

THE IMPACTS OF CLIMATE CHANGE ON COASTAL ZONE OF  
THE ARCTIC AND THE HIGH NORTH:  
IMPLICATIONS FOR SECURITY AND INFRASTRUCTURE

Alexander S. Kolker, PhD  
Remote Fellow: NATO Climate Change and Security Center of Excellence  
and  
Louisiana Universities Marine Consortium  
and  
The Coastal Climates Institute

Contact At  
alex@coastalclimates.org and akolker@lumcon.edu  
+1-504-579-2427



## 1. INTRODUCTION: CLIMATE CHANGE AND THE COASTAL NORTH

Climate change is expected to significantly impact the Arctic region and northern latitudes where NATO countries, NATO partners, and NATO adversaries operate. Arctic warming is occurring about 2 to 4 times faster than the global average, and warming is predicted to accelerate in the years ahead.<sup>1,2</sup> The Arctic's coastal zones are particularly susceptible to climate change, and this change is both regionally and globally significant. Nearly 15% of all shorelines in the world are in the Arctic,<sup>3</sup> and the Arctic Ocean has nearly 20% of the world's continental shelf space even though it makes up only 1% of the global ocean.<sup>4</sup>

This article examines how climate change affects coastal areas in the Arctic and how it can influence operations for organizations like NATO that rely on large equipment in these frigid - but warming- environments. There are multiple definitions of high-latitude environments, and this article broadly considers all of them. "The Arctic," typically refers to the area north of the Arctic Circle (66° N), while the, "Arctic Region," often refers to areas where summer temperatures do not exceed 10°C (Figure 1). The term, "High North," refers to a broader range of high-latitude, sometimes frigid environments that includes places such as the Baltic Sea, Scandinavia, Siberia, Northern Canada, Alaska and the Bering Strait.

Coastal zones in the Arctic and High North are important for security for multiple reasons. They contain critical infrastructure, significant energy resources, defense assets, and population centers (Figures 1 and 2). These areas support global shipping logistics, environmental monitoring, and productive fisheries. Additionally, they are ecologically sensitive and are an important part of the heritage and culture of the region's residents.<sup>5</sup>

This article will describe how climate change in the Arctic and High North can impact the capacity of militaries to conduct operations. For example, climate change and sea level rise can destabilize critical infrastructure and reduce access to some coastal sites. At the same time, climate change can lead to a growing demand for military presence in the Arctic and High North as polar shipping routes expand, and as some actors mine or ship energy products from previously frozen environments. In the years ahead, as sea level rise and coastal erosion increase flood risks to military sites, leaders will face difficult choices about whether to increase flood protection (which can be expensive) or relocate (which could reduce capacity). As such, knowledge of climate change in the Arctic should be a crucial part of effectively directing resources in the years ahead.

There are numerous examples of key assets in the Arctic and High North's coastal zone (Figures 1, 2). Notable defense infrastructure includes Canada's Nanisivik Naval Facility and the United States' Oliktok Point facility that is part of its Long-Range Radar System (Figure 2). The region is also rich in energy and mineral resources. The United States has its National Petroleum

Reserve near Prudhoe Bay, Alaska, and multiple countries have potentially billions of undiscovered oil in the Arctic and High North.<sup>6</sup> The region has active mining sites and oil and gas pipelines.<sup>7</sup> Major ports include Finland's Port of Hamina and Russia's Yamal Liquefied Natural Gas port in Sabetta - both of which are linked to liquefied natural gas (LNG) shipping facilities.

### Overview Maps Of The Arctic

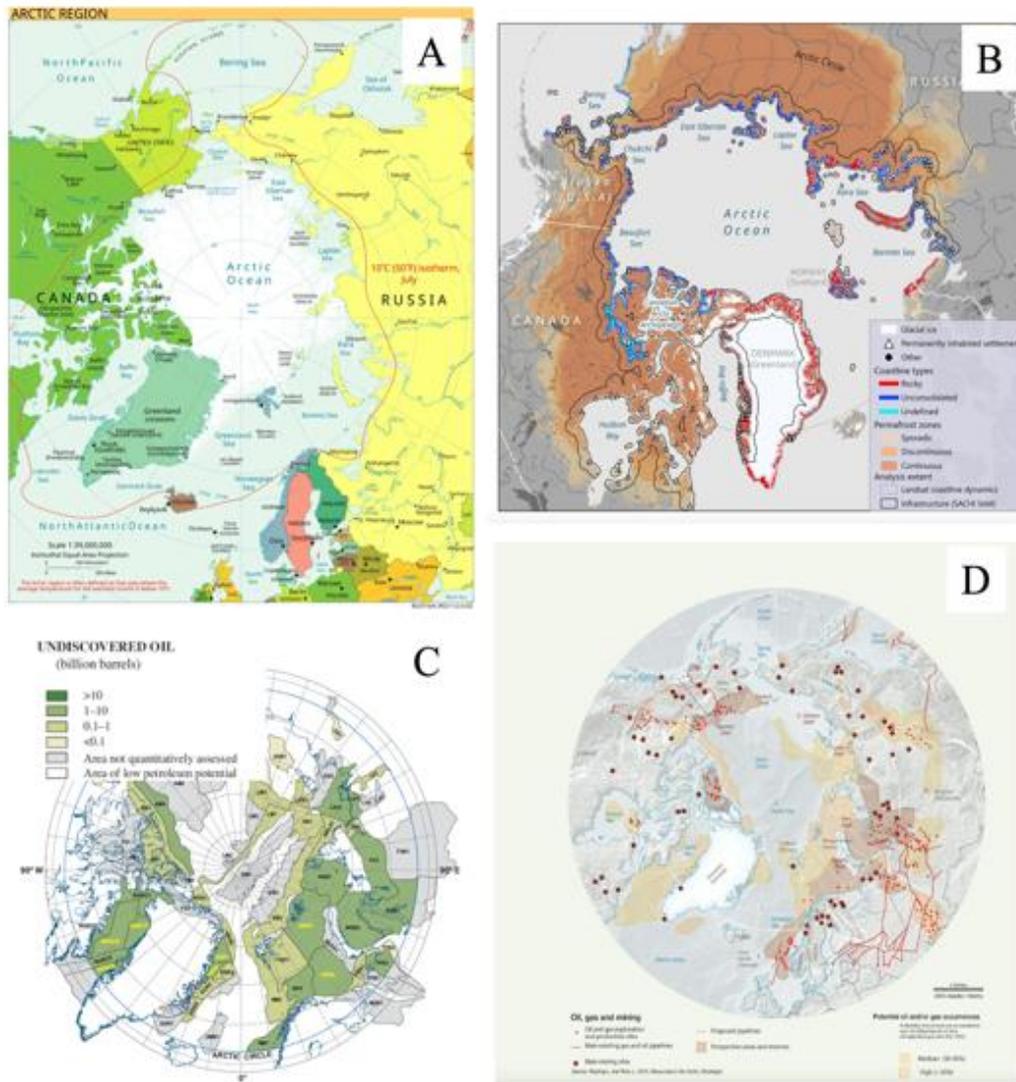


Figure 1. Overview maps of the Arctic. A. Political map of the Arctic and high north. The red line marks areas where the high temperature is below the 10° isotherm, a general proxy for the Arctic region. Source: <https://commons.wikimedia.org>. B. Distribution of permafrost and major shoreline types in the Arctic and High North [59]. C. Estimate of undiscovered barrels of oil in the Arctic and High North [6]. D. Map of major oil and gas activities in the Arctic and high north [7].

Environmental monitoring resources include the Global Radiation Monitoring Network, which tracks global radiation levels and provides an early warning system for accidental or intentional nuclear releases. The Arctic and the High North are home to major fisheries - for cod, salmon, and snow crab. These fisheries all depend on coastal ports to unload and offload supplies and for related logistics.<sup>7</sup>

The importance of Arctic coastal infrastructure will expand in the years ahead.<sup>8</sup> As the region warms and sea ice melts, shipping routes through the Arctic Ocean and across the North Pole are expected to expand - and indeed are already doing so.<sup>9,10</sup> Scientists predict that an ice-free day in the Arctic may take place as soon as 2030 and that ice-free days will be so common by 2050 that transarctic shipping will be feasible during summer and early autumn.<sup>9,10</sup> An Arctic with little or no ice in the spring and summer could reduce shipping times between the United States and Asia (avoiding the Panama Canal) by about 4 days and between Europe and Asia (avoiding the Suez Canal) by about 10 days.<sup>11</sup> However, transarctic shipping will presumably require coastal resources for support services such as search and rescue, refueling, and oil spill response.

