Hydrometeorological forcing of coastal dynamics in the Russian Arctic: link to erosion rates in the last decades

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Abstract

Coasts in the Russian Arctic are extremely vulnerable to the ongoing environmental changes. Temporal evolution of their retreat rates is driven by hydrometeorological processes. Permafrost of the coastal bluffs rapidly thaws under the influence of air and water temperature increase. Along with that, sea ice decline results in wave energy increase because of longer wave fetch and ice-free period when the waves are able to erode the unprotected coasts. The combined thermal and wave action is defined as hydrometeorological forcing of coastal erosion. We estimated temporal variability of the air thawing index (sum of annual positive temperatures) reflecting the thermal factor, and the wind-wave energy flux since the 1970s for five sites in both the western and eastern Russian Arctic where observations of coastal erosion rates derived from both field measurements and remotely sensed data are available: Varandey (Pechora Sea), Yamal and Ural coasts of the Baydaratskaya Bay (Kara Sea), Cape Chukochiy (East Siberian Sea) and Lorino (Bering Sea). We further calculated the total hydrometeorological forcing of coastal erosion for the periods with known retreat rates and compared the temporal variability of the two parameters. Comparison of the hydrometeorological forcing shows a link between erosion rates and the hydrometeorological forcing in all the areas. The best correlation is noted for sites where remotely sensed data for relatively long periods were analyzed. For areas with more frequent direct field observations, the variability of the two parameters shows more differences. Such findings imply that while long-term erosion rates are determined by general trends of climate and sea ice extent change in the Arctic seas, coastal retreat in one single year can be driven by local factors, such as lake drainage, random failure of large blocks or peat lenses, exposure and burial of ice bodies, and other reasons. Therefore estimation of mechanisms and trends of coastal erosion in the Russian Arctic should be made based on average retreat rates over relatively long timescales (several years or even decades). Studies on the variability of climate parameters were funded by the RFBR grant 18-05-60300 (S.Ogorodov, N. Shabanova). Studies on rates of coastal erosion were funded by the RSF grant 16-17-00034 (A.Baranskaya, A. Novikova). B.Jones was supported by US National Science Foundation award OISE- 1927553.

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PRESENTED AT:

HOW DOES CHANGING CLIMATE AFFECT COASTAL DYNAMICS IN THE RUSSIAN ARCTIC?

Most of the Russian Arctic coastline is composed by perennially frozen sediments (permafrost). Because of this, they are extremely vulnerable to ongoing climate change. Coastal erosion in the Arctic is driven by two main hydrometeorological drivers: thawing of the frozen ground in the bluffs and their destruction by waves.

