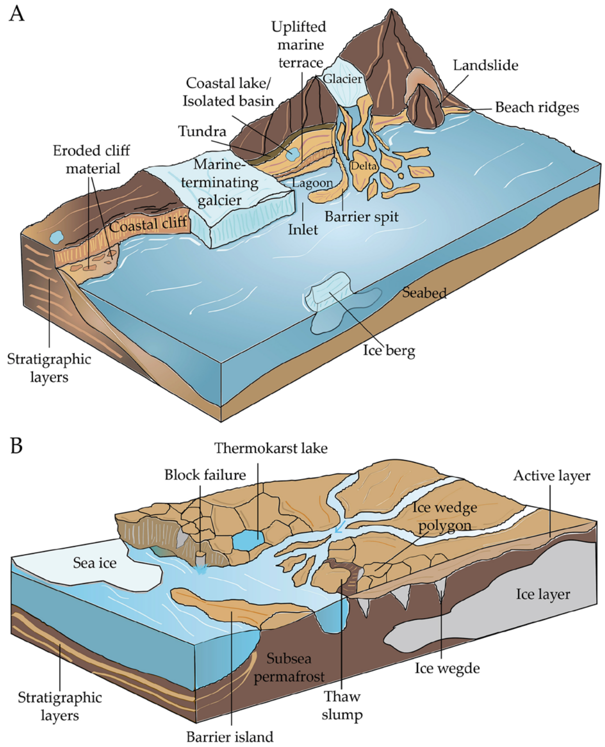


Fig. 2. Schemes of the Arctic coasts: A – Coast of the still-glaciated part of the Arctic; B – Coast dominated by permafrost (non-glaciated domain).

Iceland and southeast Alaska. The non-glaciated domain applies to Siberia, north and northwest Alaska, and northwest Canada (Kavan, Strzelecki 2023).

According to Kochtitzky, Copland (2022), 85.3% of marine-terminating glaciers in the Northern Hemisphere have retreated during the 2000–2020 period, and only 2.5% have developed. As a result, new coastlines were formed and are prone to rapid geomorphological modifications. In recent decades paraglacial processes, understood as *nonglacial earth-surface processes that are directly conditioned by glaciation and deglaciation* (Ballantyne 2002), have played a significant role in the transformation of the coastal landscape (Strzelecki 2011a). Sediment cascades activated by rapid land exposure can lead to the formation of solifluction slope covers, river floodplains, lakes, and in the coastal zone they can lead to the development of beaches, mudflats or as marine sediments in fjord beds (Strzelecki et al. 2020).

Permafrost thawing

The term permafrost is here understood as *condition existing below ground surface, irrespective* *of texture, water content, or geological character, in which: the temperature in the material has remained below 0°C continuously for more than 2 years, and if pore water is present in the material a sufficiently high percentage is frozen to cement the mineral and organic particles* (Stearns 1966). However, other definitions were suggested (e.g. Dobiński 2011).

The permafrost coast in the Arctic makes up more than 30% of Earth's coastline (Lantuit et al. 2011b). Attempts to determine the extent of permafrost in the Northern Hemisphere were made by Obu et al. (2019), Obu (2021). According to their study, almost 22% of the exposed land is permafrost, of which more than half is continuous permafrost, and the remainder comprises discontinuous, sporadic, and isolated patch zones (Obu et al. 2019). Intensified thawing of subsea, coastal, and inland permafrost is one of the major factors contributing to the rapid retreat of Arctic coasts (Strzelecki 2011a). Erosion often has a form of ice-wedge polygons block failures or thaw slumps (Fig. 2B) (Berry et al. 2021). Recent projections suggest that by 2050, 70% of the coastal infrastructure in the permafrost domain is expected to face a direct threat posed by permafrost degradation (Hjort et al. 2018), while the pan-Arctic coastal erosion is likely to double by the end of this century (Nielsen et al. 2022).

Sea ice extent

Rising air temperatures, in line with the resulting longer ice-free season, also play a role in the sea ice extent decrease and modifications in its spatial distribution (Urbański, Litwicka 2022, Sumata et al. 2023). Arctic summer sea ice cover has more than halved since 1979 in terms of surface area, while its volume has been reduced, by as much as three-quarters (Overland et al. 2014, Irrgang et al. 2022). After 2007, the new Arctic sea ice has been developing thinner and more uniform, becoming even more susceptible to summer melt. Moreover, in areas of sea ice formation, its summer extent and thickness have not returned to their pre–2007 state (Sumata et al. 2023). The summer sea ice is projected to disappear in the Arctic this century (Lenton et al. 2008, 2019) or even in the following decade or two (Kim et al. 2023), regardless of the applied greenhouse gas emission scenarios, including the low emission one. It is in line with the data provided by Barnhart et al. (2016), who show that under the current pattern of sea ice decrease (in both its extent and persistence) by 2070, it will cover the region's coasts for half of the year only. This implies the possibility of new maritime routes, important not only for environmental, ecological, and economic reasons but also for military considerations (Smith, Stephenson 2013). Sea ice forms the protective zone for the shores. Due to the reduction of its extent, waves can haunt Arctic coasts with greater frequency resulting in greater vulnerability of Arctic coasts to erosion (Jaskólski 2021).

Extreme waves

Waves are an important factor contributing to coastal development. They can be divided into standard and extreme ones and Arctic extreme waves can be caused by wind (storms), iceberg formation and rolling or by marine-terminating or submarine landslides. While many such events occur naturally away from settlements (e.g. Jaskólski et al. 2017, Strzelecki and Jaskólski 2020), they have become a significant threat to coastal communities and the infrastructure. Long waves that cause threats to coastal ecosystems are termed tsunamis (Buchwał et al. 2015) even if they are not earthquake-provoked as the majority of tsunamis are from lower latitudes.

Glacial calving is another source of waves. The calving into the ocean is predicted to be one of the largest contributors to future sea-level rise (Moore et al. 2013, Pattyn, Morlighem 2020). This process accounts for ~50% of the mass loss of the Greenland and Antarctic ice sheets (Rignot et al. 2011, Aström et al. 2014). Glacier calving is a sudden rupture event that releases large amounts of ice during short-lived events (Lüthi, Vieli 2016). Ice is released in a variety of ways (Benn et al. 2007, Alley et al. 2023): collapse of the ice front, detachment of ice blocks, underwater calving, and iceberg rotation (Amundson et al. 2008, Nettles et al. 2008). Such calving waves produce low-frequency seismicity that can be detected up to 150 km away (Amundson et al. 2012, Walter et al. 2013). The calving of glaciers and rolling of icebergs in fjords can trigger large tsunami waves that have the potential to be life-threatening and cause coastal damage (e.g. Levermann 2011, Macayeal et al. 2011, Lüthi, Vieli 2016). Tsunamis generated by icebergs are frequently observed in parts of Greenland, where they routinely reach wave heights of 2 m (Amundson et al. 2008, Macayeal et al. 2009). Iceberg calving is of great interest for many other reasons, including hazards to navigation caused by icebergs (e.g. Bigg, Wilton 2014) and the distribution of freshwater and nutrients released into the ocean by iceberg melting (e.g. Duprat et al. 2016). Tsunami hazards caused by glacier and iceberg calving appear to be a growing threat in the Arctic (Long et al. 2015, Benjamin et al. 2018).

However, the biggest tsunamis noted in the Arctic are those generated by big landslides entering bays and fjords (e.g. Buchwał et al. 2015, Benjamin et al. 2018, Strzelecki, Jaskólski 2020). Big landslides are located mainly in regions of the glacial domain: in Greenland, southeast Alaska, the Canadian Arctic Archipelago. This is due to the paraglacial oversteepened slopes, glacial debuttressing processes, and, in some cases, available glacial and fluvioglacial sediments on the slopes (Ballantyne 2002, Kargel et al. 2013, Strzelecki, Jaskólski 2020). Since 2000, three tsunamis generated by landslides have been documented – two in west Greenland and one in southeast Alaska (e.g. Higman et al. 2018). Numerous landslides, including submarine ones, are thought to be associated with Early Holocene warming and could have generated tsunamis. It is suggested that recent warming can result in a similar geomorphological response (Mccoll et al. 2012, Cossart et al. 2013, Steffen et al. 2020).

The 21st century has brought considerable advancement in filling out paleoenvironmental knowledge gaps in the studies on the Arctic coasts. Despite this progress, a fundamental issue requiring further investigation revolves around the dynamics between the Arctic coastal areas and the storminess. Along with the environmental and socio-economic consequences, we lack a better understanding of the prospective changes in Arctic storminess under warmer and less icy conditions (Nielsen et al. 2022). Moreover, current climate models do not yield consensus, indicating either a weakening and southward displacement of mid-latitude westerly storm tracks or their poleward shift in these tracks (Screen et al. 2014). Also, the quantification of mechanical wave erosion's contribution to coastal erosion lacks proper parameterisation, leading to discrepancies in estimates of up to 20% (Nielsen et al. 2022). To resolve this knowledge gap and assess the most probable scenarios under future warmer, less icy conditions, we ought to study the Holocene paleostorm records, particularly from the seasonally ice-free and warmer-than-present Early Holocene (e.g. Müller et al. 2012, McFarlin et al. 2018), and the Mid-Holocene, characterised by conditions that were similar to today (e.g. Müller et al. 2012, McFarlin et al. 2018). In recent years, several non-Arctic studies focussing on paleostorm records in coastal areas have delivered accurate, high-resolution reconstructions of Holocene storm events spanning centennial to millennial timescales (e.g. Jackson et al. 2005, Sorrel et al. 2012, Goslin et al. 2018, Kylander et al. 2023). Thus, we believe that the paleoenvironmental data from the Arctic coastal archives can also provide us with longer-term baseline data on the links between changes in sea ice, storminess, and coastal evolution (particularly erosion) under different climate conditions. The robust preservation of many Arctic coastal deposits is due to isostatic uplift rates, typically outpacing global sea-level rise since deglaciation (Lambeck et al. 2014, Long et al. 2015), potentially preserving the entire Holocene sediment sequences.