An ice-free Arctic will allow for shipping from Arctic ports of which Russia's Sabetta is

Examples OF Coastal Infrastructure In The Arctic And High North



Figure 2. Examples of key assets in the Arctic and High North. Top. Canada's Nanisivik Naval Facility, Source Wikipedia. Bottom. Finland's Port of Hamina. Source:/www.haminakotka.com/fi. Inset maps from Google Earth

particularly noteworthy. Construction started on this facility in 2012, and it now exports 17.5 million tons per year of liquified natural gas.<sup>12</sup> Further expansion appears to be planned, as Russia seeks to triple LNG exports by 2035.<sup>13</sup> According to Wikipedia, the region that Sabetta serves, Yamalo-Nenetsky Avtonomnyy Okrug, contains 80% of Russia's gas supplies and 15% of the world's gas supplies.<sup>12</sup>

While coastal resources are critical to operations in the Arctic, these capabilities could be threatened by rising global sea levels, increased waves in the coastal zones, and the thawing of permafrost in the coastal region. These changes can lead to coastal erosion, subsidence and increased flooding. The importance of shoreline change in the Arctic is an area of growing concern. A 2016 report by the USA's Sandia National Labs described the challenges faced by coastal communities and military assets in the region.<sup>8</sup> Sections of this report include the following:

"Rapid Arctic coastal erosion stands to adversely impact native, scientific, industrial, and military communities in Alaska. Recent estimates suggest that 86 percent of the native villages in Alaska situated along rivers or coasts are now more frequently affected by floods or erosion [Clement et al., 2013]. Homes have fallen into the sea [...] Archaeological sites and landfills have been compromise [...] The Barrow and Oliktok Point facilities are situated along one of the most rapidly eroding sections of coast in the world (Figure 1.6). Oliktok Point is also home to one of the 15 sites (a multi-billion dollar portfolio) dedicated to the U.S. Long Range Radar Program. The objective of the facility is to, in perpetuity, spot foreign aircraft heading into U.S. airspace [...] Remediation projects on the North Slope, however, are extremely expensive due to the remote nature of the Arctic. Protecting the runway at the Cape Lisburne Long Range Radar site from coastal erosion, for example, could cost 47 million dollars [Hughes, 2016]. Coastal erosion [...] poses a significant threat to the existing infrastructure and, without an accurate predictive model, it also threatens future infrastructure development and relocation."<sup>8</sup>

The purpose of this article is to help NATO prepare for a changing future in the Arctic and High North. While there are many elements to consider, this manuscript focuses on one particularly important collection of topics: the impacts of sea level rise, coastal erosion, and subsidence on arctic infrastructure, and how organizations can adapt to these changes. NATO countries, NATO partners, and NATO adversaries all operate large pieces of infrastructure in the Arctic and High North. This includes infrastructure that includes ports, airstrips, cranes, weapon systems, weather and radar stations, energy facilities, pipelines, and transmission lines. Military organizations are not alone in facing the challenges of changing Arctic shorelines; civilian governments, indigenous communities, and private industries face similar challenges.

## 2. OVERVIEW OF CLIMATE TRENDS IN THE ARCTIC AND HIGH NORTH

### 2.1. Trends in Temperature and Precipitation

To understand the importance of climate change to the Arctic's coastal infrastructure, it is important to have a general understanding of the broad climate trends in the region. The Arctic is indeed warming, and temperatures are rising across the Arctic and High North (Figure 3). Air temperatures in the Arctic have increased 3°C to 4 °C since 1900, with a steady rise in temperature occurring after 1980 (Figure 3). While warming is widespread, it has generally been greatest in the Russian and Eurasian Arctic. One analysis shows that ocean waters in the Arctic have warmed about 1.3°C since 1982,<sup>14</sup> while another found a rapid rate of warming near Novaya Zemlya and the Kara Sea.<sup>2</sup> The 2024 Arctic Report Card, issued by the USA's National Oceanographic And Atmospheric Administration (NOAA), showed that sea surface

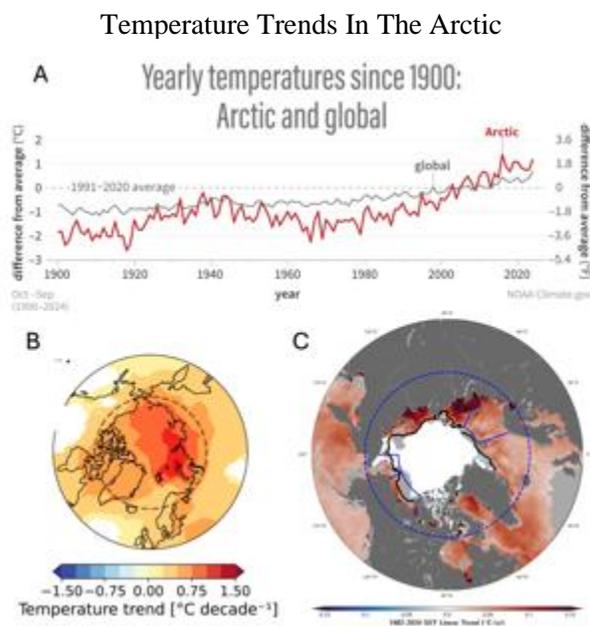


Figure 3. Temperature trends in the Arctic and High North. A. Arctic-wide temperature trends since 1900 [14]. B. Arctic temperature trend 1950-2020 [2]. C. Sea surface temperature trends 1982-2024 [14].

further warming the region.<sup>2,18</sup> These impacts combine to create a region that warms rapidly and where such warmth accumulates over time.

Precipitation trends in the Arctic are complex. Overall, there has been a weak trend of an increase Arctic-wide in precipitation.<sup>14</sup> More significantly, there has been an increase in extreme events, such as floods or droughts. For example, there were particularly strong storm systems in western Alaska/eastern Siberia during the winter of 2023/2024, which was linked to unusually

temperatures are rising most rapidly in the Kara and Laptev Seas (Figure 3), where warming has reached nearly 5°C since 1982<sup>14</sup>. There have also been pronounced episodes of regional warming. Parts of Siberia, the Baltic states, and Finland experienced heat waves in 2020 and 2021,<sup>15,16</sup> while the Canadian Arctic and parts of USA's Alaska experienced heat waves in 2023 and 2024.<sup>14,17</sup>

Overall, the Arctic is warming faster (about 2X to 4X) than the rest of the planet.<sup>2,14,18</sup> Multiple mechanisms have been proposed for this "Arctic Amplification." Several major atmospheric and ocean currents transport heat to the region. There are also fewer aerosols in high latitudes, which allows more light to reach Earth's surface. In addition, ice melt reduces the amount of light that is reflected into space,

warm ocean temperatures in the region.<sup>14</sup> On the other hand, droughts and unusually warm temperatures contributed to fires in northern Canada and Siberia between 2020 and 2024.<sup>2,15,16</sup>

## 2.2. Trends in Ice-Covered Areas

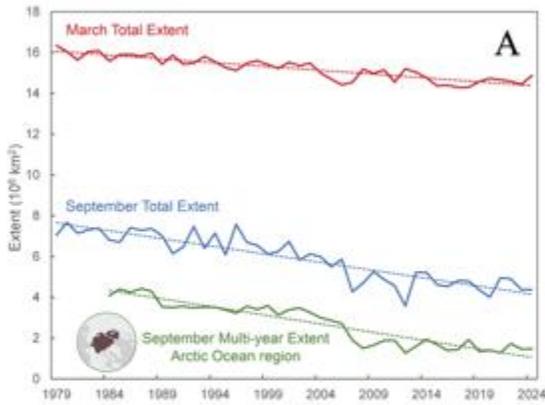
One major change in the Arctic and High North is a decrease in the size of ice-covered areas. According to the 2024 Arctic Report Card, the amount of sea ice present during March, the normal seasonal maximum, declined from about  $16.5 \times 10^6 \text{ km}^2$  in 1979 to about  $14.9 \text{ km}^2$  in 2024 (Figure 4). During the same period, the amount of sea ice in September, the normal season minimum, declined from between  $7.5$  to  $8.0 \times 10^6 \text{ km}^2$  to about  $4.4 \times 10^6 \text{ km}^2$  in 2024 - a roughly 42% decrease.<sup>14,19</sup> Arctic sea ice is also melting earlier in the season and freezing later in the season.<sup>14</sup> In 1979 sea ice started melting in early June. By the start of the 2020s sea ice melt began in mid-May. Sea ice is also freezing later in the season. One study found that sea ice started to freeze around October 4 in 1979, while by 2009 it took place around October 20.<sup>20</sup> Further compounding ice loss are ocean currents that tend to export sea ice from the Arctic Ocean - largely through the Straits of Greenland and into the North Atlantic Ocean.<sup>8</sup>

There has also been a long-term decline in sea ice concentration in the Baltic Sea, the size of which researchers have been able to determine since the 1700s. Presented in Figure 4E and 4E are sea trends since 1800, which show both year-to-year variability and a 15-year running mean. Between about 1850 and 1990, there was a modest decline in sea ice with substantial annual and decadal variability. However, since about 1990, sea ice concentrations in the Baltic Sea have been declining. The average concentration for the period 2015 - 2024 is about 30% smaller than during the period 1995 - 2004.<sup>21,22</sup>