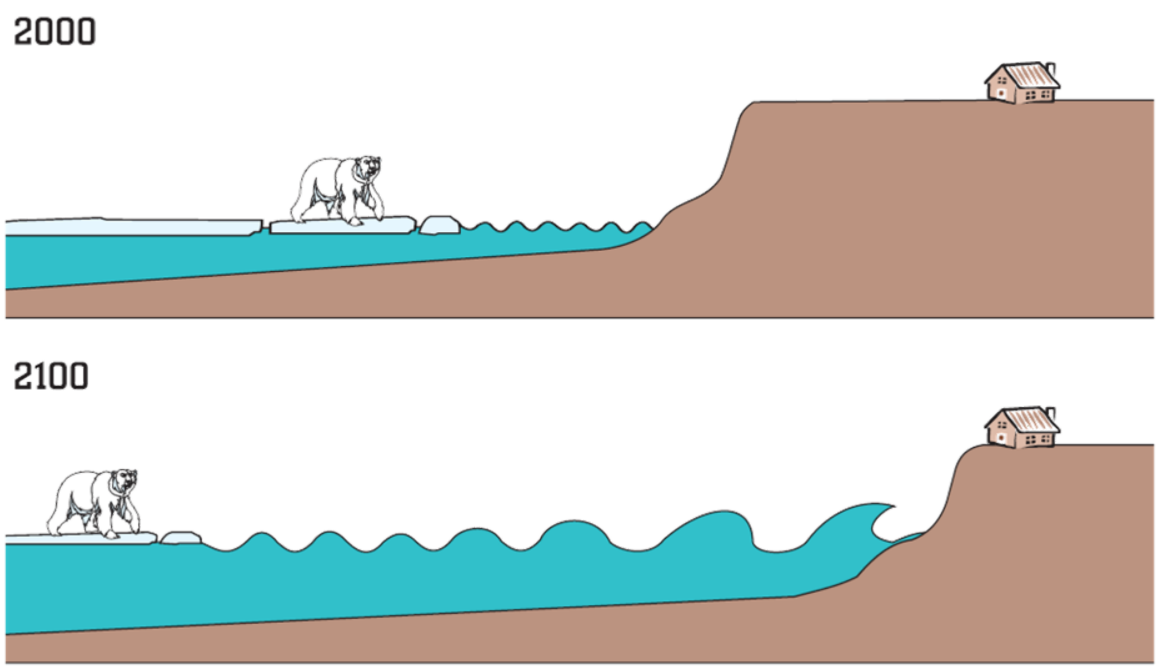
Coasts of Severnaya Zemlya, previously protected by sea ice almost year-round

Photo by A.Kamenev

In the conditions of the ongoing climate change, both of these drivers contribute to increasing coastal erosion. Rising air temperatures lead to faster thawing of permafrost in the coastal bluffs. At the same time, warming leads to increased wave action because of global sea ice reduction. The coasts that were previously protected by sea ice during most of the summer, are now exposed to waves for a much longer time. The ice-free period in different locations across the Russian Arctic increased from several weeks to two months (Ogorodov et al., 2020).

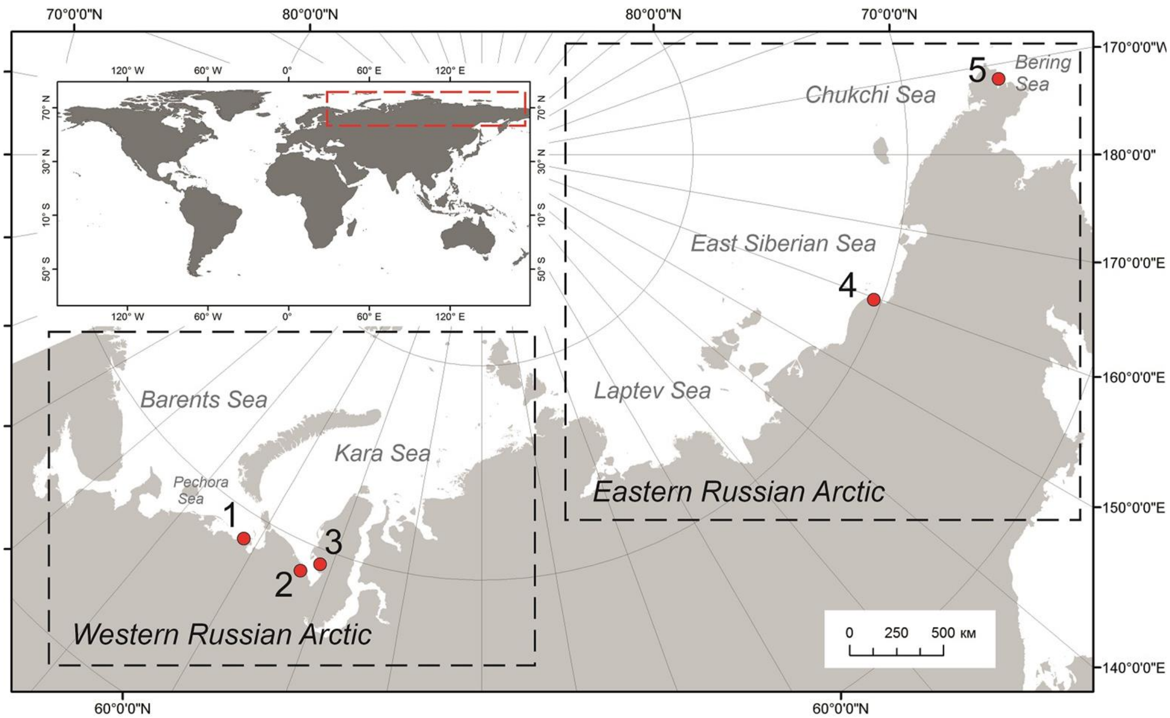
Melting fast ice at Beliy Island, Kara Sea