Sea-level changes

Post Last Glacial Maximum (LGM) crustal isostatic rebound and relative sea level (RSL) changes have strongly influenced the morphodynamics of Arctic coastal processes over the Holocene (~11.7 ka BP–present, Overduin et al. 2014). The glacial isostatic adjustment has dominated spatial sea-level variability over millennial time scales (including the Quaternary), constituting noteworthy background components in historical and recent sea-level changes in the millimetre range annually, partly due to the ongoing isostatic adjustments following deglaciations (Dutton et al. 2015). However, the specifics vary across the region. The highest rebound occurs in areas located in the former central parts of ice sheets, and the trend significantly diverges at their margins or in places with sparse ice cover (e.g. Forman et al. 2004, Wake et al. 2016). On Greenland, the uplift is generally the fastest in the west-central part (Wake et al. 2016, Paxman et al. 2022), while in the northwestern Barents Sea realm, the GIA is the highest in its north-central part – the past centre of the Svalbard-Barents Sea ice load (Forman et al. 2004, Ingólfsson, Landvik 2013). For the region formerly affected by the Laurentide ice sheet load, the northeastern coasts of Hudson Bay (Canada) experience the fastest GIA in the World (Lavoie et al. 2012, James et al. 2014, Boisson et al. 2020).

As the postglacial crustal uplift has generally outpaced global sea-level rise since the last deglaciation (Lambeck et al. 2014), many Arctic coasts are rich in sedimentary archives of their evolution, sometimes located up to several hundred meters above current sea-level (e.g. Forman et al. 2004, Stankowski et al. 2013). Not affected by contemporary glaciation, Holocene coastal archives (here understood as sedimentary deposits, landforms, and other geological features that preserve a record of past coastal processes and environmental conditions, e.g. lake sediment, beach ridges) have a high preservation potential and may encompass a record of the varied climatic states of the current interglacial, including warmer-than-present conditions (De Vernal et al. 2013, Lecavalier et al. 2014). They have the potential to determine the magnitude, rate, and source of sea-level rise from the perspective of progressive climate change. At the same time, postglacial RSL studies remain scarcely recognised (Baranskaya et al. 2018). Limitations are due to the inaccessibility of the sites but sometimes also due to the poor preservation of RSL change archives, for example, erosion or submergence, leading to the transformation or removal of forms. Reconstructing the rates, mechanisms or local patterns of Holocene RSL changes will enable the development of accurate models for predicting GIA and future sea-level rise (Khan et al. 2019).

Impact on coastal communities

Ongoing geomorphological processes in the Arctic affect the local communities. The main reports on infrastructural problems focus on Alaska, Canada, and Siberia, which are still largely controlled by permafrost melting and coastal erosion (e.g. Smith, Sattineni 2016, Irrgang et al. 2019). This is directly linked to a higher rate of erosion – 1.1 $m \cdot a^{-1}$, compared to 0.5 $m \cdot a^{-1}$ in other Arctic regions affected by permafrost (Table 1) (Jones et al. 2020). Coastal erosion along the oceans threatens not only local communities but also national infrastructure. For example, over 85% of Alaska native villages are affected by coastal erosion and flooding. Damage to infrastructure caused by permafrost degradation and coastal erosion also affects the activities of extractive industries, security and humanitarian agencies, and the defence industries of Arctic countries (Smith, Sattineni 2016). In addition to impacts on infrastructure, culturally important aspects of heritage sites are at risk. In the Yukon (in the northern part of Canada), 44 cultural sites have been destroyed due to the retreat of the coast. In addition, the ongoing coastal retreat is predicted to destroy a further 32 or 58, depending on the scenario (Irrgang et al. 2019). A good example is the community of Newtok in Alaska, where melting permafrost and erosion washed away the landfill and severely threatened the construction of fuel tanks. Collapsing infrastructure and the risk of flooding forced regional authorities to decide evacuating the entire population of 350 people (Welch 2019). The melting of the permafrost has even led to an international threat with the flooding of the Global Seed Bank in Svalbard (Carrington 2017). Climate change is also contributing to increased precipitation (e.g. Screen et al. 2014). For example, in Kugluktuk (Nanavut, Canada) in 2007, 173.5 mm of rain fell in the area (where the annual average is about 250 mm), washing-out many homes and destroying many roads (Prno et al. 2011). Predicting how permafrost coasts will change in the coming warmer decades is already complicated. Influencing mechanisms such as wave regimes and sediment delivery operate on many different temporal and spatial scales, while sea ice, storms, tides and constantly changing wave regimes interact with and influence ice-rich cliffs, deltas, lagoons, and barrier islands. This creates a dynamic system with a diverse and constantly changing morphology. Although coastal erosion in Arctic permafrost areas has been documented for decades, its social and environmental impacts have only recently been amplified and better recognised due to accelerating shoreline retreat (e.g. Jones et al. 2009). The main role of geomorphological research in the Arctic is to better predict the consequences of these threats, as well as to provide guidance for mitigation and adaptation to future changes.

Arctic coastal change studies – regional characteristics

Greenland

Greenland is considered the biggest island on Earth. Most of its surface is covered by the Greenland Ice Sheet (GIS) and minor ice caps. The shoreline is well developed with numerous fiords, peninsulas, and islands. The coast is typically steep and rocky and marine-terminating ice flows are common. However, the significant glacial sediment runoff increased by recent ice loss results in the formation of big accumulation forms. Due to the high rate of GIA the RSL in Greenland is falling (Bendixen et al. 2017, Steffen et al. 2020, Luetzenburg et al. 2023).

The development of deltas between 1940 and 1980 is described as stable, but it has continued to progress, and since the 1980s an increased development of these forms has been observed due to the melting of glaciers and the associated supply of fresh material (Bendixen et al. 2017). The delta progradation in Greenland represents a contrast to the remaining areas of the Arctic (Alaska, Siberia, and western Canada) where sedimentary coastal erosion is the dominant process (e.g. Lantuit et al. 2011b, 2012). The progradation of deltas is related to the supply of large amounts of freshwater and rock material from melting glaciers and the increasing number of open water days (Bendixen, Kroon 2017, Bendixen et al. 2017). Despite the longer period of open water and therefore the stronger impact of wave action, deltas develop stadily which is directly related to high freshwater runoff from the GIS. There is a noticeable tendency for more delta progradation in the southern and southwestern parts e.g. the coasts of Disko Island (west Greenland) at the deltas show an accretion rate of 1.5 to 7.0 $m \cdot a^{-1}$ (Bourriquen et al. 2018). Progradation also occurs on the eastern part, but it is more limited due to lower temperatures, lower freshwater runoff, and the presence of sea ice flux from the East Greenland Current (Bendixen, Kroon 2017). A detailed study conducted by Bendixen, Kroon (2017) on an 85-km-long coastal section of Disko Island revealed highly variable erosion. The biggest changes were observed in the Tuapaat and Skansen deltas where their mouths moved seaward at a rate of approx. 40 m per decade and 100 m per decade, respectively. The changes in the position of the Tuapaat delta are related to the classic development of this form, but the shift of the Skanen delta was related to the extreme flow of the river, which managed to get through the spit to form a new delta mouth (Bendixen, Kroon 2017).

Moreover, Greenland's glaciated coastline creates conditions for the creation of new islands − which is particularly linked to retreating marine-terminated glaciers. Therefore, there are already speculations that 5 small islands and straits will be created in the northwest part of Greenland, between Upernavik and Kap (Cape) Alexander (Ziaja, Haska 2023).

As a result of a warming Arctic, sedimentary Greenland coasts are being eroded by: (1) longer open water season and, as a result, greater susceptibility to wave action (Casas-Prat, Wang 2020), (2) melting glaciers and rising sea-level (Box et al. 2022), and (3) increased precipitation (McCrystall et al. 2021). A recent study by Luetzenburg et al. (2023) has shed new light on the erosion rate of coastal cliffs (Fig. 3) in west Greenland. According to the study, cliff erosion has reached 0.3 $m \cdot a^{-1}$ (Table 1). In some sections, the erosion rate has taken over 15 m for the given period. However, while this work fills one of the knowledge gaps regarding the development of Arctic coasts, there are still many to be studied (Kavan, Strzelecki 2023). Kavan, Strzelecki (2023) point out that the rate of erosion of soft-sediment cliffs (Fig. 3A) will intensify in the near warmer future with the reduction of sea ice extent and more wave action. Also increasing precipitation may lead to surface runoff and rill erosion that will destroy the cliff face (Luetzenburg et al. 2023).

The Vaigat Strait (west Greenland) has been recognised as the most potential (and the best studied) tsunamigenic area in the Arctic (e.g. Pedersen et al. 2002, Dahl-Jensen et al. 2004, Buchwał et al. 2015, Benjamin et al. 2018, Korsgaard et al. 2023, Svennevig et al. 2023). More than 20 rock avalanches or slides have been found here, on the slopes of Nuussuaq (Benjamin et al. 2018, Korsgaard et al. 2023). Occurrence of slides is influenced by favorable geological conditions (Pedersen et al. 2002, Benjamin et al. 2018), high topography relief (Pedersen et al.

2002), permafrost degradation (Pedersen et al. 1998, Svennevig et al. 2023), and climatic factors controlling permafrost (Buchwał et al. 2015). However, not every landslide, despite reaching the waters of the strait, triggers a tsunami (Svennevig et al. 2023). Two recent tsunamis were described from that location. The first one took place in 1952 (Niiortuut). While its occurrence has been attributed to permafrost degradation, more precise recognition is missing (Higman et al. 2018, Svennevig et al. 2023). The second one happened in 2000 (Paatuut) and the wave run-up reached up to 50 m above water level (Dahl-Jensen et al. 2004, Long et al. 2015). Greenland settlements are usually built near the coast (Fig. 4A, B) due to better access to fishing and hunting, however such locations make them more vulnerable to tsunami, storms, and flooding risk. The wave in 2000 caused damage to buildings in the previously abandoned settlement of Qullissat (Fig. 4C, D) (Pedersen et al. 2002) and left accumulated wood and salt-damaged vegetation visible in the landscape (Buchwał et al. 2015).

Another tsunami occurred in 2017 in Karrat Isfjord (also west Greenland) as a result of a landslide on the slopes of Ummiammakku mountain. The wave reached a runup to 90 m and led to the destruction of 48% of the infrastructure in the Nuugaatsiaq settlement (Strzelecki and Jaskólski 2020). According to Schiermeier (2017) and Gauthier et al. (2018), the aforementioned landslide was much larger than the famous tsunamigenic landslide in Lituya Bay (southwest Alaska, 1958).