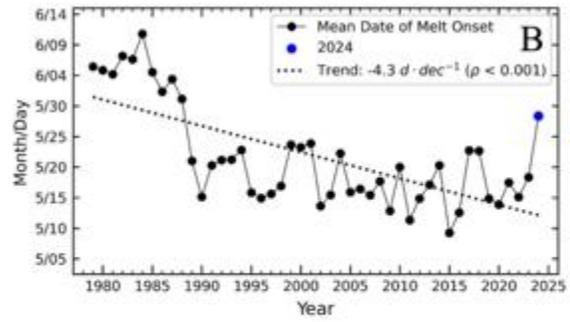
Greenland's ice sheets are also melting, releasing large volumes of water into the sea. Overall, the island has lost nearly 5,000 gigatons ( $5 \times 10^9$  tons) of ice since 2002, when reliable measurements began<sup>14</sup>. A map of the changes in the elevation of the Greenland Ice Sheet is presented in Figure 4E. It shows that the most ice was lost from the edges of the continent, as ice-sheets retreated away from warmer ocean waters<sup>23</sup>. Ice sheet retreat has been particularly significant in steep gullies and canyons where ice can move quickly to the ocean<sup>24</sup>. However, there is some accretion occurring in Greenland, and some areas on top of the ice sheet have gained elevation. However, areas that are experiencing thinning are often doing so at much faster rates than areas that are accretion: 10 to 40 m of elevation loss between 2003 and 2023 versus 0 to 5 m of elevation gain between 2003 and 2023.<sup>23</sup>

## Trends In Ice Extent In The Arctic And High North

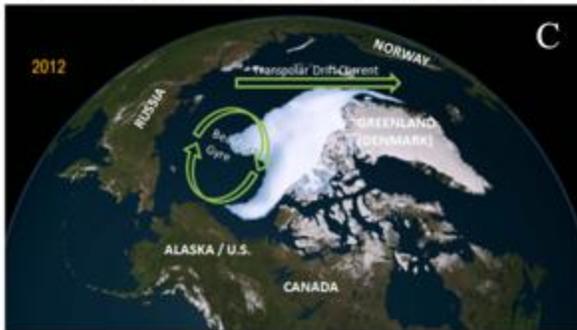
Area of Arctic Sea Ice



Start Date Of Arctic Ice Break-Up



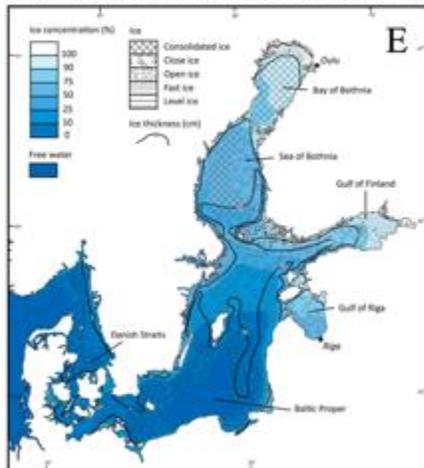
Arctic Ice Area In 2012, And Major Currents



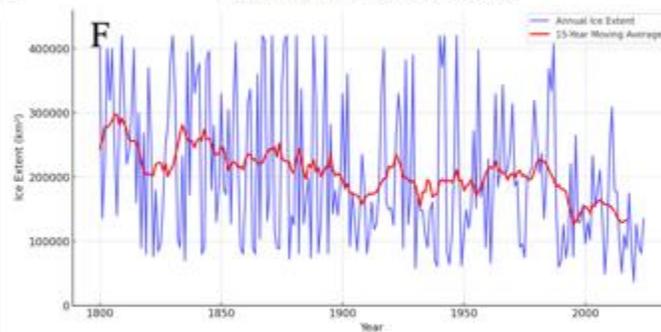
Arctic sea ice summer minimum (September 2024)



Common Distribution Of Baltic Sea Ice

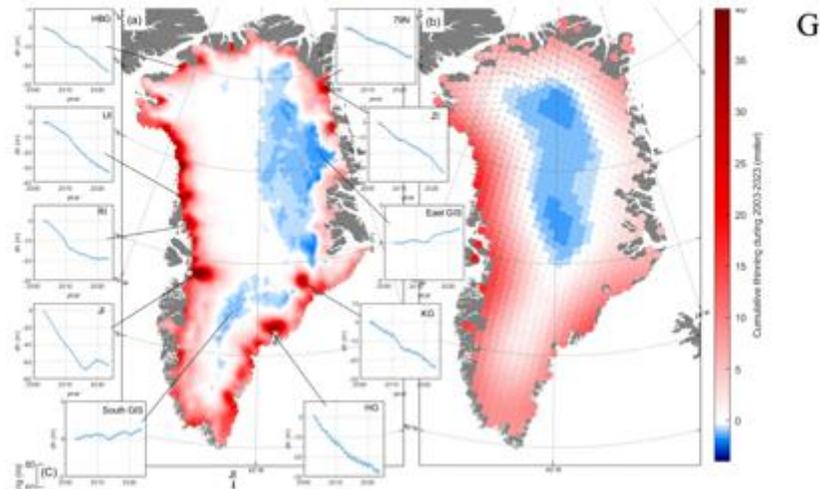


Ice Area In The Baltic Sea



## Trends In Ice Extent In The Arctic And High North Continued

### Greenland Ice Area Change 2003-2023, From Altimetry (Left) and Gravity (Right)



### Change In Greenland Ice Mass

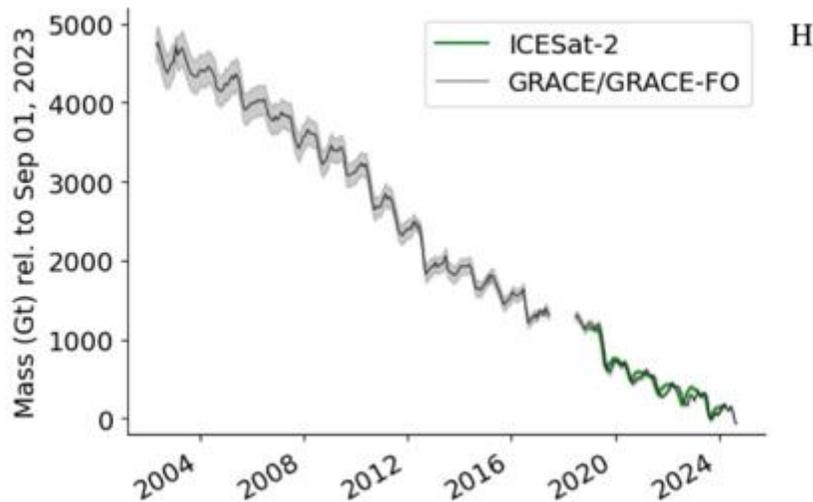


Figure 4 Patterns and trends in ice cover in the Arctic. A. Time series of sea ice in the Arctic, including the March (seasonal maximum), September (season minimum) and multi-year ice [14]. B. Onset date of sea ice melt in the Arctic [14]. C. Area of minimum sea ice extent in 2012, and schematic of major currents that move and export ice from the Arctic [8]. D. Area of sea ice at summer minimum in 2024, and median conditions in two previous 30-year intervals [14]. E. Map of average March 1 ice area in the Baltic Sea [22] F. Long-term trends in sea ice extent in the Baltic Sea [22 and refs therein]. G. Map of elevation change on the Greenland ice sheet between 2003 and 2023. Note that ice loss is greatest along the coastal regions, while there is modest ice gain in the center of Greenland. Left: Changes determined from altimetry (height measurements), Right: Changes determined from gravimetry (mass and gravity measurements) [23]. H. Change in ice mass of the Greenland Ice Sheet. The IceSat-2 and GRACE lines refer to two different satellite measurement systems while the shaded area marked measurement uncertainty [14].

### 3. PERMAFROST MELT AND ITS ROLE IN COASTAL CHANGE

#### 3.1. The Geography of Permafrost

Permafrost melt is a key process driving coastal erosion, subsidence, and retreat in the Arctic and High North. Permafrost is generally defined as a soil or sediment that remains solid and below 0°C for two years or more. It can hold together coastal sediments, creating stable landforms in the coastal zone.<sup>4,25</sup> Melting in the Arctic and High North can also impact structures that are not formally permafrost but consist of frozen material, such as rock formations that are bound together by ice.

Permafrost is widespread across the Arctic and the High North (Figure 5). It is most prevalent in Russia's Siberia, in Canada's Nunavut and Northwest Territories, and along the North Slope of Alaska, USA. Countries with the greatest amount of permafrost (including permafrost in the Arctic and High North, as well as lower latitude, high altitude settings) include Russia, followed by Canada, China, United States, Mongolia, Greenland, and Norway (Table 1). There is also permafrost on the Arctic Ocean's seafloor, along a zone that extends from western Alaska, through much of Siberia, and into the Kara Sea. This subsea permafrost was formed during the last Ice Age - at least 25,000 years ago- when the global sea level was over 100 meters lower than today. Subsea permafrost remains frozen today because deep ocean temperatures are extremely cold but could warm as ocean waters warm due to climate change.<sup>26</sup>

Table 1 Area of permafrost by country. Source: <sup>27</sup>

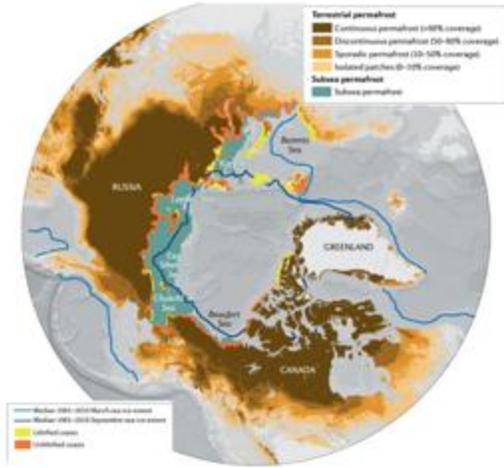
Country	Permafrost Region (10 <sup>3</sup> km <sup>2</sup> )	Permafrost Zone (10 <sup>3</sup> km <sup>2</sup> )
Russia	9619–12 006	6966–9541
Canada	5238–6695	3637–4978
China	1457–2463	673–1676
United States	902–1242	530–877
Mongolia	357–758	165–394
Greenland (Denmark)	282–303	226–276
Norway	35–127	25–65
Kyrgyzstan	47–88	19.6–54
Sweden	11.3–123	4.7–43
India	21–88	7.8–65
Tajikistan	30–62	11.6–48
Pakistan	12.2–60	4.4–43
Kazakhstan	27–49	12.2–27
Finland	0.9–97	2.6–23