Another consequence of sea ice reduction is retreat of the sea ice rim in summer which increases the wave fetch. Because of it, wind waves can gain more energy, and their action on the coasts increases with time.



As air temperatures are rising, and stronger waves affect the coasts for a longer time each year, coastal ecosystems experience higher pressure than before. The combined thermal and wave action is defined as hydrometeorological forcing of coastal erosion. In this study, we aim at estimating changes of its both components in the eastern and western Russian Arctic and identifying if theit variability can be linked to the temporal evolution of coastal erosion rates.

COASTS OF THE RUSSIAN ARCTIC: EASTERN VS WESTERN



1 - Varandey, 2 - Ural coast, Baydaratskaya Bay, 3 - Yamal coast, Baydaratskaya Bay, 4 - Cape Maliy Chukochiy, 5 - Lorino

Coasts of the western and eastern Russian Arctic are different both in terms of permafrost properties and climate or sea ice conditions.

Western Russian Arctic

Coasts in the western Russian Arctic (Barents and Kara Seas) retreat with average long-term retreat rates of up to 4 m/yr (Baranskaya et al., 2020). The mean long-term retreat rates for erosional segments generally vary from 0.5 to 2 m/yr.

The coastal bluff is generally relatively straight and steep, sometimes with thawed sediments accumulating under the slope

Typical thermoabrasional coast of the Kara Sea

Typical thermoabrasional coast of the Kara Sea (Beliy Island)

The ice-free period is relatively long and lasts from two-three months to five months (Ogorodov et al., 2020), except for the northern part of the Kara Sea near Novaya Zemlya and Severnaya Zemlya archipelagoes, where the ice-free period lasted for several weeks or even days until recently

Photo by A. Kamenev

Thermoabrasional coast of Vilkitskiy Island (northern Kara Sea) protected by sea ice in late August.

One of the typical feature of permafrost in the western Russian Arctic is the presence of massive ice beds: thick continuous layers of ice in the frozen ground. They contribute to faster coastal erosion and thermal denudation. At outcrops of massive ice beds, large thermocirques often form.