Recent studies indicate that the calving of glaciers and the rolling of icebergs also trigger tsunamis (Strzelecki 2011a, Overduin et al. 2014, Wolper et al. 2021). In Greenland, long waves caused by calving glaciers are a common phenomenon in narrow fjords, affecting the coasts at

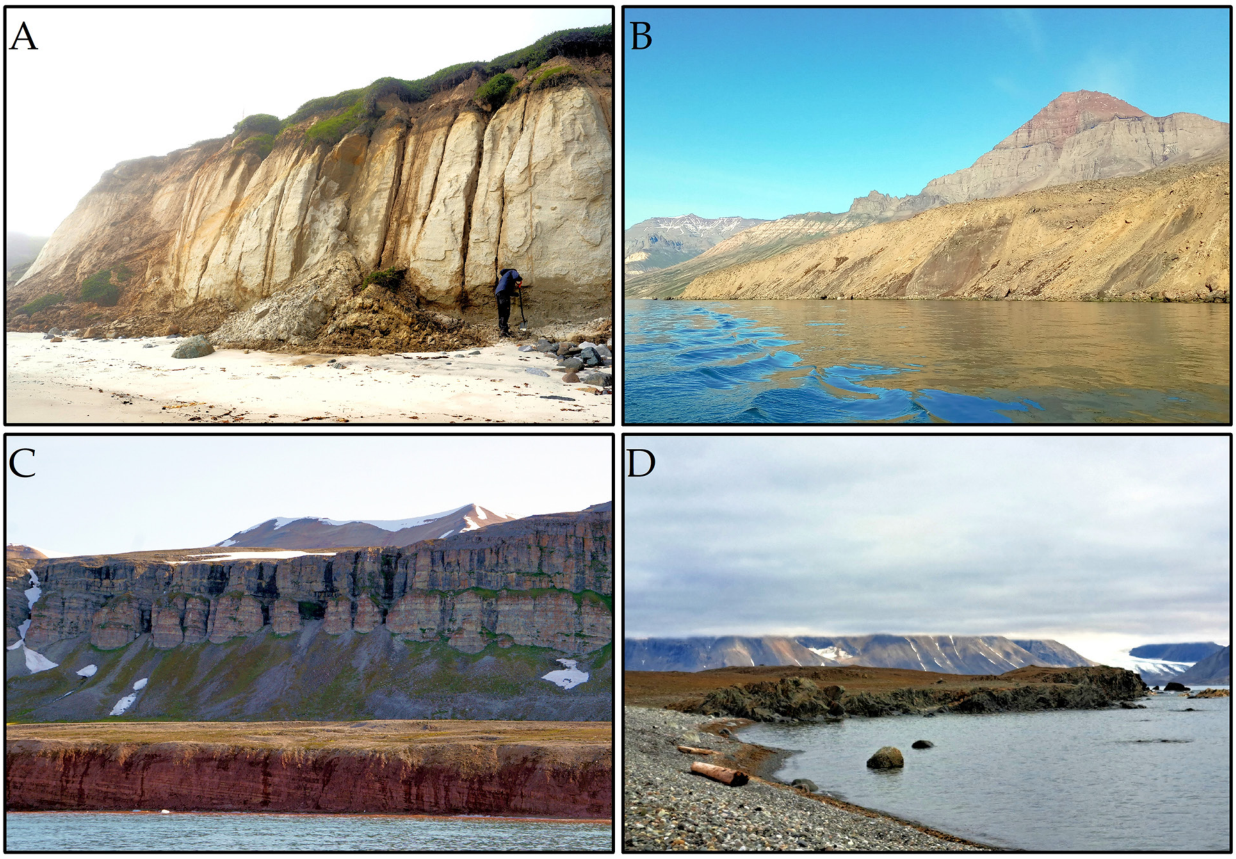


Fig. 3. Cliff coasts: A – Unconsolidated sedimentary cliff formed in glaciofluvial sediments, southwest Disco Island coast (west Greenland); B – Cliff made of deposits from Paatuut landslide which entered the strait in 2000 and caused a tsunami wave, view from the Vaigat Strait (west Greenland); C – Bedrock cliffs covered with marine deposits, Kongsfjorden (northwest Spitsbergen) views to the southwest; D – Low rocky cliff skerry coast formed in marble, Wilczekodden in Hornsund (Svalbard), view from the west. Photo by M.Kasprzak (A), M.Szczypińska (B), A.Wołoszyn (C), Z.Owczarek (D).

Table 1. The average rate of coastline changes in the Arctic since the end of the Little Ice Age, based on recent research.

Location	Region	Average rate of coastal changes [m a^{-1}]	Publication
Arctic coasts	Arctic	−0.50	Lantuit et al. (2011)
Arctic coasts	Arctic	from −1.00 to −2.00	Forbes (2011)
Siniffik	Greenland	−0.30	Luetzenburg et al. (2023)
Disko Island	Greenland	−1.50	Bourriquen et al. (2018)
Isbjørnhamna	Svalbard	−13.00	Zagórski et al. (2015)
Calypsostranda	Svalbard	−0.19	Zagórski et al. (2020)
Hornsund	Svalbard	−1.90	Lim et al. (2020)
Rekvedbukta	Svalbard	−2.22	Wołoszyn et al. (2022)
West Euroasian	Siberia	−4.00	Ogorodov et al. (2022)
East Asian	Siberia	from −2.00 to −7.00	Ogorodov et al. (2020)
Bykovsky Peninsula	Siberia	−0.59	Lantuit et al. (2011a)
Muostakh Island	Siberia	−20.00	Vonk et al. (2012)
Ozero Mogotoyevo	Siberia	−12.40	Wang et al. (2022)
Northen Alaska	Alaska	−1.40	Gibbs, Richmond (2017)
Drew Point	Alaska	−38.30	Wang et al. (2022)
Cape Krusenstern	Alaska	−0.13	Farquharson et al. (2018)
Cape Espenberg	Alaska	−1.53	Farquharson et al. (2018)
Yukon	Canada	−0.70	Irrgang et al. (2018)
Herschel Island	Canada	−0.68	Obu et al. (2016)

Fig. 4. Coastal residential buildings in Greenland are exposed to the destructive activity of the sea: A – Ilulissat; B – Oqaatsut. Buildings of Qullissat were destroyed by the tsunami in 2000; C – Damaged residential building; D – Damaged mining infrastructure. Photo by M.Szczypińska (A, B, C), M.Kasprzak (D).

great distances from the glaciers (e.g. Reeh 1985, Long et al. 2015, Lüthi, Vieli 2016). However, few studies have focussed on tsunamis generated by calving glaciers. Lüthi, Vieli (2016) reported a 45–50 m high tsunami wave generated by the calving of a 200 m high ice cliff at the head of the Eqip Sermia glacier (west Greenland) (Fig. 5A, B). The result of this phenomenon was the destruction of the coastal infrastructure (wharf) and the washing of the soil cover into bedrock. Nielsen (1992) noted that the calving of the Eqip Sermia glacier resulted in the transformation of a glacial form (a moraine) into a marine-controlled form (a boulder spit closing the lagoon) (Fig. 5B). This is a unique example of a rapid transformation of glacial to paraglacial processes, taking place within a few decades. There is currently not much research into the effects of iceberg rotation on the Arctic coast. The work of Long et al. (2015) also suggests that a tsunami triggered by iceberg rotation once occurred (Middle Holocene), as confirmed by sediment layers in the isolated lake. The focus on iceberg seismology has created a new opportunity to study several processes occurring in icebergs (Rosser et al. 2015). Long et al. (2015) and Benjamin et al. (2018) conclude that rock avalanches occurring in stagnant fjords, calving glaciers (Fig. 6), and icebergs have grown a significant threat of tsunamis.

Data for Upernivik in Disko Bay record a course of deglaciation from 8 cal ka BP, with the RSL ~43 m above the present level (Long et al. 2006). More recent data have shown significant spatial and temporal gradients of the RSL in the gulf. Preceded by deglaciation ~11 cal ka BP, RSL fall occurred promptly, with an initial marine limit at ~80 m and a faster pace in the southeast part of the bay. The rapidity of the regression slowed down ~6 cal ka BP, continuing for three more millennia, and being eventually replaced by a Late Holocene RSL rise. However, in the west part of the bay, transgression began nearly

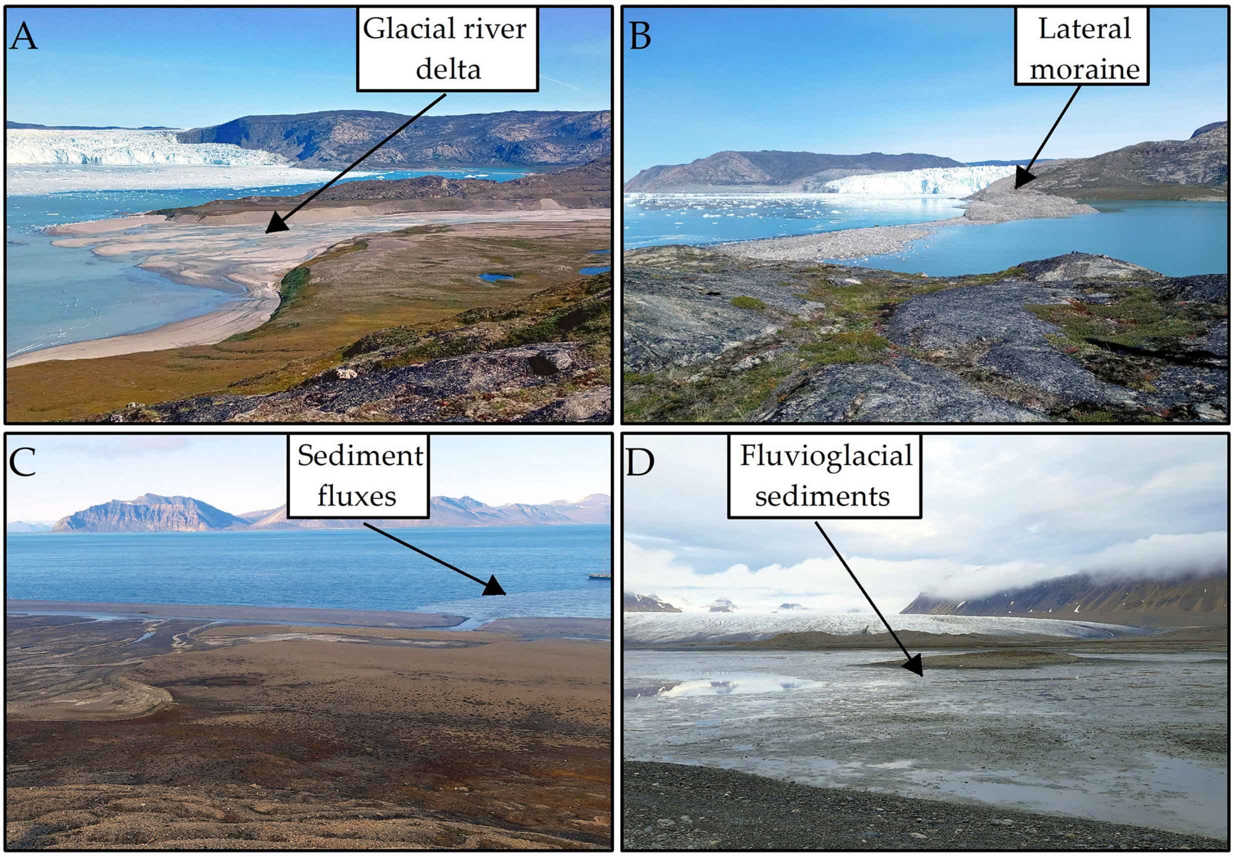


Fig. 5. Examples of accumulation coastal landforms in the Arctic: A – View of the glacial river delta and marine-terminating glacier Eqip Sermia in the background; B – Lateral moraine of retreating glacier Eqip Sermia separating the lake (previous lagoon) from the open sea; C – Extramarginal outwash of the Scott River with visible sediment fluxes (Calypsostranda, Svalbard); D – Josephbukta Bay with fluvioglacial sediments and Renardbreen Glacier in the background. Photo by M.Szczypińska (A, B), O.Kostrzewa (C, D).