Permafrost has been viewed as a stable structure upon which to build infrastructure, including roads, buildings, airports, and pipelines. According to one review, in the northern hemisphere, there are at least 120,000 buildings, 40,000 km of roads, and 9,500 km of pipelines that are situated in permafrost.<sup>28</sup> For example, there are extensive permafrost areas by Point Barrow, USA - an Arctic oil and gas port. Permafrost underlies part of the Trans-Alaska pipeline and many oil

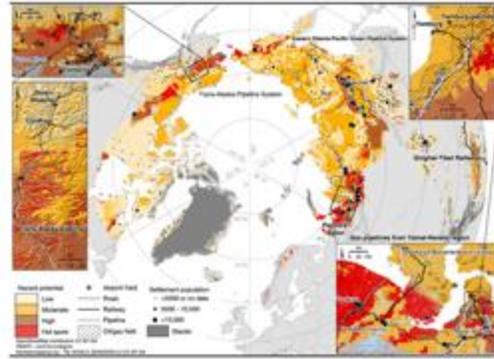
and gas pipelines in the Russian Arctic.<sup>7</sup> Arctic-wide, there are nearly 3,000,000 people who live on permafrost,<sup>29</sup> including two cities in Russia, Norilsk (pop. 175,000) and Yakutsk (pop. 311,000), that are built on areas inside the continuous permafrost zone.<sup>30</sup> Roughly 70% of pan-Arctic infrastructure is located on permafrost that is at risk of melting by about 2050.<sup>28</sup>

## Maps of Permafrost Distribution And Thaw

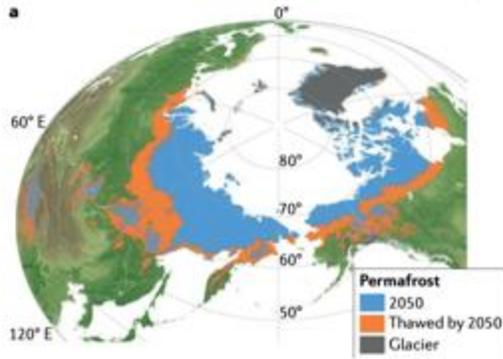
### A. Present Day Permafrost Distribution



### B. Permafrost Thaw Risks To Infrastructure



### C. Permafrost Distribution And Thaw By 2050



### D. Hazards From Permafrost Thaw By 2050

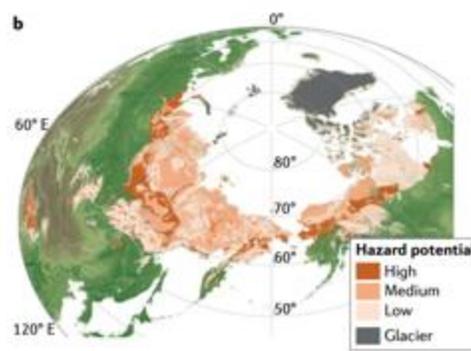


Figure 5 Maps of permafrost distribution and thaw impacts. A. Map of permafrost distribution, sea ice extent and shoreline type [5]. B. Map of permafrost distribution hazards and some key vulnerabilities [33]. C. Map of permafrost distribution and areas of likely melt to occur by 2050, following the Intergovernmental Panel on Climate Change's RCP 4.5 scenario [28]. D. Map of permafrost hazards due to thaw by 2050, following the Intergovernmental Panel on Climate Change's RCP 4.5 scenario [28]

### 3.2. Mechanisms of Permafrost Thaw

The drivers of permafrost deterioration can be placed into several broad categories, including thermal and mechanical.<sup>31</sup> Thermal deterioration is the melting of permafrost as temperatures rise. It can be coupled with soil decomposition, which occurs when previously frozen organic matter is exposed to the air. Thermal degradation can result in subsidence, which is the downward movement of the land surface. Subsidence can lead to land surface deformation, the formation of sinkholes and potholes, cracks in infrastructure, and geological slumps.<sup>28,32</sup> Mechanical permafrost deterioration involves physical erosion, i.e. the removal of material. In the coastal zone, mechanical deterioration typically results from waves breaking on permafrost-dominated shorelines, and it can result in shoreline retreat.

In areas where permafrost does not completely deteriorate, an increase in the freeze/thaw cycle can also be a significant process. As water freezes and thaws, the volume expands and contracts, which cracks soils, geological structures, and human-built infrastructure. Indeed, active cycling between frozen and unfrozen soils near the surface has long been common in the permafrost zone, and another impact of climate change is the expansion of this active layer.

Maps show areas at risk of permafrost melt. As indicated in Figure 5, the greatest amount of permafrost thaw by 2050 will likely be in the areas between about 55°N and 65°N, including places such as southeastern Siberia and northern Kamchatka in Russia, both the USA and Russian sides of the Bering Straits, and the coastlines of central Hudson Bay, Canada. Research shows that sections of USA's Trans-Alaska (oil) Pipeline are at risk from permafrost thaw by mid-century (2041-2060), as are Russia's Obskaya-Bovanenkovo railway near the northern Ural Mountains, and parts of Russia's Yamburg Gas Field.<sup>33</sup> While not formally in the Arctic or High North, sections of China's

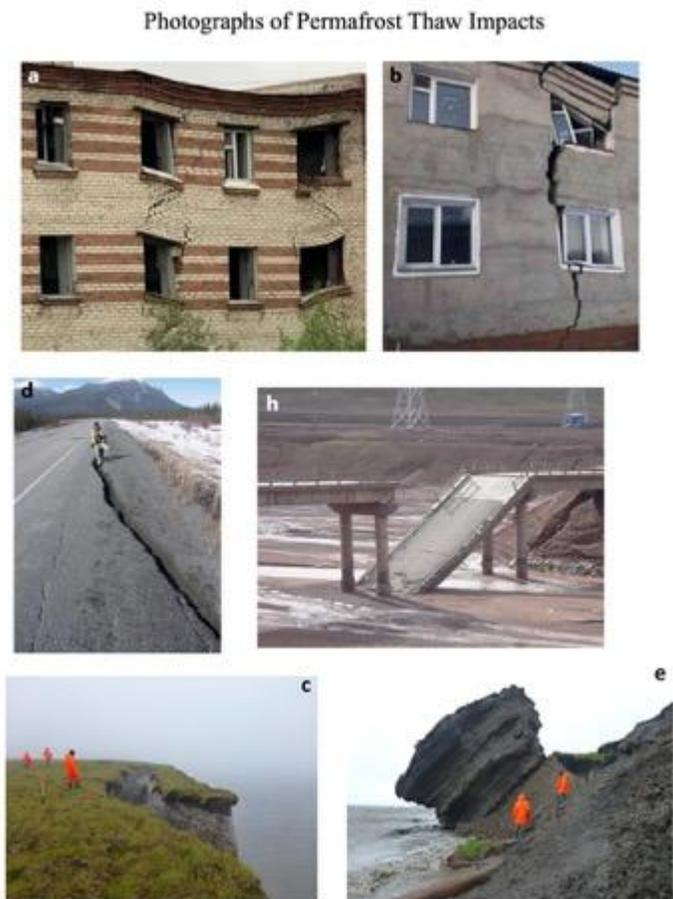


Figure 6 Photographs of permafrost thaw impacts. The top two images are from Yakutia, Russia. The middle images from the Qinghai-Tibet Plateau in central Asia. The bottom two images are from Russia's Lena River Delta. Sources: Top 4 Images [28]. Bottom 2 images [22].

Qinghai-Tibet Railway are also at risk from melting by mid-century.<sup>33</sup>

### 3.3. Impacts of Permafrost Melt on Coastal Infrastructure

Permafrost melting can have a range of impacts to coastal infrastructure.<sup>28,33</sup> Roads built on top of permafrost can deform. Buildings that were built on permafrost foundations can crack or shift. Pipelines that traverse across permafrost can move or break. Some Arctic shorelines—particularly river deltas like Russia's Lena River Delta, are composed of permafrost cliffs, and these cliffs can crumble and decay when they thaw or erode. Photos documenting the impacts of permafrost melt are present in Figure 6 and the references cited therein.