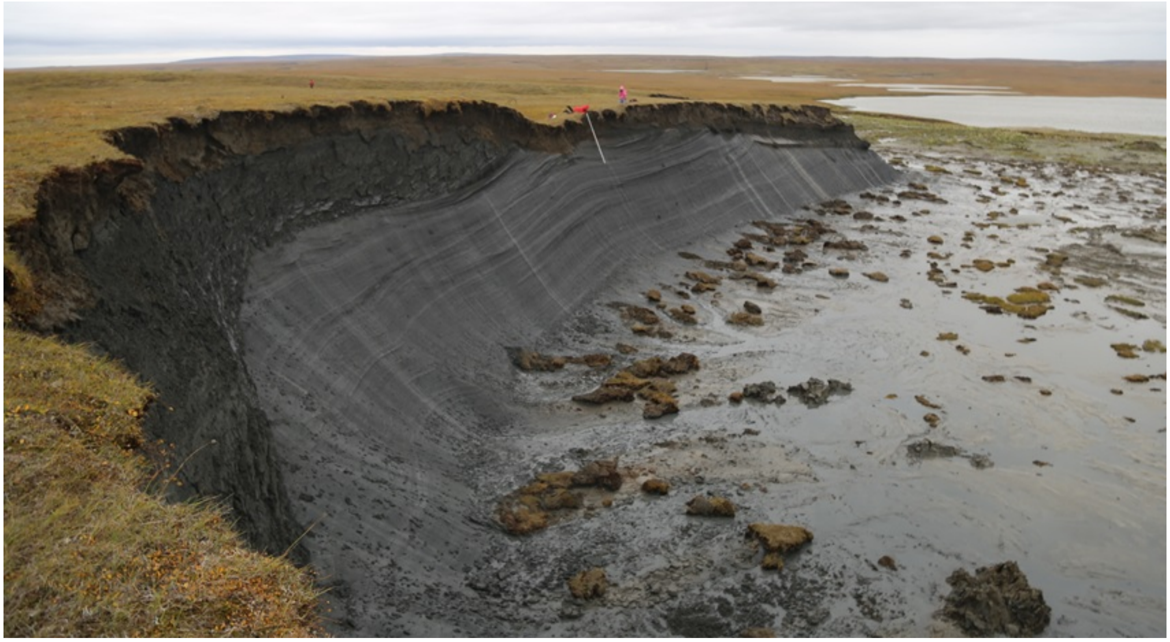


Photo by N. Belova

Outcrop of massive ice beds in a thermocirque near Amderma, Kara Sea

Eastern Russian Arctic

In the eastern Russian Arctic, coastal retreat rates are generally higher than in the western Russian Arctic; their average long-term values vary from 0.5 to 7-8 m/yr with extremes up to 12-17 m/yr (Ogorodov et al., 2020). Such fast erosion is possible because of a winde presence of Ice Complex, or Edoma deposits. They are encountered in the East Siberian Arctic mostly and are composed by sediments dissected by a polygon net of large ancient ice wedges. The wedges have grown so wide with time that most of the ground volume consists of ice; sediments form inclusions in the ice walls of the coastal bluffs.

Photo: https://arcticcoast.info/resources/coastal-photo-gallery (https://arcticcoast.info/resources/coastal-photo-gallery)

Coastal bluff of the Laptev Sea composed by Ice Complex, or Edoma

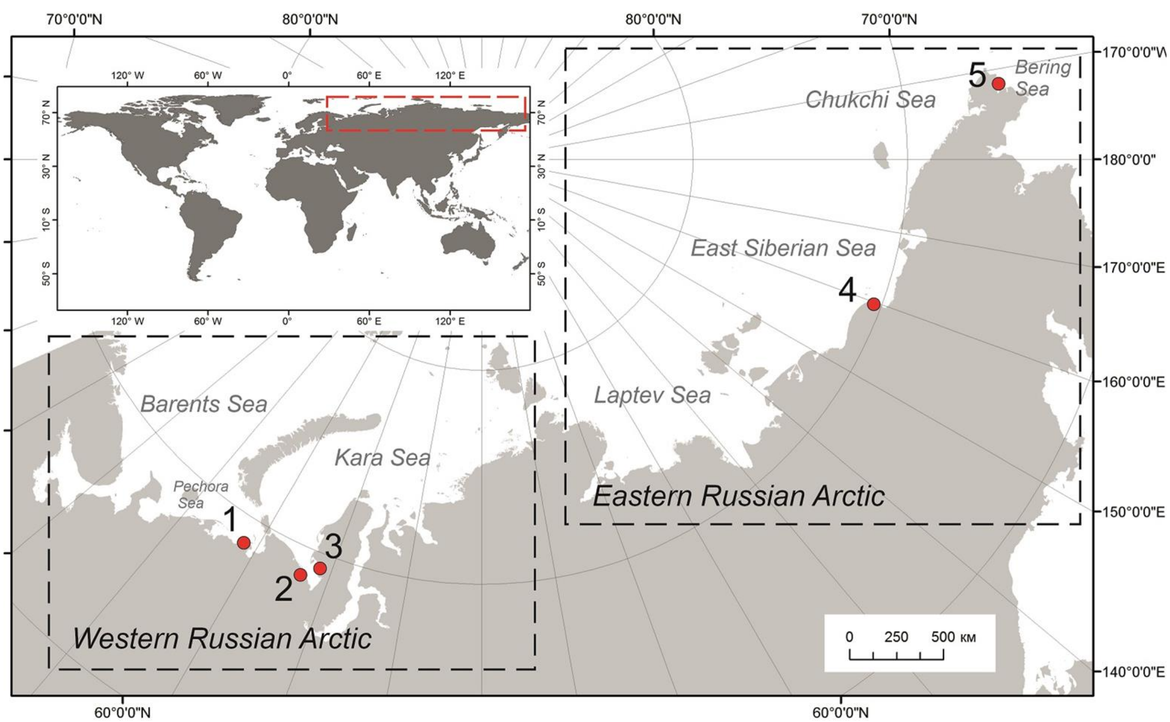
Active retreat of such coasts is mainly driven by thermal denudation, or thawing of the ice. When the ground ice melts, sediment inclusions from the polygon centers are left forming several rows of regular mounds, or "baidgerakhs"