Fig. 6. The coast opposite the Eqip Sermia glacier affected by a tsunami, which happened due to a calving glacier, was observed on August 8th, 2023. Photo by M.Kasprzak.

a 1000 years later (Long et al. 2011). Long et al. (2011) link this with stronger subsidence of the west part, due to Neoglacial ice sheet regrowth (Rasch, Jensen 1997, Long et al. 1999). The course of RSL changes in Disko Bay is similar to those observed in Sisimiut (central-west Greenland, (Weidick, Bennike 2007, Long et al. 2009, Bennike et al. 2011). There, too, the RSL underwent a rapid decline of ~10.9 cal ka BP (marine limit of ~140 m). However, it slowed way sooner, ~9 cal ka BP (Bennike et al. 2011). Data from Long et al. (2009) indicate that the RSL reached the lowstand of ~–4 m in mean tide level ~2.3–1.2 cal ka BP, but after AD 1600 the RSL was already close to the present, which all indicate a similar timing of the Late Holocene transgression as one observed for the Disko Bay. Overall, the RSL has increased at both sites to ~5 m in the last 3 millennia, resulting in the inundation of coastal habitats and settlements (Long et al. 2009, 2011).

Different timing and nature of changes were noted for south Greenland. Data from isolation basins in Nanortalik, where ice sheet recession on land occurred ~13.8 cal ka BP, reveal a steep Early Holocene RSL fall, explained by its closer location to the GIS margin. There, the RSL fell below its current level earlier, ~10–8 cal ka BP, reaching the biggest lowstand (~10 m below the highest tide level) between ~8–6 cal ka BP, well before the Neoglacial (Sparrenbom et al. 2006). Thus, the lowstand south Greenland was larger and reached much faster (Long et al. 2011, Woodroffe, Long 2013). The following rise to the current level occurred in Nanortalik during the last 6–4 cal ka BP. The Late Holocene transgression is marked more rapidly in this area at sites distal to the GIS (Sparrenbom et al. 2006). The marine limit of ~52 m at or before ~10.9 cal ka BP observed at Paamiut is yet another confirmation of this trend in south Greenland. There, a sea-level close to the present reached ~9.5 cal ka BP, and the further decline continued throughout the rest of the interglacial. However, the exact level of the RSL lowstand has not been precisely recognised, yet assumed to be ~5–10 m (Woodroffe, Long 2013). The RSL data from Ammassalik indicate quite a similar trend for southeast Greenland as the one observed for Disko Bay, as the local marine limit of ~70 m reached ~11 cal ka BP. The sharp decline in RSL led to reaching a level close to the present one ~6.5 cal ka BP, much later than in Nanortalik. Although no evidence of an RSL decline below the present level has been indicated (Long et al. 2008), such a scenario of a Middle to Late Holocene RSL fall, terminated by another rise, should be considered in many areas (Long et al. 2011, Woodroffe, Long 2013).

Extensive and long (>10 km) sequences of beach ridges in north Greenland record a marine limit of 45–70 m a.s.l. and a history of gradual RSL decline, beginning with deglaciation of an area ~10 cal ka BP until reaching the present level of ~3 cal ka BP. Note that the GIA and RSL changes often contribute to the development and morphology of beach ridges, as the change in coastal elevation can affect the wave dynamics, and sediment supply or cause the coastline migration (e.g. Brückner et al. 2002, Long et al. 2012). The onset of Holocene Thermal Maximum (HTM) ~8.5–6 cal ka BP was characterised by an intense deposition of beach ridges due to reduced sea and land-fast ice. Middle Holocene changes brought a limitation of their growth in the area, as most of them stopped forming ~5 cal ka BP. Eventually, the Neoglacial cooling ~2.5 cal ka BP terminated their development, except in Holm Land, where they are continuously formed, although poorly (Funder et al. 2011). Pedersen et al. (2011) presented an RSL curve for northeast Greenland based on data from Young Sound. Dates extracted from raised beach ridges indicate periods of transgression, while dates from paleoterrestrial surface levels presently buried beneath intertidal levels mark the RSL fall. A sharp decline in RSL occurred at ~9.5 to 7.5 ka BP, then slowed until reaching its present level of ~3 ka (Pedersen et al. 2011), similar to the north Greenland (Funder et al. 2011). The further decline was recorded in a marine limit of ~–0.5 m below the current level of ~2.3 ka BP, followed by a transgression: slow, yet still ongoing (Pedersen et al. 2011).

Sites of low marine limits (~20 m) are characteristic of areas where the ice sheet remains near the coast, e.g. Melville Bay (northwest Greenland), and parts of southeast Greenland. The reasons for this can be attributed either to the lack of significant changes in ice volume since the LGM or to the significant rebuilding of the cover during the Neoglacial (Woodroffe and Long 2013).

In general, most RSL data for Greenland come from the rapid postglacial regression phase (Woodroffe, Long 2013). Long et al. (2011) attribute the variation in RSL changes to the amount of ice load alteration over time since the LGM, although they also point to the contribution of external processes, most notably the disintegration of the Laurentide forebulge and an ice equivalent sea-level change. In contrast to the rapid drop in the early part of the interglacial, the course of the RSL rise in the Middle and Late Holocene was slower and more gradual (Sparrenbom et al. 2006). Interestingly, the deglacial model of GIS (Huy3) presented by Lecavalier et al. (2014) indicates that the present-day coastline was reached in Greenland by ~10 ka BP.

Svalbard

Svalbard is located in the Arctic Ocean, east of the northeast coast of Greenland and north of the coast of the Scandinavian peninsula (Fig. 1). Svalbard is an archipelago of several islands, the largest of which are Spitsbergen, Nordaustlandet, Edgeøya, and Barentsøya. The area is characterised by a mountainous landscape with a harsh polar climate and large areas covered by glaciers. The islands are characterised by deeply indented bays and numerous fjords. The coasts are often high and rocky, but some of them are covered with marine sediments. This shift is associated with the rapid retreat of glaciers since the end of the Little Ice Age (LIA) (more than 20% of the glaciated area has been lost since then) (Strzelecki, Jaskólski 2020). During the 20th century, the landscape of Svalbard has been increasingly affected by paraglacial erosion rather than by glacial processes (Overduin et al. 2014). Lantuit et al. (2011b) analysed 61,000 km^2 of coastline and estimated that the average erosion to be 0.5 $m \cdot a^{-1}$ with a maximum exceeding 8.4 $m \cdot a^{-1}$. However, the study is characterised by a global scale, so erosion in particular locations may reach different levels. Moreover, many Arctic coasts had not been taken into their consideration.

Studies on the Isbjørnhamna coast (Hornsund Fjord, south Spitsbergen) show that due to erosion over the past 50 years, the coastline has reduced, on average, by 13 meters (Table 1), resulting in a loss of 31,600 m^2 (Zagórski et al. 2015), posing a threat to the storage facility of the Polish Polar Station (Fig. 7A, B) (Zagórski et al. 2015). Research conducted in Calypsostranda (Bellsund Fjord, central Spitsbergen) also show that the analysed coastline decreased by 28,800 m^2 from 1936 to 2017. However, in between the dominant erosion (6 years between 2007–2017), there were also periods with dominant accumulation (4 years between 2007–2017) (Zagórski et al. 2020). On the other hand, Strzelecki et al. (2017b) focussed on the morphodynamics of rocky coastlines along the Wilczekodden (Hornsund Fjord, south Spitsbergen) (Fig. 3D) where they noted that the development of permafrost is controlled