One example of the impacts of permafrost melt comes from near the Russian city of Norilsk, where a fuel tank associated with the Norilsk-Taimyr Energy Company (linked to the Russian mining firm Nor Nickel) spilled on May 29, 2020. (Neglect, poor construction, and mismanagement may have played a role in this collapse as well). The resulting spill released nearly 21,000 m<sup>3</sup> of diesel fuel, polluting large areas of the nearby Russian Arctic.<sup>28,34</sup> Other potential environmental impacts of permafrost melt include the release of toxins like mercury that is bound in water and frozen soils, the release of organic carbon that could further accelerate global warming, or the release of nutrients that can fuel algae blooms in the ocean.<sup>35,36</sup> Furthermore melting permafrost can release methane into the atmosphere, increasing climate risks globally as methane is a powerful greenhouse gas.<sup>37,38</sup>

For organizations like NATO that operate coastal infrastructure, permafrost melt can lead to significant challenges. If roads and runways shift or crack, that can impact transportation networks. Pipeline cracks can threaten energy supplies and lead to environmental damage. Uneven subsidence can cause port infrastructure like cranes and dry docks to lean and become difficult to operate. Ground movements can displace sensitive assets like radio towers, channel markers, and radar stations. When subsea permafrost melts, it can destabilize the seafloor,<sup>39</sup> potentially impacting structures like underwater pipelines, powerlines, or data cables. Therefore, permafrost melt is an important concern for security organizations like NATO because it can degrade the capacity of militaries to move equipment and operate critical infrastructure.

#### 4. SEA ICE RETREAT AND WAVE AMPLIFICATION

Another important part of coastal change in the Arctic involves the feedback between expanding ice-free areas, permafrost melt, and coastal erosion. As the area of open water increases, and the seasonal duration of open water increases, the size of waves in the Arctic Ocean is increasing, and the duration of the wave-driven erosion season is expanding. This increases the overall power of waves, increasing their potential for erosion. Erosion is then particularly pronounced in parts of the Arctic where permafrost is thawing. This can lead to growing security concerns because it could contribute to flooding on low lying military bases that might impact operations.

An example of the feedback between expanding ice-free areas, permafrost melt, and coastal erosion comes from a study .<sup>20</sup> It showed that the area of open water in the Beaufort Sea increased from roughly 66 days per year between 1979 and 2001 to roughly 88 days per year between 2000 and 2009 (Figure 7). This study also showed a near doubling of the cumulative wave height (i.e. the height of the waves multiplied by the total number of hours of waves) during this period. This increase led to an increase in wave action to erosion of a permafrost-dominated coast near Drew Point, Alaska, USA.<sup>20</sup> A follow-up study compared the number of days of open water along the coast in 1979 and 2012, and found that the start of open water came earlier in the season, the end of the open water season came later, providing change maps of the area of open water.<sup>40</sup>

A more recent paper showed an increase in open water, wind speeds, and wave height in the Bering Sea between 2003 and 2023.<sup>41</sup> Significant wave height (i.e. the height of the highest 1/3 of waves) increased by about 1 meter between 2000 and 2023. The area of the Bering Sea covered by sea ice decreased from nearly 60% during winter 2011/12 to less than 25% during winter 2017/18 season.<sup>41</sup> The erosive power of waves in this region was made more significant by

permafrost thaw and the subsequent reduction in the physical strength of Arctic shorelines. In places that include Alaska's Drew Point and Russia's Lena River Delta (Figure 6), authors have

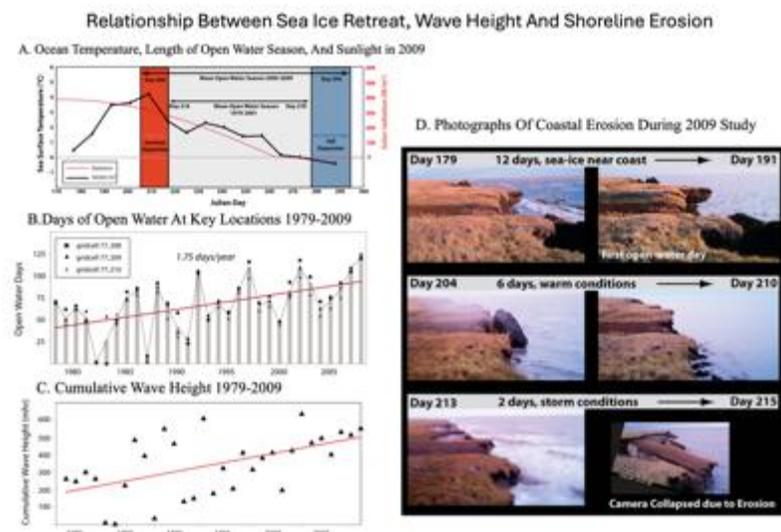


Figure 7 Interaction between sea ice retreat, wave climate and coastal erosion from Overeem et al., (2011). A. Change in length of the open water season in the Arctic between 1979 and 2009, and incoming solar radiation, and sea surface temperatures in 2009. B. Days of open water at key locations in the Arctic between 1979 and 2009. C. Cumulative wave height, a metric that combines the height of waves and the amount of time of waviness at key locations in the Arctic, 1979-2009. D. Photographs of wave-driven coastal erosion during 2009 study. Source for all images [20].

shown photographic evidence of large sections of the coast eroding and linked this erosion to increased wave power.<sup>20,42</sup>

## **5. WATER LEVEL CHANGE: GLOBAL SEA LEVEL RISE, SUBSIDENCE AND COASTAL FLOODING**

Water levels are rising across the Arctic, much of which is a direct result of climate change and the subsequent melting of ice sheets in Greenland and Antarctica.<sup>43</sup> Rising waters are a growing security concern for multiple reasons. For example, increased flooding can make it difficult to move personnel and equipment on roads or airstrips that are flooded, and shoreline retreat can expose infrastructure to ocean waves.

Figure 8 provides an examination of key sea level trends for the region. One analysis of satellite data indicated that the average, Arctic-wide rate of sea level rise between 1996 and 2018 was 3.7 mm/yr.<sup>44</sup> This rate is similar to the current rate of global sea level rise between 1993 and 2024, 3.3 to 3.6 mm/yr.<sup>43,45,46</sup> These rates are roughly double the 20th-century rate of global sea level rise, which was 1.5 to 1.8 mm/yr.<sup>43,45</sup>

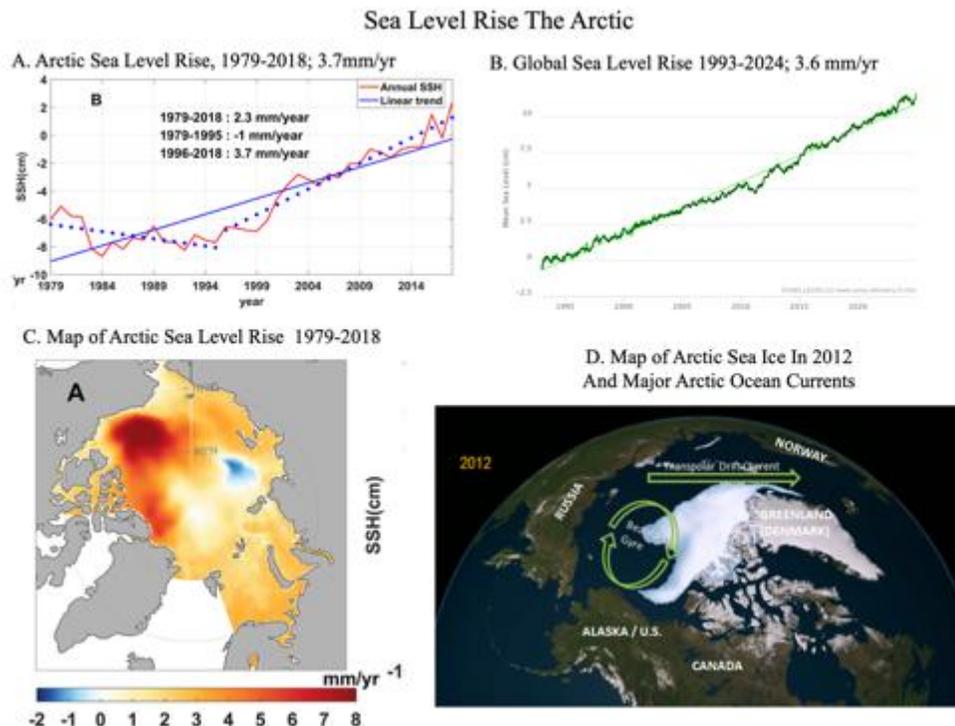
Rates of sea level rise in the Arctic also vary spatially. The satellite study<sup>44</sup> indicated that sea levels were rising fastest in the Beaufort Sea region, with rates that ranged from about 5 to 10 mm/yr (Figure 8). The cause of this intensified sea level rise is likely persistent winds associated with the Beaufort High air pressure system and its oceanographic component, the Beaufort Gyre, which forces water ashore<sup>47</sup>. This leads to a "coastal set-up" in western Canadian/east Alaskan Arctic while also contributing to a local water level drop near the North Pole.<sup>44</sup>

Water levels are also rising across parts of the Arctic as land surfaces sink due to subsidence. Subsidence, as described earlier, is the downward movement of the land surface (or another geological strata). Subsidence can be caused by permafrost melt and the subsequent oxidation of organic matter, i.e. wetland peat.<sup>48,49</sup> However, other factors can play a role, too. In river deltas and other coastal settings with thick sedimentary deposits, the mass of sediments can cause the ground beneath it to sink. Furthermore, the decomposition of organic matter, which is common in the soils of river deltas, can further increase coastal subsidence. Canada's Mackenzie River Delta is experiencing subsidence and is predicted to be a hotspot for wetland loss as global sea levels continue to warm<sup>48</sup>. Russia's Lena River Delta is also a hotspot for subsidence<sup>49,50</sup> and accelerated coastal retreat due to the combined impacts of permafrost thaw and wave-driven erosion.<sup>42</sup>