Coast of Muostakh Island, Laptev Sea, with three rows of baidgerakhs

The ice-free period in the eastern Russian Arctic is shorter than in the western Russian Arctic and lasts up to two months, rarely reaching three months (Ogorodov et al., 2020).

Key areas

To compare the evolution of the thermal and wave energy factor of coastal dynamics and their joint effect, providing the total hydrometeorlogical forcing of coastal dynamics, we chose five key areas: three in the western Russian Arctic (Varandey, Pechora Sea, Yamal and Ural coasts of the Baydaratskaya Bay, Kara Sea), and two key areas in the eastern Russian Arctic (Cape Maliy Chukochiy, East Siberian Sea and Lorino, Bering Sea).



1 - Varandey, 2 - Ural coast, Baydaratskaya Bay, 3 - Yamal coast, Baydaratskaya Bay,
4 - Cape Maliy Chukochiy, 5 - Lorino

At each of the key areas, a series of coastal erosion rates' obervations is available, including field measurements and remote sensing analysis.

Varandey, Pechora Sea. Coastal erosion threatens the buildings of the settlement and the oil terminal

1) Varandey area is characterized by low thermoabrasional coasts composed by sand. Permafrost is sporadic; coastal erosion depends highly on extreme events like strong storms and high surges

Ural coast of the Baydaratskaya Bay, Kara Sea

The bluffs at the Ural coast of the Baydaratskaya Bay are composed by silts, sands and clays and contain abundant massive ice beds.

Yamal coast of the Baydaratskaya Bay, Kara Sea

The sediment composition of the bluffs at the Yamal coast of the Baydaratskaya Bay is similar to the Ural coast, although no massive ice beds are present.

Photo: https://arcticcoast.info/resources/coastal-photo-gallery (https://arcticcoast.info/resources/coastal-photo-gallery)

Cape Maliy Chukochiy

The bluffs at Cape Maliy Chukochiy are composed by the Ice Complex, and have the classical shape with ice walls and baidgerakhs.

Photo by A. Maslakov

Lorino, Bering Sea

The coasts at Lorino are mostly sandy, with segments composed by silts and peat, and occasional ice wedges. Their erosion threatens the local indigenous fishing community of Lorino settlement.