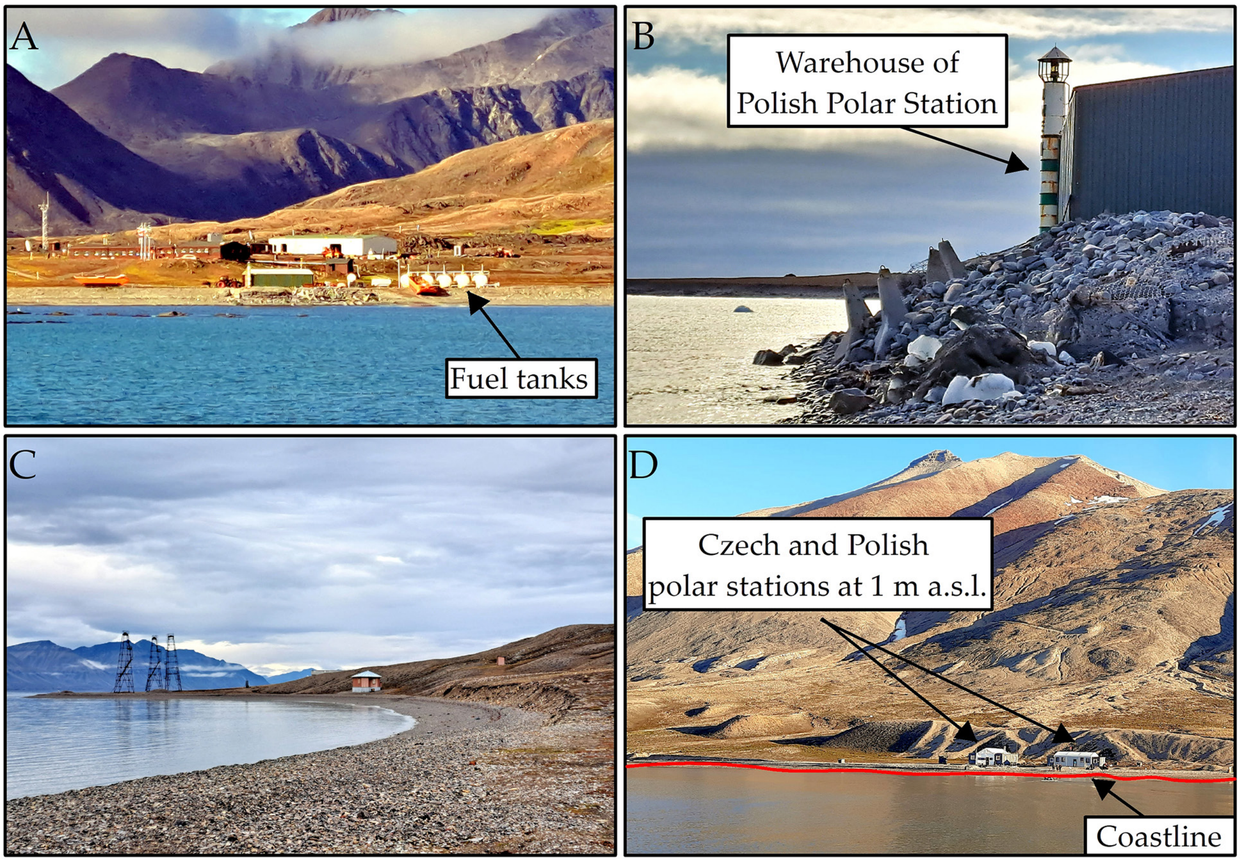


Fig. 7. Examples of coastal buildings and facilities in Svalbard vulnerable to damage due to their location: A – The Polish Polar Station buildings and facilities on the northern, eroding coast of Hornsund; B – The warehouse of the Polish Polar Station, as a result of long-term erosion of the Hornsund coast, is now on the edge of the land. Its southern wall has already been reinforced several times to prevent damage to the building; C – The remnants of 20th century mining activities are still visible in the landscape of Spitsbergen; D – Polish and Czech polar station buildings located ca. 25–30 m from the coastline at the bottom of Pyramiden Hill. The photo was taken from Petuniabukta Bay. Photo by Z.Owczarek (A, B, C), O.Kostrzewa (D).

by the thermal influence of seawater and that the strength of the surface of the rocks building coastal platforms and cliffs depends on the efficiency of the processes of weathered and eroded material. In earlier studies, Strzelecki (2011b) suggested that coastal processes (tidal wetting and drying, salt weathering, wave action, sea ice action) weaken the rock surfaces more efficiently than other subaerial agents operating on rocky landforms in more inland locations, allowing deeper and more efficient rock weathering. The importance of better understanding the control of rocky coastlines in an era of a warming climate was also pointed out (Strzelecki 2011b, Strzelecki et al. 2017b). They allow the response of rocky coasts to climate change and associated erosion to be assessed on relatively short, recent time scales (less than 100 years) (Lim et al. 2020). A more recent study by Lim et al. (2020) of rocky shores in Hornsund Fjord shows that erosion is lower than previously indicated by Jahn (1961), who suggested that the disappearance of sea ice and increased storminess would affect intense coastal erosion. Lim et al. (2020) used a new method of three-dimensional thermal mapping to spatially map process zones, confirmed by measuring rock hardness. They conclude that the cryogenic impact has decreased and that understanding the effectiveness of thermal processes may have implications for understanding the rate of strandflat development. The study of Aga et al. (2023) has provided the new insight into ongoing erosion in the rocky parts of the Brøgger peninsula over the last 5 decades (1970 to 2021). The results of the study indicate steadily increasing erosion from 1970–1990 (47%) to the last decade 2010–2021 (65%) when the erosion rate significantly accelerated as a result of changing climatic conditions and the permafrost thawing, as well as increased precipitation (Aga et al. 2023).

Ziaja et al. (2009), in their study on the northeast coast of Sørkapp Land (south Spitsbergen), noted that the coastline was shifted inland between 1936 and 2005 by up to 460 m. This was influenced by increased sea wave activity as a result of the retreat of the Hambergbreen glacier and thus the loss of its protective function. Ziaja's team has described and presented changes concerning, only one of Svalbard's lagoons (Ziaja et al. 2009, 2023). The context of lagoons as a whole in this Archipelago has not been sufficiently described in the literature. Lagoons are most often described for their favourable conditions for the development of flora and fauna (Haug, Myhre 2016) or making the description usually about specific lagoons (e.g. Fraley et al. 2021). Meanwhile, lagoons are highly sensitive and indicative coastal environments. Their disappearance, development, loss or formation of inlets are consequences of external factors such as wave action, storms, glacial retreat, glacial isostatic adjustment, or sediment supply. Lagoon transformations can occur even in a century (Ziaja et al. 2009, 2023). Temporal observations of lagoon systems provide information about the variability in the environmental conditions.

In connection with the abovementioned, in response to glacial melt and associated glacio-isostatic movements, new landscapes are emerging in Svalbard (Strzelecki et al. 2020). A recent study by Kavan, Strzelecki (2023) showed that 929.9 km of new coasts have been created since 1930s as a result of the glacier's retreat and during the last 70 years, 40 bedrock islands have been created (Ziaja, Haska 2023). These 'youthful' areas are vulnerable to wave action and intense erosion, which can remodel the current coast into new coastal features (Kavan, Strzelecki 2023). An interesting case of new island formation is located in south Spitsbergen (Ziaja, Ostafin 2015, Grabiec et al. 2018, Ziaja, Haska 2023), where two rapidly retreating glaciers, Hambergbreen and Hornbreen, form an icy isthmus between Torell Land and Sørkapp Land. It is presumed that with the ongoing climate change, by 2055 the glaciers retreat will cause a breaching between the lands (Grabiec et al. 2018), although Ziaja, Ostafin (2015) supposed that the disconnection will take place faster between 2030–2035 or several years earlier, thus creating a new island – presumably called Sørkapp Land. The new strait would connect the Barents Sea with the Greenland Sea, generating huge environmental changes. In addition, glacial melting delivers massive amounts of sediment to the sea and leads to the development of deltas (Figs 5C, D) (Huss, Hock 2018).

Floods pose another significant threat to human infrastructure, as they can rapidly remodel the landscape (Rachlewicz 2009), especially during the spring melt (ice jams), when Arctic rivers are more erosive (Jaskólski 2021). With a greater supply of water from melting glaciers also comes much greater accumulation in estuaries and shallow harbour basins resulting in reduced sea transport and a direct threat to ships (e.g. Bogen, Bønsnes 2003, Mercier, Laffly 2005). Research by Wieczorek et al. (2023) and Wołoszyn et al. (2022) focussed on the hazards of glacial lake outburst floods (GLOFs). Wieczorek et al. (2023) focussed on the inventory of Svalbard's lakes and pointed out those in which GLOFs have occurred in the past, and indicated those lakes where this may occur in the future. The second work led by Wołoszyn et al. (2022) focussed on a small catchment area located on Svalbard in which GLOFs occurred. The results showed that large hydrological changes can occur in just a few days (the disappearance of a glacial lake and a lagoon) as well as coastline changes (progradation and/or erosion of barrier sand spits). Studies indicate that such threats will increase in a warming future (Wołoszyn et al. 2022, Wieczorek et al. 2023).

The marine limit on Svalbard is highly diverse, often varying between selected points within a single fjord (Sessford et al. 2015). This is due to the variation in ice thickness within the multi-domed Svalbard-Barents Sea ice sheet, entailing different degrees of ice loading and isostatic uplift (Hogan et al. 2010, Hormes et al. 2011, Long et al. 2012, Ingólfsson, Landvik 2013). Comprehensive systematics by Forman et al. (2004), describing Holocene RSL changes (including transgressive-regressive events) on Svalbard, Franz Josef Land, and Novaya Zemlya, illustrate this well, pointing to significant differences in the timing of the onset and subsequent course of deglaciation in the region, as well as varying rates of isostatic and RSL changes.

Long et al. (2012) delivered one of the most precise sea-level change curves for central

Spitsbergen. Located at a maximum elevation of ~40–45 m a.s.l., the sand and gravel paleobeaches (Figs 6C, D) in Ebba Valley in northeast Petuniabukta, Billefjorden formed shortly after local deglaciation, ~10 cal ka BP (Long et al. 2012), which remains coherent with Forman et al. (2004). The described succession represents a record of postglacial steady decline in RSL until ~3.1 cal ka BP (Long et al. 2012). Traces of the regression were also noted by Strzelecki et al. (2018) in their study of the adjacent Ferdinand Fans and Spits, indicating, among other things, the incision of the paleoalluvial fan by the Ferdinandelva delta, proceeding with a rapid drop in RSL. No formations younger than 3 cal ka BP have been found in the Ebba Valley, indicating that the RSL, which was declining in the Middle to Late Holocene interglacial, must have undergone a slow rise in recent millennia (Long et al. 2012). This is consistent with estimates of Forman (1990), suggesting the RSL rise in the last 2 ka. Strzelecki et al. (2018) also noted changes in the orientation of paleobarriers in the northwest Petuniabukta, interpreting them as a sign of rapid adaptation of local geomorphology to the Late Holocene RSL rise. Another interesting study for the central Spitsbergen was presented by Sessford et al. (2015), who reconstructed a large spatial and chronological variation in the dynamic evolution of the Fredheim, south Sassenfjorden coast. There, the oldest raised marine terraces were uplifted during the HTM, ~11.06 cal ka BP, fully entering the land before 9.1 cal ka BP. The uplift of two other terraces terminated later, during the post-HTM cooling or more recent Neoglacial period (7.2–6.8 and 4.2–3.77 cal ka BP, respectively). The youngest part of the area, the relict alluvial plain, was presumably uplifted more recently, during the Medieval Warm Period (1200–950 cal ka BP).