Coastal flooding near river mouths is also an area of growing importance. While localized flooding has long taken place near river mouths after spring floods, the dynamics of this process are changing. Climate warming can lead to increased freshwater pulses along a river - both because warmer climates tend to have more precipitation and because warmer conditions cause snow to melt earlier in the seasons. Furthermore, ice can obstruct flow on rivers, creating

temporary "ice dams." However, as the climate warms, the dynamics of these ice dams change. With climate change, ice dams can fail and break up earlier in the season, increasing coastal flooding. Enhanced coastal flooding has been noted near the mouths of some Canadian rivers, like the Mackenzie,<sup>51</sup> and Russian rivers like the Northern Dvina River. While the Mackenzie River discharges into an area with few inhabitants, the Northern Dvina River's mouth is close to the Russian city of Severodvinsk - potentially putting that region at risk.<sup>52</sup>

It should be noted that there are other reasons sea levels can rise and fall in the Arctic, and these topics can be addressed in a follow-up paper. For example, the loss of ice mass in Greenland is predicted to be so large that it can alter Earth's gravitational field, impacting local sea level dynamics.<sup>53</sup> Furthermore, the retreat of glaciers, both in the modern era and thousands of years ago when the last Ice Age ended, can cause the land to move. This, "Glacial Isostatic Adjustment," can lead to the land rising in places like Scandinavia and Greenland, causing sea level falls in those areas, and subsidence in parts of North America and central Europe, contributing to sea level rise in those areas.<sup>54</sup> These topics, while important, are beyond the scope of this article. They can be addressed in a future review.



*Figure 8 Sea level trends in the Arctic. A. Sea level trend in the Arctic derived from satellites. The record shows an Arctic-wide rate of rise of 3.7 mm/yr for the period 1996-2019. However, this rate is not uniform across the entire basin (see C)[44]. B. Satellite-derived trend in sea level for the global ocean. The record shows a rate of 3.6 mm/yr for the period 1993-2024- which is similar to the Arctic trend [46]. C. Spatial distribution in sea level rise for the period 1996-2018 derived from satellites. Note that the rate of sea level rise is highest in central and western Canada, and in eastern Alaska, USA [44]. D. Schematic of sea ice and major ocean currents in the Arctic. Note that the Beaufort Gyre can direct ocean waters towards the parts of Canada and Alaska, USA that have higher rates of sea level rise [8].*

## 6. RATES OF SHORELINE CHANGE IN THE ARCTIC

Permafrost thaw, subsidence, and accelerated wave-driven erosion all contribute to shoreline retreat in the Arctic Ocean. Figure 9 presents a Pan-Arctic map of shoreline change rate in the Arctic. It shows that some of the highest rates of coastal erosion occur in the central Russian Arctic, in areas like the Laptev Sea and the Anzhu Islands, where rates can range between 2 and 10 meters per year.<sup>3,7</sup> High rates of shoreline retreat are found in parts of the US Arctic, such as near Prudhoe Bay, and parts of the Canadian Arctic- particularly around the Mackenzie River Delta. In these regions, the average rates of shoreline retreat can range from 1 to 10 m per year.<sup>3,7</sup> There are moderate rates of shoreline erosion (about 1 to 2 m yr<sup>-1</sup>) near Russia's White Sea, by the country's western Arctic region. Shoreline change rates are less than 1 m per year near Canada's Queen Elizabeth's Islands, and in the parts of the Scandinavian Arctic. As described earlier, shoreline erosion is likely to be fastest in areas with thawing permafrost. Sections of the Arctic with rocky coasts will likely remain resilient to erosion, at least for the near future (see Figure 1 for a map of shoreline features for the Arctic). In the Baltic Sea, shorelines are accretionary in the northern Baltic/Bothnian Bay, relative stable in the central parts of the Baltic Sea, and erosional in the southern Baltic Sea, along the coasts of parts of Latvia, Lithuania, Kaliningrad (Russia), Poland and northeastern Germany.<sup>55</sup>

The average rates of shoreline change presented in Figure 9 should be viewed with a degree of caution, as localized rates can vary. For example, when the US Geological Survey quantified rates of shoreline change in the Alaskan Arctic, they found that while rates in many places averaged about 1 m per year, localized rates could exceed 20 m per year.<sup>56</sup> Likewise, along Poland's Baltic Coast, near the city of Debki (about 60 km NW of Gdansk), shoreline retreat rates were 1.6 m/yr or less from 1875-2001 but accelerated to over 6 m/yr- even reaching as high as 15 m/yr between 2001 and 2020. In this Polish study, the authors attributed the accelerating erosion to reduced sea ice cover and intensified wave erosion.<sup>57</sup>

Furthermore, the maps presented in Figure 9, which are among the best available data, do not include all shorelines in the broader High North region. Shoreline retreat rates for Canada's Queen Elizabeth Islands, for example, are not included in this analysis. Furthermore, shoreline change in Greenland is complex. For example, small deltas are forming in parts of coastal Greenland where glacial melt causes increased sediment transport to the ocean.<sup>58</sup> Climate change in Greenland should indeed be the subject of further study by NATO and its partners.

Looking into the future, it is recommended that NATO countries and NATO partners develop a high-resolution map of an Arctic shoreline change to better understand shoreline change at a higher spatial and temporal resolution. Such a map would involve an examination of satellite data, coupled with historical maps of the area and on-the-ground measurements, if feasible.

### Maps of Recent Shoreline Change For The Arctic (Left) And Baltic Sea (Right)

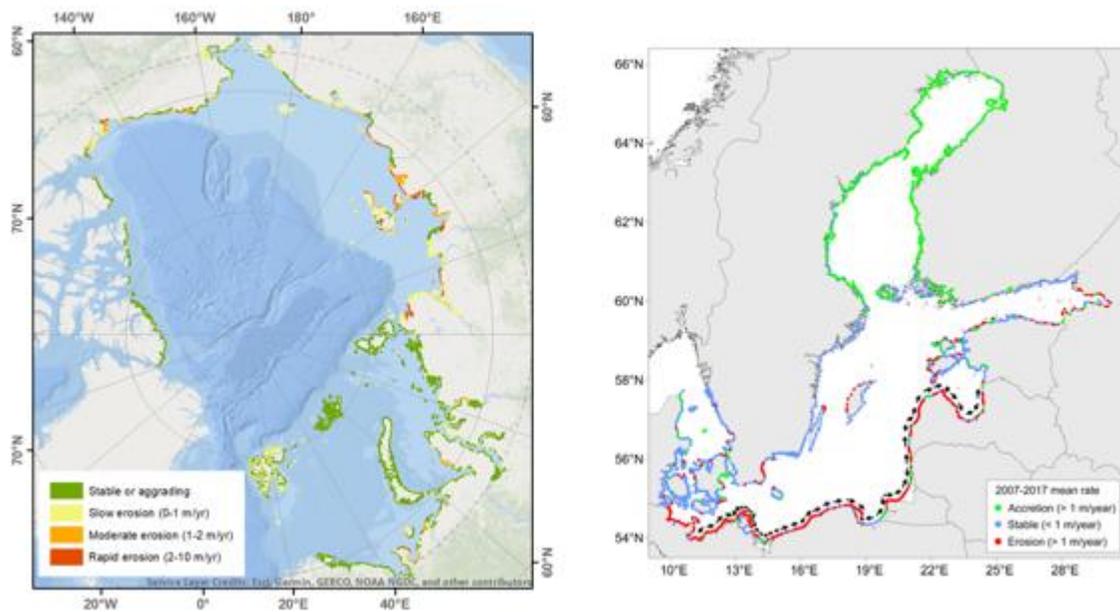


Figure 9. Maps of shoreline change. Left: Pan-Arctic map of shoreline change [3]. Right: Map of shoreline change in the Baltic Sea; 2007-2019 [55]. It should be noted that these area average rates and local rates can be significantly higher or lower.