THE THERMAL FACTOR: AIR THAWING INDEX

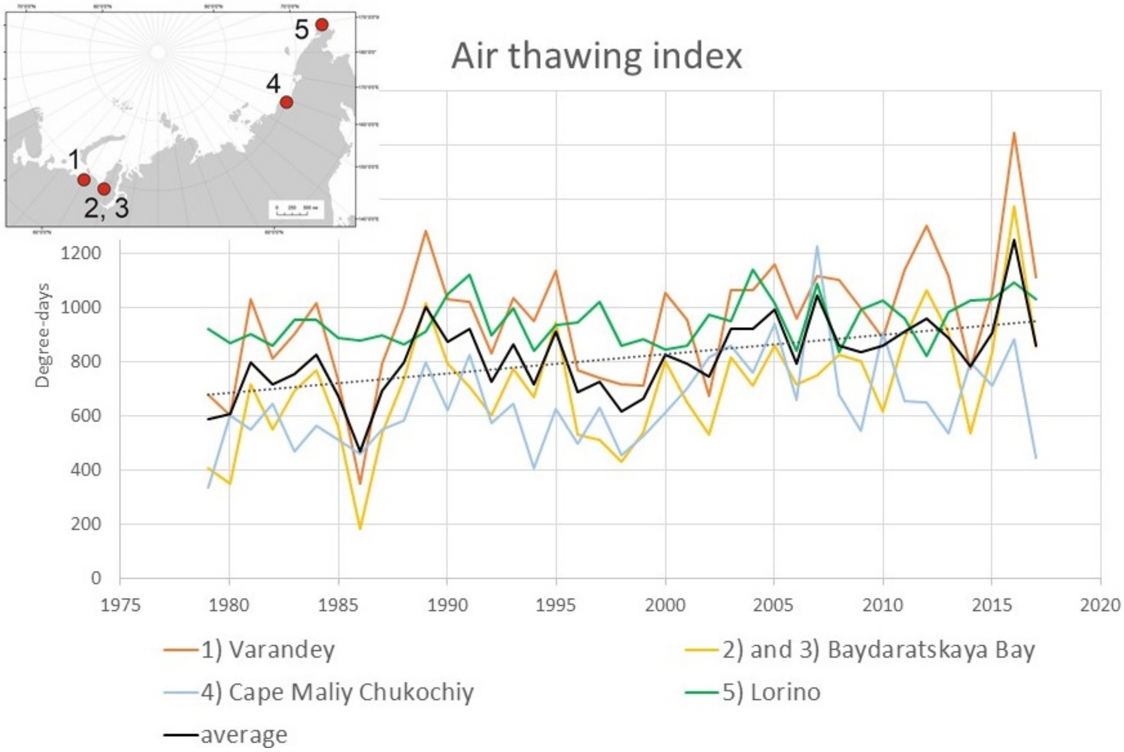
Credit: Getty Images

One of the main drivers of coastal erosion in permafrost areas is melting of the frozen ground of the coastal bluffs during the contact with warm air. This process is called thermal denudation.

The potential of thermal denudation was assessed by the air thawing index (It) showing the number of positive/negative °C·days per year (Andersland and Ladanyi, 2004):

$$I_t = \sum_{i=1,}^{N} t_i, t > 0$$

where t_i is is the daily mean temperature, and N is the number of warm (t > 0ºC) days per year. This index is an evaluation of the annual amount of heat added to the ground and permafrost during warm periods. For its calculation, we used observational data from Varandey, Amderma, Cape Maliy Chukochiy and Lorino hydrometeorological stations



In the last fourty years, there has been a trend to increase of the air thawing index in all of the key areas, except Lorino. The highest values are typical for Varandey and Lorino, however, patterns of their distribution are different for two areas: while at Varandey there is a clear tendency to increase of the air thawing index with considerable fluctuations, both positive and negative, Lorino shows no clear trend and a relatively smooth curve. The values for Cape Maliy Chukochiy and Baydaratskaya Bay are lower, and have comparable curves, although poitive extreme values at Baydaratskaya Bay were higher.

On average, the air thawing index increased by 250-270 degree-days since the 1980s.