Russian Arctic

The Russian Arctic starts in the northern stretch of the Russian coastline, extending from the Barents to the Chukchi Sea, encompassing the islands of Novaya Zemlya, Franz Josef Land, Severnaya Zemlya, and the New Siberian Islands. Permafrost exerts significant control over the coasts in this region, with thickness generally increasing from the west (characterised by massive ice beds and ice wedges) to the east (featuring continuous permafrost). Marine and glacial Pleistocene and Holocene sediments dominate the western coast. During deglaciation, the western coasts were uplifted and, although a slowdown of this process was observed in the Middle Holocene, it is still a key element controlling the present coasts. The eastern coasts are composed of the Pleistocene ice complex. The coastal cliffs, in this part of the Russian Arctic, resemble ice walls with laminated sediments (Baranskaya et al. 2018, Obu 2021).

The ice-rich coasts of the Euroasian part of the Arctic (Fig. 2B) are susceptible to thermo-erosion (Belova et al. 2019), and thus the coastline changes occurring there mainly relate to erosion averaging up to 4 $m{\cdot}a^{-1}$ in the western part and up to 12–17 $m{\cdot}a^{-1}$ in the eastern part (Ogorodov et al. 2022). Waves and tides have the greatest impact on changes to the western Asian Arctic coastline, according to Ogorodov et al. (2016). Wind-driven waves, along with prolonged less icy periods, affect coasts longer, more strongly as well as further inland. The greatest damage occurs during storms when the energy transmitted by the wind is greater. On the other hand, Lantuit et al. (2011b) state that depending on the region, different conditions affect coastline changes, and show that in the Laptev Sea area, the erosion rate ranged from 0.0 to 5 $m{\cdot}a^{-1}$. They also show that the highest erosion rate (in the pan-Arctic context) did not only occur along the coast of the Beaufort Sea but also on the Laptev Sea, ranging up to 3 $m{\cdot}a^{-1}$.

In another work focussing on the permafrost-dominated coast of the Bykovsky Peninsula in north Siberia, Lantuit et al. (2011a) determined that the average rate of change was –0.59 $m{\cdot}a^{-1}$ during the period from 1951–2005, but during the period of prevailing storms, the average erosion rate ranged from 2–6 $m{\cdot}a^{-1}$ and may have reached up to 20 $m{\cdot}a^{-1}$. Ogorodov et al. (2020) presented a case where in one year as the result of a storm surge the coast of Varandey Island, retreated more than 19 m. Studies on permafrost-rich coasts of Muostakh Island (southeast Laptev Sea) by Vonk et al. (2012), show the average –20 $m{\cdot}a^{-1}$ changes, though not related to storms, but to direct wave action on exposed ice-rich cliffs, and therefore thermal erosion, making these coasts vulnerable to retreat by up to 5–7 times faster than other permafrost-rich coasts. In addition to climate change and associated impacts, coastal changes in the Russian Arctic are also influenced by anthropogenic activities, as highlighted by Ogorodov et al. (2016). He draws attention to the removal of sediment carried by rivers or tidal flows as the most hazardous activity, particularly on low coasts. Chan et al. (2023), on the other hand, investigated the unique environment of the Lena Delta and pointed out that Arctic deltas are particularly affected by climate change, sea ice, permafrost thawing, and wave action. That would indicate that the natural factors have the greatest impact on the low coasts. Chan et al. (2023) also attempted to predict the evolution of the delta, taking shallow ramps into their consideration. Using numerical models, they found that with RCP7–8.5, ramps will be degraded over the century and may even disappear completely within a millennium. With the disappearance of these forms, the impact of wave action will increase, resulting with higher erosion rates. In comparison, the second-largest Arctic delta – the Mackenzie Delta – is retreating by as much as 1–10 $m \cdot a^{-1}$ through flooding (Overduin et al. 2011).

The new land included in the Siberian Archipelago are two small islands that emerged as a result of the recession of the Molotov Glacier to Komsomolets Island and the Schmidt Glacier to Schmidt Island (Ziaja, Haska 2023). Their areas are 0.4 km^2 and 1.2 km^2 respectively. According to Ziaja, Haska (2023), these are the first islands to appear outside Greenland and the European Arctic as a result of glacial recession. Moreover, it is suspected that another island will also be created by the retreat of the Molotova glacier from the most northern part of Komsomolets Island. The newly formed island would be much larger than the previously mentioned ones and would cover an area of 64 km^2.

Baranskaya et al. (2018) described sequences of numerous raised beaches in Franz Josef Land and Novaya Zemlya (Figs 1, 2A). They reflect a gradual but continuous RSL regression from ~35 to 25 meters ca. 9 ka to ~10–5 m ca. 3 ka. Interestingly, the trend of constant RSL fall was not observed for the White Sea coast. While the western area experienced an initial post-LGM transgression followed by an RSL fall, the northwest Russian Plain was covered by an early and Middle Holocene lowstand followed by an RSL rise and highstand (Baranskaya et al. 2018). The history of these complex and alternating cycles is recorded in a series of paleoforms. In addition to raised marine terraces and beaches, isolation basins and ancient lagoons were recognised in the White Sea (Boyarskaya et al. 1986, Kolka et al. 2013, Repkina et al. 2018 [cited in Baranskaya et al. 2018]). A very different story unfolds for the Timan coast, subjected to a steady increase in RSL during the Holocene (Polyak et al. 2000, Krapivner 2006, Zhuravlev et al. 2013 [cited in Baranskaya et al. 2018]), linked to the collapse of the proglacial forebulge. However, data coverage for this area is spatially and temporally limited, entailing rough estimates (Baranskaya et al. 2018).

The shallow Siberian shelf has never been covered by Quaternary ice sheets, except for the western parts of the Kara Sea shelf (Svendsen et al. 2004). In contrast to the western regions of the Russian Arctic, vastly affected by postglacial vertical movements, the Holocene transgression that covered the Siberian shelf was primarily driven by eustatic changes, although some divergence in the Laptev Sea and East Siberian Sea is also the result of eustatic processes (Klemann et al. 2015). Together with the poor exploration or differences in tectonic vertical movements (e.g. Drachev et al. 2003) and complex tectonic setting (Klemann et al. 2015), the data for RSL history in the region is severely varied (Baranskaya et al. 2018).

A steady increase in RSL in the Kara Sea shelf was due to the same proglacial forebulge disintegration that affected Timan coastlines. However, compared to data for more eastern territories (Laptev Sea shelf), ~9 ka was covered by a much lower RSL (–38 to –40 m). A strong fluctuation in RSL history, however, was observed for the Yamal and Gydan Peninsulas and Severnaya Zemlya. There, the high LGM RSL initially dropped during the recent interglacial, being later marked by a small highstand in the Late Holocene (Baranskaya et al. 2018). Yet, the exact mechanisms controlling the history of RSL in this region remain poorly explored. An interesting point was provided by Whitehouse et al. (2007): their model indicates a strong (and still observed) increase in RSL in the Pyasina, Yenisey, and Ob Rivers mouths from ~7 ka, associated with a decrease in the rate of global ice-melting.

Located away from the Eurasian Ice Sheet (Patton et al. 2017), the active continental margin of the Laptev Sea (Drachev et al. 2003), was scarcely affected by vertical motion from the forebulge disintegration. At ~9 ka, the RSL was about –27 m in the region. Numerous marine terraces reveal a steady rise: by ~7–5 ka the upstand reached ~10–5 m (Baranskaya et al. 2018). Bauch et al. (2001) suggest that this rapid postglacial transgression was terminated ~5 cal ka by an onset of RSL stability at a level similar to the present. Series of barrier, prograded spits and beach-ridge formations folded within local depressions in Buor Khaya Gulf bear a record of more than 1 km of progradation of ridges at an interval of 6.2–2.6 cal ka BP, with little change in their surface elevation (Sander et al. 2017, 2019). There, gravel and pebble-dominated beaches were formed under storm-wave or surge conditions: not only intense but also continuous. This also indicates a high extent of storm waves, and RSL stability during the described period (Sander et al. 2019): more than a millennium earlier than indicated by Bauch et al. (2001), up to at least 2.6 cal ka BP (Sander et al. 2019). Similar to the observations of St-Hilaire-Gravel et al. (2010) in the Canadian Arctic Archipelago (CAA), Sander et al. (2019) indicate that the beach ridges in Buor Khaya were deposited during warmer periods, of a longer open-sea season. Bolshiyanov et al. (2015) proposed an interesting counter-story for the RSL history in the region. Based on marine signals in the Lena River mouth, they suggest the occurrence of marked RSL fluctuations within the Laptev Sea during the Middle to Late Holocene, indicating episodes of 5 m transgression and 1–2 m regression (relative to current sea-level). The increase in RSL over the past ~3 ka in the mouths of the Lena, Indigirka, and Kolyma rivers, however, has not been confirmed by Whitehouse et al. (2007). The only record of RSL increase in this period was reported for Khatanga River (~3 m rise). Baranskaya et al. (2018), on the other hand, report a single regression archive in the last millennium, reconstructed in several raised beaches from the Laptev Sea and western New Siberian Islands.

Canadian Arctic and Northern Alaska

Canada's northern coasts represent up to 70% of the country's coasts (Ford et al. 2018). Canadian islands located in the Arctic Ocean are included – known collectively as the Canadian Arctic Archipelago (Fig. 1). These coasts are controlled by permafrost, taking forms from small ice lenses to massive ice bodies (Berry et al. 2021). Areas rich in permafrost and unconsolidated material are highly susceptible to erosion, whereas coasts with permafrost in consolidated sediments are generally resilient (Lantuit et al. 2011b). The coasts of Northern Alaska (Fig. 8A) are geomorphologically similar to those of northern Canada, e.g. Yukon (Fig. 8B).