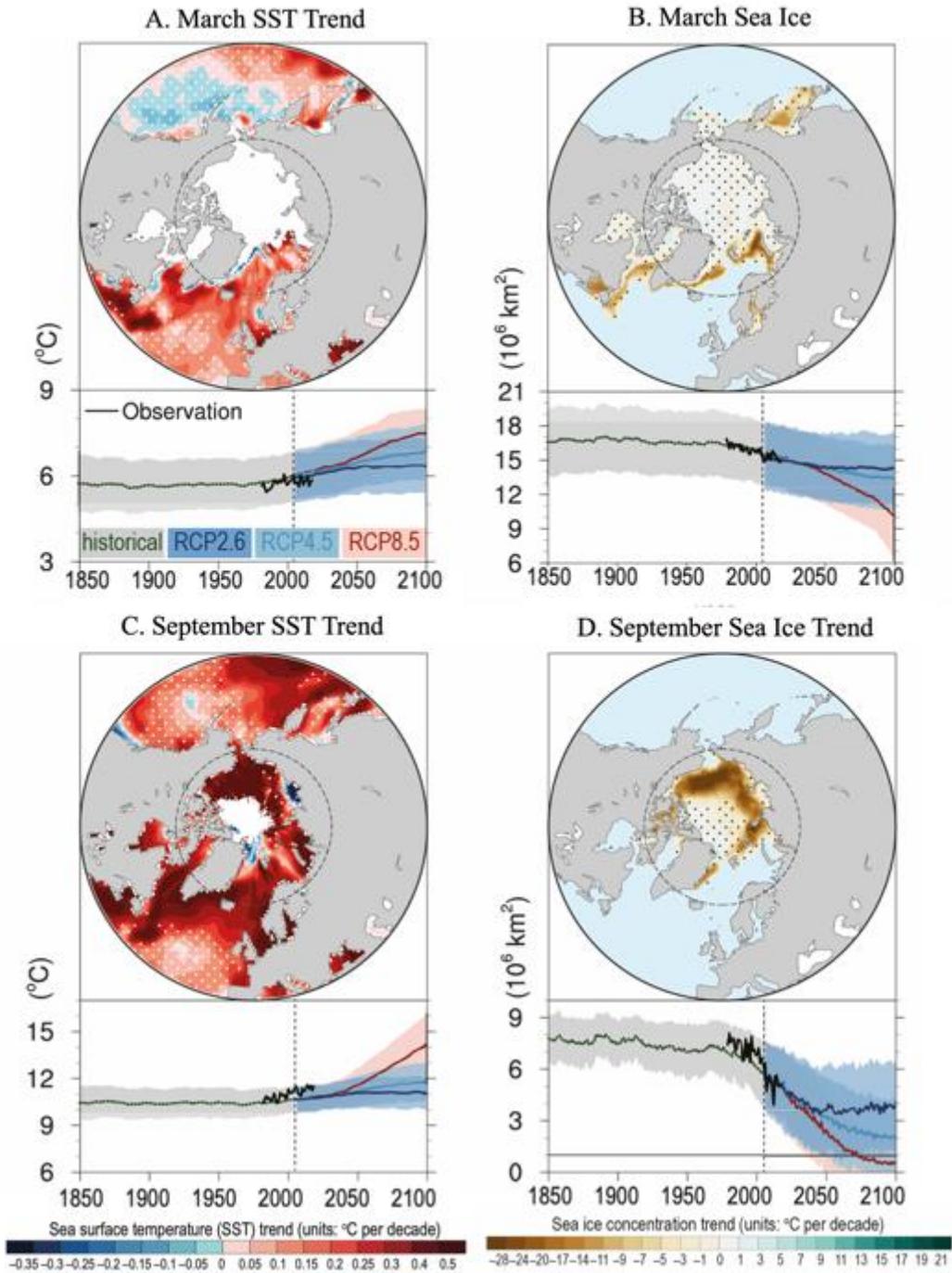
## 7. PROJECTIONS OF CLIMATE CHANGE AND COASTAL CHANGE IN THE ARCTIC

Existing climate trends in the Arctic are very likely to continue and, indeed, accelerate in the years ahead. Figure 10 presents maps and charts of existing and predicted climate change in the Arctic. It shows maps of sea surface temperature and ice cover for the Arctic from 1982 to 2017, along with trend lines of experienced and predicted change from 1850 to 2100.<sup>1</sup> These projections are based on three scenarios used by the Intergovernmental Panel on Climate Change (IPCC): RCP 2.6, RCP 4.5, and RCP 8.5, which are effectively low, medium, and high scenarios.

These projections indicate that the Arctic Ocean will warm by about 1°C to 2°C in March and about 1°C to 5°C in September by 2100.<sup>1</sup> Sea ice retreat will continue to accelerate, particularly during summer months. While the IPCC's (2019) report indicates an ice-free Arctic by about 2050, more recent authors indicate that the Arctic may be ice-free in the summer by 2030.<sup>9</sup> Sea level is expected to rise across the Arctic. One study based on RCP 4.5 (the medium climate scenario) indicates that many Arctic shorelines will see relative sea level change (combined impact of subsidence and sea level rise) of up to 1 m by 2100.<sup>59</sup> Under extreme climate change scenarios involving the collapse of major ice sheets, about 1 m more of sea level rise is possible<sup>60</sup>. Arctic rates of sea level rise are roughly in line with projections of global sea level rise by the IPCC.<sup>1,43</sup> However, rates could well be higher in localized areas where permafrost degradation leads to coastal subsidence,<sup>33</sup> such as the Lena River Delta and the Mackenzie River Delta.<sup>48,49</sup> The impacts of sea level rise are likely to be greatest during intense storms, when winds force water onshore, creating storm surges and localized high water events.

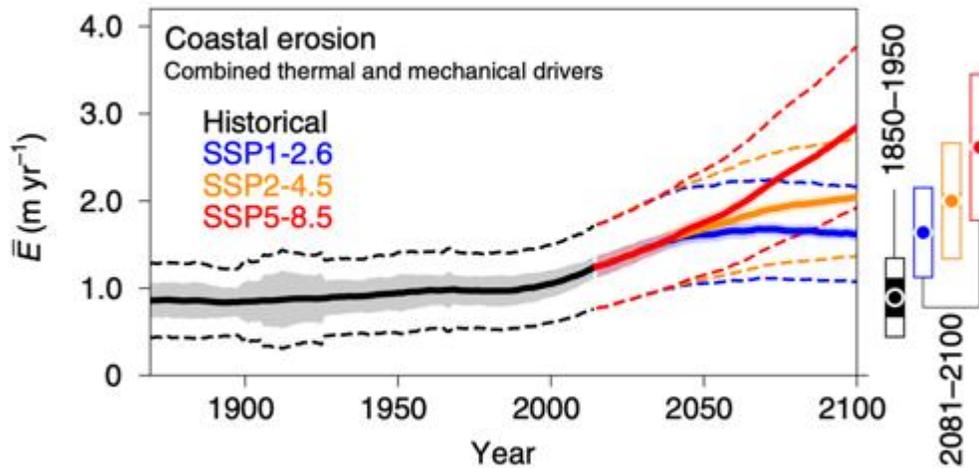
Shoreline erosion is likely to continue and accelerate as permafrost melts, sea ice retreats, and global sea levels rise. For example, one report indicated that the combination of thermal and mechanical permafrost degradation could roughly double Arctic shoreline erosion rates by 2100. Rates will increase from about 0.9 m/yr for the period 1850 to 1950 to between 1.6 ± 0.5 to 2.6 ± 0.8 m/yr by 2100.<sup>31</sup>

### Climate trends and projections in the Arctic and High North



## Climate trends and projections in the Arctic and High North Continued

### E. History and projections for coastal erosion rates in the Arctic



### F. Projections of relative sea level rise in the Arctic by 2100

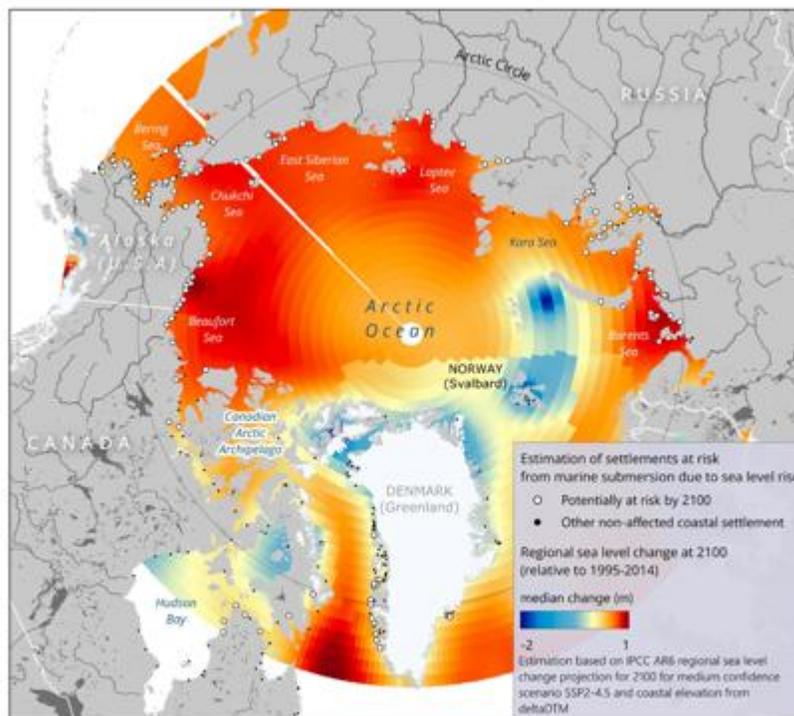


Figure 10 Climate history and projections for the Arctic. A-D. Observed (maps; 1982-2017) and predicted trends in sea surface temperature (SST) and sea ice in the Arctic and High North. RCP 2.6, 4.5 and 8.5 refer to climate scenarios that correspond to a low, medium and high rate of climate change [1]. E. Observed and predicted erosion rates along Arctic shorelines. SSP 2.6, 4.5 and 8.5 are climate scenarios that are very similar to the "RCP" scenarios in Fig 10a. [31]. F. Predicted rate of relative sea level rise in the Arctic, i.e. the rate that includes both global sea level rise and local subsidence by 2100. This projection is based on SSP2-4.5, which is a medium climate projection. Also included are major human settlements [59].