THE WAVE ENERGY FACTOR: WAVE ENERGY POTENTIAL

Most of the wave energy in the shallow Russian Arctic seas comes from wind-induced waves. Therefore, the potential of wave action on the coasts can be derived from data on parameters of wind generating these waves, length of the wave fetch, and the topography and bathymetry of the coastal areas.

The wave energy potential (WE) was calculated according to the Popov–Sovershaev method (Popov, Sovershaev, 1982; Ogorodov, 2011; Shabanova et al., 2018). The method is based on the wave processes theory and applies correlations between wind speed and parameters of wind-induced waves.

For deep-water conditions, when the sea floor does not affect wave formation, the wave energy potential, coming from 1 m of the wave front per second during a storm with the wind speed V_{ji} with a wind speed class *j* from a chosen wave direction *i* at the outer coastal zone boundary is proportional to the wind speed to the power of three and to the wave fetch:

$$WE_{ji} = 3 \times 10^{-6} V_{ji}^{3} x_i,$$

where Vji is the real wind speed of a chosen direction measured by anemometer at 10 m above sea level [m/s], x_i is the wave fetch [km] along the current wind direction.

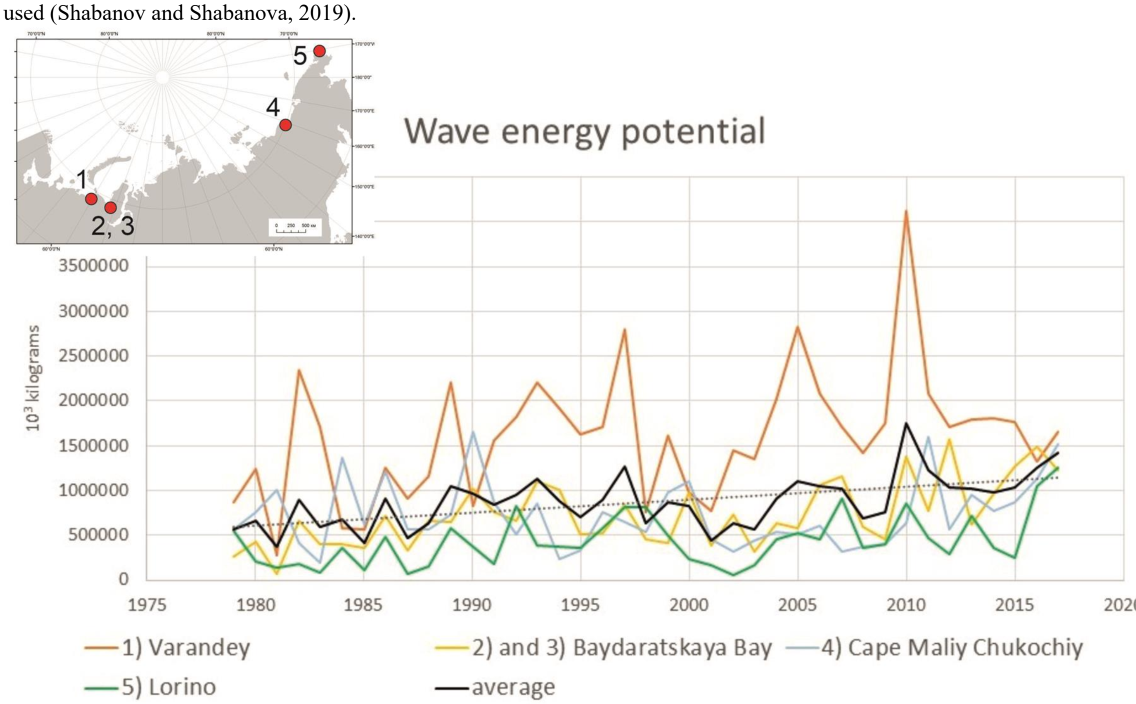
Wind data was derived from ERA Interim and ERA 20C reanalyses. Landward wave-dangerous directions of winds, wave fetches and depths were obtained from ETOPO1 digital elevation model, which also includes bathymetry (NOAA, 2017).