Gibbs, Richmond (2017) conducted a study on the rate of Alaskan coastal change over the period 1940s–2010s from the Icy Cape to the US and Canadian border. According to Gibbs, Richmond (2017), the northern Alaskan coast was changing by an average of $-1.4\ m{\cdot}a^{-1}$. They also reported that up to 84% of the examined transects showed

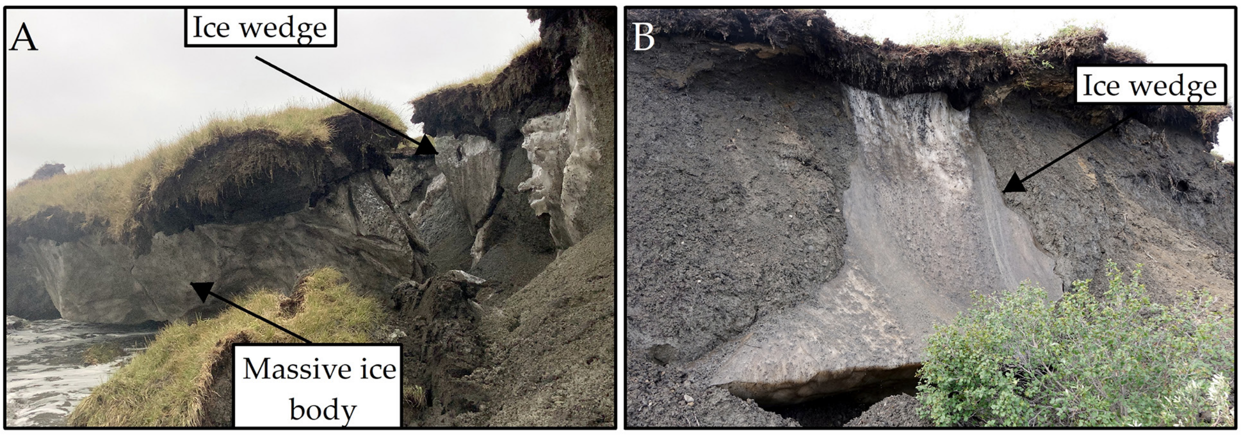


Fig. 8. Coasts with visible ice wedges and massive ice bodies: A – Alaska; B – Yukon. Photo by L.Farquharson (A), M.Lim (B).

coastal erosion and, in addition, the recorded changes were greater along the Beaufort Sea coast which is similar to the Chukchi Sea coast. The highest mean coastline change was on the exposed continental parts compared to the rest of the coast. It is interesting to note, however, that the highest erosion value of –25.1 m·a^{-1} was recorded for the sheltered coast. In contrast to these data, Wang et al. (2022), determined that the erosion rate for Drew Point, Alaska was even up to 50 m·a^{-1}. Increased erosion was mainly influenced by sea surface temperature, which could explain why also the sheltered coast was heavily affected. This might also answer the uncertainties brought up by Jones et al. (2018), who established that erosion now could be up to 2.5 times greater than in the previous century but could not point out which factor (higher sea surface temperature (SST), longer ice-free periods or storm number and its strength) was dominant. Irrgang et al. (2018) studied the 210-km-long Yukon coast between 1951 and 2005. They determined that 87% of this coastline was eroded (Fig. 9B, D) and 13% remained stable or was prograding (which is similar to the Gibbs, Richmond (2017) results). They also determined that, on average, the coast erodes by –0.7 m·a^{-1}, but also noticed that the rate of coastline change increases westward, from –0.1 m·a^{-1} near the Northwest Territories to –1.4 m·a^{-1} near the Alaskan border. After combining changes with the fraction of coastal building materials, they found that the gravelly coasts were subject to the greatest changes in coastline movements.

It is worth mentioning that the islands of the Canadian Arctic Archipelago are also rich in permafrost, and such coastlines are particularly prone to erosion (Obu et al. 2016) (Figs 9A, C). According to Lantuit, Pollard (2008) and Obu et al. (2016), the Herschel Island, located close to the Yukon coast in Canada (the Beaufort Sea), is a remnant of a push moraine and is composed of unconsolidated marine sediments with a high content of ground ice (Fig. 2B). Obu et al. (2016) indicated that 72% of the 36 km of coastline

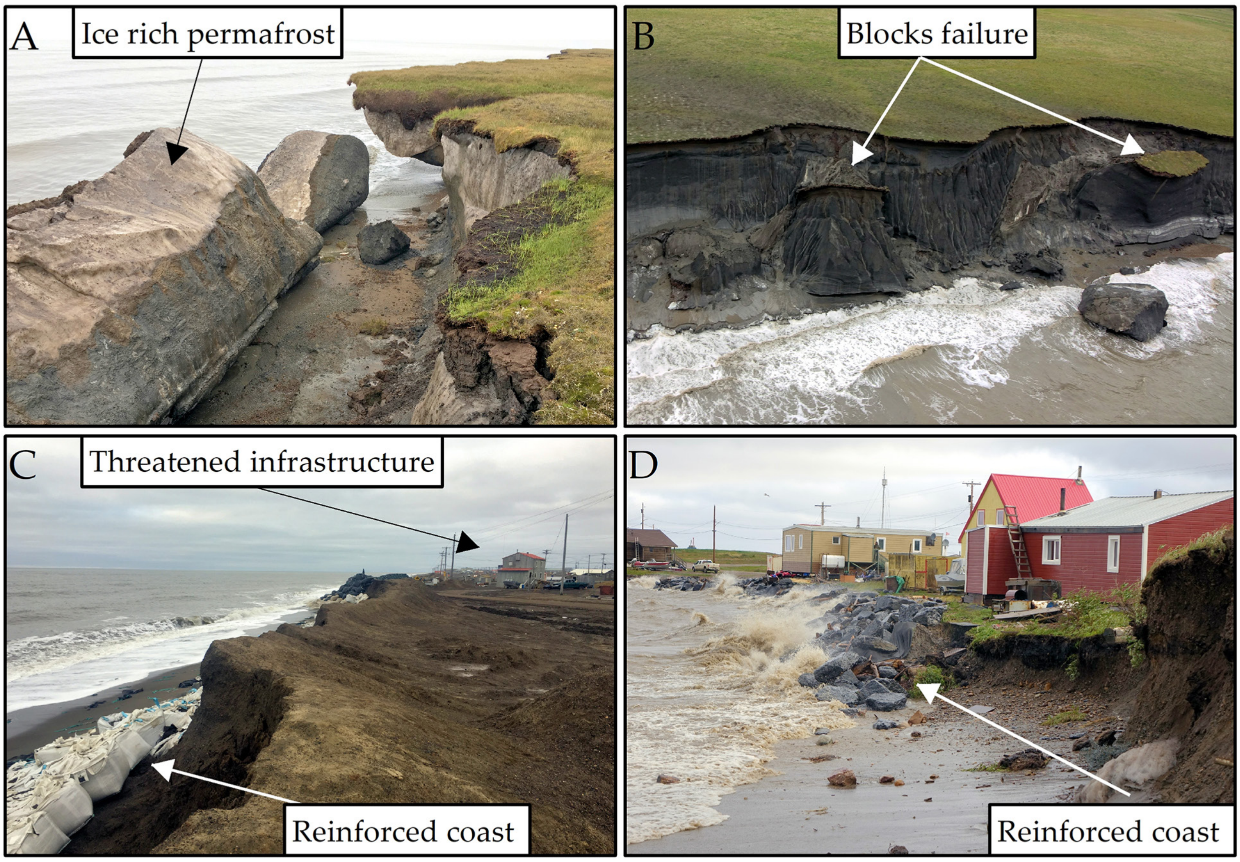


Fig. 9. Blocks failure caused by thawing permafrost: A – Alaska, B – Yukon. Coastal infrastructure threatened by coastal erosion: C – Alaska, D – Yukon. Nowadays, coastal strengthening can be encountered to slow down erosion processes. Photo by L.Farquharson (A, C), M.Lim (B, D).

studied is retreating, 17% is not changing and 11% is aggregating. They indicated that the average rate of change for 2000–2011 was –0.68 m·a^{-1}, while the erosion rate reached 0.88 m·a^{-1} and the progradation rate was 0.20 m·a^{-1}. The highest rate of change equalled 5.2 m·a^{-1} and was associated with low cliffs on the eastern coast. Interestingly, the greatest accumulation (20 m·a^{-1}) was recorded close to the site of the highest erosion and relates to the spit extension. Lantuit, Pollard (2008) also calculated changes on Hershel Island but for the 20th century. In their study for 1952–1970, the erosion rate was 0.61 m·a^{-1}, then slowed to 0.45 m·a^{-1} between 1970 and 2000. They linked the decrease in erosion in the second period with the decreasing number of storms that affected the area in the late 20th century. They also indicate that the observed changes relate to those observed in the Alaskan Beaufort Sea and East Siberian Sea coasts. Interestingly, when observations for 2000-2011 were compared with those provided for former 3 decades (Lantuit, Pollard, 2008), Obu et al. (2016) observed a steady rise in the erosion rate, and concluded that this increase had occurred in places where Lantuit, Pollard (2008) had formerly observed a drop.

Farquharson et al. (2018) presented a comprehensive paleostudy on the Pelukian Transgression (PT) (Brigham-Grette, Hopkins 1995) and the Pelukian barrier system, one of the most prominent relict geomorphic systems on the present Beaufort Sea coast. Extending ca. 180 km east from Utqiavik (Barrow), the barrier system is elevated at 6–10 m a.s.l. Utilising the optically stimulated luminescence (OSL) dating and detailed geomorphological analyses, Farquharson et al. (2018) established that the PT climaxed after the peak in eustatic sea rise of the last interglacial. A closer analysis of the OSL results combined with the occurrence of similar facies at markedly different elevations in the barrier system revealed that the barrier sections may had been formed at different periods and during two separate transgressions – first between 110–95 ka BP, forming for the Walrus section, then between 90–77 ka BP, creating for the Black Lagoon section. The PT was most likely caused by the isostatic depression beneath the grounded margin of an ice shelf fed by the Innuitian Ice Sheet. According to the age of the PT, the maximum Late Pleistocene glaciation in this area was asynchronous with the global ice volumes (mostly regulated by the dimensions of the Laurentide and Fennoscandian ice sheets). The study by Farquharson et al. (2018) provided an insightful review on the local response of the cryosphere to global climate change, as the Arctic ice sheets developed independently of the lower-latitude sectors of the Laurentide and Fennoscandian ice sheets and did not coincide with the global eustatic sea-level maximum. Instead, authors suggested that the creation of the Arctic ice sheets took place during the whole interglacial period, when high latitudes saw plentiful moisture penetration and low summer insolation supporting their growth, up to the glacial maxima at interglacial-glacial transitions.

The northeast coastlines of Nunavik and Hudson Bay are an archive of the Laurentide ice sheet load and an excellent testing ground for research on rapidly emerging coastlines (Boisson et al. 2020). During deglaciation at ~8 ka BP, the Tyrrell Sea intruded into a broad strip of coastline, reaching up to ~250 m above the present sea-level (Gray, Lauriol 1985, Gray et al. 1993). At a rate of 11.8–13 mm a^{-1}, the isostatic uplift (Inukjuak and Umiujaq areas, respectively) (Lavoie et al. 2012, James et al. 2014), has exceeded more than four times the global sea-level rise (~3 mm a^{-1}) (Boisson et al. 2020). As a consequence of the rapid RSL decline, bedrock is overlaid by a variety of raised marine paleodeposits (Lajeunesse, Allard 2002).