## **8. LESSONS LEARNED FOR OPERATOR OF INFRASTRUCTURE IN THE ARCTIC AND HIGH NORTH**

The shift towards a more dynamic coastal zone in the Arctic region has implications for organizations that operate infrastructure there. Numerous entities operate infrastructure in the Arctic, including the military and civilian branches of NATO countries, NATO partners, and NATO adversaries, as well as mining and energy companies, local governments, and indigenous communities. Presented here is a review of how permafrost melt, rising waters, and increasing coastal erosion impact operators of equipment, how these changes can be mitigated, and security and strategic implications of these changes.

Overall, this review finds several ways that climate change in the Arctic and High North impact security. For example, climate change can reduce the readiness of militaries and their ability to conduct operations by destabilizing infrastructure. Sea level rise, storms and coastal erosion can also increase vulnerabilities by making some coastal sites difficult to access. At the same time, climate change is creating an increased demand for military presence in the Arctic and High North as polar shipping routes expand and mining activities increase. Military leaders will also face tough decisions about whether to maintain existing facilities in the face of growing climate risks -- which could be expensive or relocate them to other environments -- which could change their operational readiness.

In terms of climate risks, permafrost thaw and subsequent land subsidence can be of critical importance. As thawing ground shifts and subsides, buildings can settle, roads and airstrips can deform, and pipelines can crack. Subsidence can make buildings more difficult to use as they become structurally less stable. Shifting grounds can alter the dynamics of RADAR systems and weather stations, where the angle of transmitted and incoming radio waves is of critical importance to their function. The settlement of roads and bridges can make it more difficult to move military equipment or troops by land, while similar shifts on runways can make it more difficult to land planes. Subsidence can also destabilize heavy equipment, like the cranes used at ports and naval bases, or heavy military equipment like artillery pieces. Shifting grounds can cause pipelines to crack, threatening energy supplies to cities and military facilities - or financial systems that depend on the flow of oil and gas.

Shoreline retreat and increased flooding pose related challenges. Flooding makes it more difficult to move people and equipment by road. Aircraft may have difficulties taking off and landing from a runway that is flooded by sea level rise and storms. Waves can be further destructive to infrastructure, damaging buildings and other assets on military bases. Some coastal military sites may become difficult to access as shorelines retreat.

Saltwater is problematic for electrical lines and power supplies as it can lead to short circuits and other electrical hazards, reducing the effectiveness of key electronic components.

Saltwater can also cause metal in vehicles, aircraft, cranes, and military equipment to rust, reducing their strength and increasing their vulnerability. Saltwater-induced rust is also possible in rebar and metal supports in concrete buildings, making them more vulnerable to damage -- either from a direct attack, or simply by accelerating the aging process.

On the other hand, a reduction in sea ice in the Arctic and High North can make some ports more usable, allowing for an extended period of operations. Ports like Russia's Sabetta LNG exporting facility could see increased operations as sea ice retreats. Furthermore, there is likely to be increasing need for coastal ports to support global shipping routes that traverse through an ice-free Arctic Ocean. This could create the need for increased search and rescue teams, refueling operations, or oil spill remediation. Overall, it is expected that increased shipping in the Arctic will lead to an increased demand for coast guards and navies to patrol shipping lanes and provide emergency operations.

Increased flooding and rising waters may prompt some organizations to consider a landward retreat to higher and drier ground. Yet, this poses a security risk for military facilities that need to be at the most seaward point possible. Indeed, coastal airstrips are an important part of strategic defenses, as are naval bases and radar stations. Places like the USA's Oliktok Point Radar Station, which monitors incoming aircraft, may need to stay in place to serve its mission despite increasing coastal hazards. Moving landward, while perhaps desirable from a flooding perspective, may be undesirable from a strategic perspective. Decision makers could be faced with tough choices. Should they invest resources in making current facilities more resistant to flooding (which could be expensive) or relocate to inland (which could impact operations)?

Yet, multiple tactics can be deployed to address these challenges.

For example, there are ways to mitigate or reduce the rate of permafrost thaw. Hjort et al., (2022) proposed a series of solutions that include heat drains, thermosyphons, and improved convection

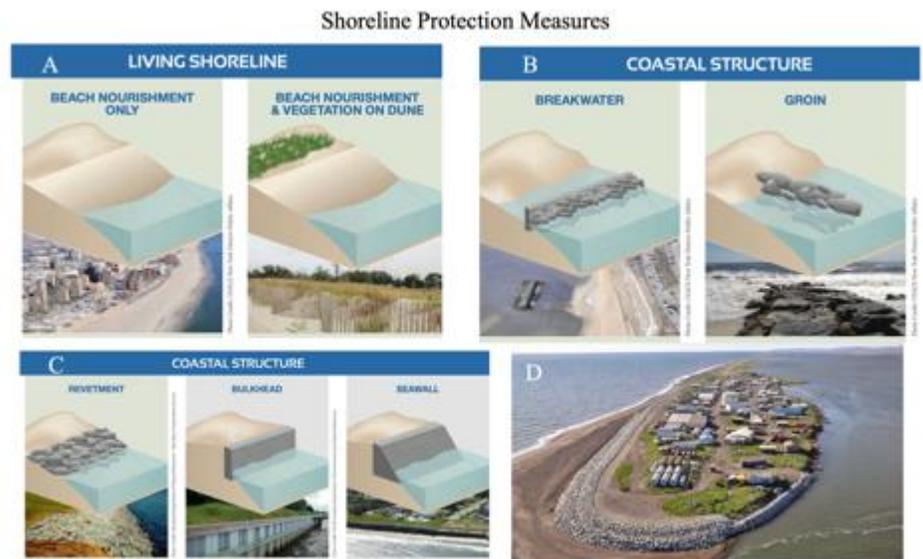


Figure 11 A-C. Schematics of shoreline protection including both nature based features, and stronger, structural protections. Source: NOAA [63]. D Example of shoreline protection, rock revetment at Kivalina, Alaska, USA [64 and refs therein].

regimes as ways to remove heat and reduce the rate of thaw. Similarly, these authors suggested constructing sunshields and creating highly reflective surfaces as a way of preventing heat from accumulating.<sup>28</sup> Risks to buildings in subsiding lands can be addressed by driving pilings, re-leveling buildings, and shoring foundations.<sup>28</sup> In cases where there is a need to build new structures in permafrost zones, buildings can be placed on top of gravel, which allows cold air to circulate, or the permafrost can be removed entirely and replaced with gravel or stone.<sup>61,62</sup>

There are also actions that can reduce the impacts of coastal flooding and shoreline retreat.<sup>63,64</sup> These actions fall into several major categories: 1) elevate structures to make them less exposed to rising waters, 2) build defenses that keep water out, 3) install pumps to lower water levels in flooded areas, 4) reduce flow constrictions to lower water levels, 4) create nature-based features that reduce wave energy, 5) change operations to live with water, 6) and retreat to stable ground. For example, buildings and other structures can be elevated, which may involve raising the foundation or floors of buildings and flood-sensitive elements like wiring and cables. Structural defenses can include levees and sea walls that prevent water from entering a facility or structure. Other situations may call for shoreline hardening through wave breaks and jetties. Additionally, pumps can be a useful way to expel water, though their utility is limited in extremely cold environments. Restoring nature-based features, like oyster reefs or wetlands, can also play a role in reducing flood risks, particularly in cases where they can reduce waves and associated erosion. In general, nature-based features provide a greater degree of ecosystem services, while engineered solutions provide a greater degree of flood risk reduction. In some cases, flood risks can be addressed through changes to operational regimes, for example by planning activities to occur during low tide. Finally, a level of retreat inland to higher and drier locations may be an option but should be judged against how a landward movement would impact operations.

There are principles for designing flood defenses in the face of climate change and sea level rise. Often, a structure such as a levee, seawall, or floodgate is designed to protect against a storm with a particular frequency of occurrence. This frequency is often a storm with a 1% or a 0.2% chance of occurring in any given year (a 100- or 500- year event), though higher and lower standards could be chosen, based on the need for cost and/or added protection.<sup>65-67</sup> A statistical frequency is determined through numerical modelling that often combines multiple storm tracks with circulation and morphological models of the coast. Climate change is incorporated into these scenarios by raising water levels in a manner consistent with an agreed upon rate of global sea level rise and local subsidence- if appropriate to that coast.<sup>65-67</sup> Organizations such as the United States' Army Corps of Engineers and the Netherlands' Deltarus, as well as numerous private engineering firms, have a long experience of building coastal flood defenses.

While coastal defenses are feasible to construct, construction is often expensive. Costs can easily run into the tens or hundreds of millions of US Dollars, and potentially into the

billions of US Dollars for the largest of systems.<sup>68,69</sup> Furthermore, maintenance of these systems is needed - for routine activities and to keep pace with climate change- and is also expensive.<sup>67,69</sup> Looking to the future, military budgets for NATO countries may need to increase to account for increased coastal flood risks. Countries that are not able to invest in coastal resilience may experience a decline in their military readiness and may experience difficulties conducting operations in the Arctic's coastal zone.

However, the climate risks that threaten NATO countries in the Arctic are also risks for NATO adversaries. Some of the highest rates of coastal retreat in the Arctic are in Russia, and Russian oil and gas pipelines cross over permafrost that is likely to melt. Countries that best understand their climate risks and have the resources and will to address them may have a strategic advantage operating in the Arctic during this century of climate change.

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