The coastal evolution of the Melville and Eglington islands (west Canadian High Arctic) was studied due to the allochronic recession of the Laurentide and Innuitian Ice Sheets in the area (Dyke et al. 2002, England et al. 2006, 2009). Data provided by Nixon et al. (2014) derived from de- and post-glacial marine sediments helped construct several curves and zones of varying RSL changes for this ~9.5 cal ka coastline. The curve at east Melville Island indicates a continuous uplift, reaching the present-day level, as the area has most likely reached its lowstand. This particular area proved heavily loaded with ice sheets during the LGM period. Places more distant from the areas of immense loading are characterised by the more fluctuating nature of the RSL. There, the initial rise was replaced in the Middle Holocene by ongoing submergence (Nixon et al. 2014), associated with forebulge migration and disintegration (e.g. Peltier 1974, Dyke and Peltier 2000, Wu 2001). Traces of ongoing immersion are represented by multiple indicators, e.g. driftwood, submerged deltas (south Eglinton Island), barrier beaches (northeast Eglinton Island), including those with overwash fans (Blackley Haven, Melville Island), old raised beaches buried under modern transgressive depressions (Melville Island) (Nixon et al. 2014).

St-Hilaire-Gravel et al. (2010) presented the historical evolution of sea ice and wave intensity in the CAA, by targeting coarse-grained sequences of raised beaches on Lowther Island and linking the timing of their (still ongoing) formation to periods of increased open water. The earliest archive, a continuous barrier, and swale at ~7.5–11 m a.s.l., extending in the landscape for many kilometres, formed ~3.03–2.34 cal ka BP during a rapid drop in RSL. A nearly identical, slightly more narrow paleobarrier and swale, elevated at ~4.5–5 m a.s.l., formed ~1.75–1.45 cal BP. The youngest sequence of continuous barrier (0–1 m a.s.l.), spit, and overwash fans has been emerging from over 500 cal BP.

Future research perspectives

Coastal processes deep understanding

Although the principal parameters driving coastal changes are already identified, more scientific effort is needed to provide complex explanations of their precise strength and connections between them. Future studies should not only include marine–terrestrial transition zones in permafrost coastal areas (Sander et al. 2017, Boisson et al. 2020), but also newly exposed paraglacial coasts (de Wet et al. 2018, Strzelecki et al. 2020, Jarosz et al. 2022, Kavan et al. 2022). Methods and knowledge concerning permafrost areas should be applied to less-known shorelines in a discontinuous permafrost zone and rocky permafrost coasts (Jones et al. 2020). Pathways of organic carbon degradation associated with increased coastal erosion need to be described in more detail (Nielsen et al. 2022). Except for dividing research conclusions into typical coast categories local conditions must be considered, as it is the only way to a deep understanding of complex nature processes. It is also important to remember that once described coastal processes still need to be observed as in recent rapidly warming climate conditions, they can not only intensify but also result in redefining of local ecosystem's operation (Overduin et al. 2014). Moreover, a detailed analysis of sudden, intensive events and their geomorphological impact on the coasts needs to be included (Fischer et al. 2018, Strzelecki et al. 2020).

Wider environmental context

Solving questions about coastal processes and their dynamics requires a broader view beyond geomorphology and geology. Climatological and hydrological context is crucial. Further investigation in the field of local wave parameters nearshore is vital to properly explain observations on erosion and sedimentation (Gibbs et al. 2021, Hamilton et al. 2021, Irrgang et al. 2022) as well as mechanisms driving sea ice extent (Wojtysiak et al. 2018, Hole et al. 2021). Characterising specific mechanisms behind Arctic amplification would undeniably help in coastal change prediction (Rantanen et al. 2022). Fischer et al. (2018) point out cloud and aerosol physics as a field that limits cryosphere-connected processes' explanation. Proper coastal model construction would not be possible without significant progress in monitoring sediment circulation. Both nearshore and Arctic rivers' sediment budgets are considered sensitive to recent warming (Irrgang et al. 2022).

Paleoenvironmental reconstructions

One of the main expected effects of coastal research is providing detailed paleoenvironment reconstructions, on both local and global scales. This goal refers at least to the whole Holocene (e.g. Hole et al. 2021), extended by some to Late Pleistocene (e.g. Last Interglacial Period – McFarlin et al. 2018). Paleoclimate data: precipitation, air and ocean temperatures, CO_2 concentrations, as well as its implications: plausible RSL curves, paleo sea ice extent, glacier volume, and paleo geohazards are the particular points of interest (de Wet et al. 2018, McFarlin et al. 2018, Fischer et al. 2018, Baichtal et al. 2021, Hole et al. 2021). Progress in past climate modeling including former shorelines and glacial history is expected to result in archaeological discoveries and therefore to improve knowledge about the historical coastal human occupation in polar regions (Letham et al. 2018, Baichtal et al. 2021, Fedje et al. 2021).

Forecast

The most important, but probably also the most challenging goal is to anticipate future coastal changes, taking ongoing global warming-driven processes, such as permafrost thawing, and deglaciation of new coasts, into account (Sander et al. 2017, Fischer et al. 2018, Jones et al. 2020, Gibbs et al. 2021). For example, existing pan-Arctic forecast erosion models need constant improvement (Nielsen et al. 2022, Rolph et al. 2022). Global trends in Arctic coastal evolution still need to be clearly determined and proved along with their spatial and temporal variation, despite the already existing data (Lantuit et al. 2011b). Such predictions relate to the natural environment e.g. result in habitat changes (Erikson et al. 2020, Strzelecki et al. 2020) but can also directly impact local communities. Therefore, scientific progress should be followed by spatial planning adaptative ideas for these communities based on sustainable development (Jones et al. 2020, Jaskólski 2021, Irrgang et al. 2022). In particular, potentially tsunamigenic landslides in the area of paraglacial coasts need to be detected and included in risk assessments. The final goal for geohazard researchers is to enable local authorities to alert local communities before the probable danger (Benjamin et al. 2018, Higman et al. 2018, Strzelecki et al. 2020). However, knowledge about Arctic coasts changes is crucial also for millions of people all over the world, who already experience the effects of recent Arctic melting (Osborne et al. 2018).

How can we make these goals real?

Data accessibility

Filling the knowledge gaps has to be based on data availability. Firstly, collecting new data through field studies is still fundamental. Some of the recent papers mention particular field data missing. For instance, detailed coastal mapping is incomplete, especially in eastern Siberia and northern Canada (Irrgang et al. 2022). Also, lake sediments from Svalbard, Alaska, and other regions can store valuable paleoclimate information (de Wet et al. 2018, Baichtal et al. 2021). Described tsunami deposits should be revisited to observe their recovery stage (Higman et al. 2018). There is a shortage of nearshore water temperature measurements in Hudson Bay, which could help to model coastal permafrost degradation (Boisson et al. 2020). Driftwood deposits investigation is yet waiting to be done across the Arctic (Hole et al. 2021). Geological evidence for young faulting in southern Greenland is currently sought (Steffen et al. 2020).

Monitoring of known coasts and, in effect, providing long-term data series is also an urgent task. Measurements should include such factors as sea-level, precise shoreline position (including short-term erosion rates), vertical land motion, wave parameters, storm frequency, permafrost degradation, and sediment transport from the rivers and along the coast (Osborne et al. 2018, Gibbs et al. 2019, 2021, Berry et al. 2021, Irrgang et al. 2022, Nielsen et al. 2022, Zhang et al. 2022).

New technologies have already improved Arctic research opportunities, and this trend is hoped to be continued. Better resolution of remote sensing data, especially for remote areas can bring breakthroughs in several research areas (Baranskaya et al. 2018, Irrgang et al. 2022, Zhang et al. 2022). The application of remote sensing in new fields will be helpful. For example, river sediment monitoring could benefit a lot, but the relationship between sediment concentration and surface reflectance needs to be described (Zhang et al. 2022). Efforts should also be put into automatisation of data processing, e.g. synthetic-aperture radar (SAR) and optical data (Svennevig et al. 2019). Denser seismograph network in Greenland will allow precise pointing of a signal source (Svennevig et al. 2019).

Cooperation

The aggregation of existing bases (local scale or focussing on one factor) into bigger models gives also a chance to generate new knowledge (Khan et al. 2019, Zhang et al. 2022). However, integrating the multisource data requires broad interdisciplinary and international cooperation among researchers (Jones et al. 2020, Zhang et al. 2022). For example, a global RSL database is built, but its development is limited due to the lack of a global-scale system encouraging to cohere and share research data (Khan et al. 2019). Finally, cold regions research can benefit a lot from close and respectful cooperation with local and native communities – a part that had been poorly conducted until recently (Thoman et al. 2020, Irrgang et al. 2022). Despite significant progress in Arctic coastal change research in the 21st century, still several key questions need to be answered.

Conclusions

This paper focuses on progress in Arctic coastal research in the 21st century. The most important publications are summarised by topic and region, and mapped to make it easier to find a study of interest.

Despite this significant progress, still several key questions remain unanswered. According to the authors, among them are:

1. What is the role of waves generated by glacier calving in shaping the neighbouring coasts? Recent research is lacking that could prove crucial at a time of increased glacial retreat and new land generation.
2. What conditions affect the development of Arctic lagoons? Do these lagoons show similar sensitivity to sea-level changes as their lower latitude analogues? Lagoons, as a highly vulnerable environment, can serve as a certain kind of archive of extreme events that are expected to occur more frequently in the less icy future.
3. What was the scale and intensity of storms in the past and their impact on coastal morphology? Paleostorm signals from warm Holocene periods better recognition will make it possible to predict the effects of modern warming.
4. Where should rapid slope processes and following extreme waves be the most expected in the near future? A destabilised landscape associated with thawing permafrost and deglaciation can threaten local communities. Interdisciplinary research is necessary to combine earth sciences and answering important social challenges.

Taking international initiatives to create publicly accessible databases, exploring yet unexplored areas, and sharing this knowledge are keys to determining what the future holds for us – people.

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Author's contribution

Z.Owczarek: Conceptualization, Data curation, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review and editing. Z.Stachowska-Kamińska: Conceptualization, Data curation, Resources, Validation, Writing – original draft, Writing – review and editing. O.Kostrzewa: Conceptualization, Data curation, Resources, Validation, Writing – original draft, Writing – review and editing. M.Szczypińska: Conceptualization, Data curation, Resources, Validation, Writing – original draft, Writing – review and editing.

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