The total wave energy potential, accumulated during the ice-free season, is calculated as:

$$WE = \sum_{i=1}^{M} \sum_{j=1}^{N} 3 \times 10^{-6} V_{ji}^{3} x_i \cdot p_{ji} \cdot n,$$

where p_{ji} is the frequency of storm with the wave direction i and wind speed class j (calculated for the ice-free season only), *n* is the sea ice-free period duration in seconds, *M* is the number of wave-dangerous directions, and *N* is the number of wind speed classes.

The duration of the sea ice-free period was determined based on satellite imagery data. We used the sea ice concentration products of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) OSI-450 (EUMETSAT, 2017) and OSI-430-b (EUMETSAT, 2020). The products are provided by the Danish Meteorological Institute; their resolution is 25 km. We determined the start and end dates of the sea ice-free period for the cells of OSI SAF data nearest to the respective key areas. To detect the sea ice-free period start and end dates, the original rolling-window method (rolling-window approach or RWA) was used (Shabanov and Shabanova, 2019).



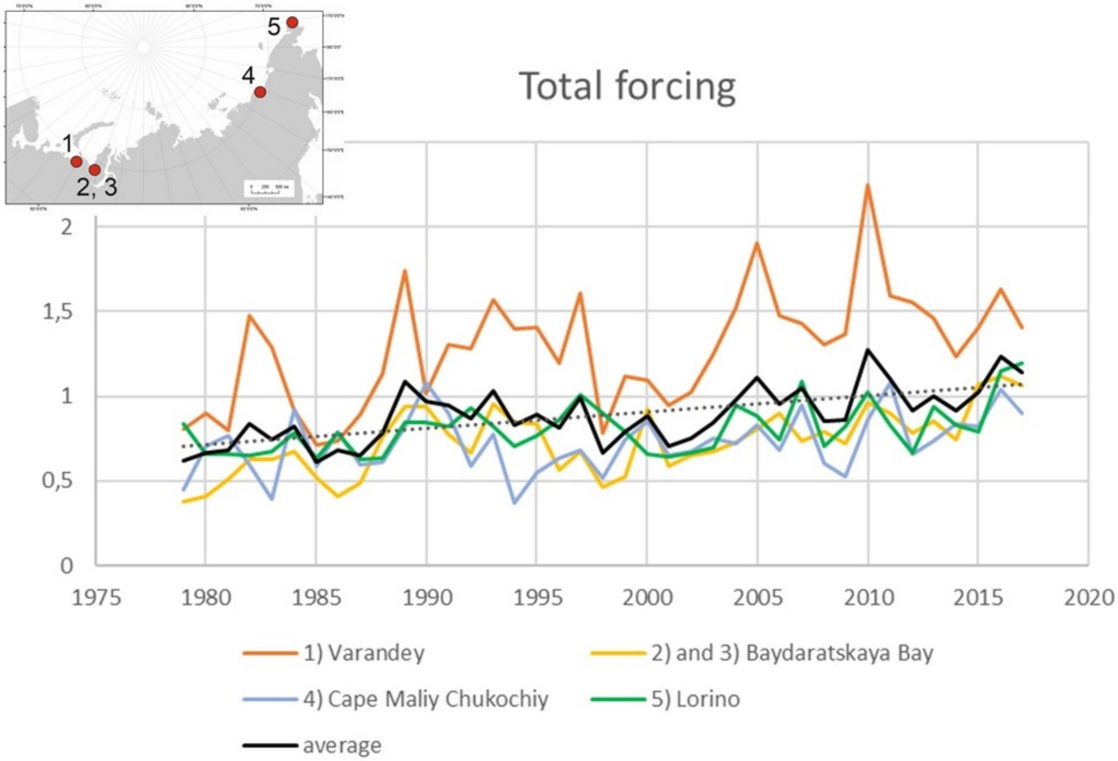
There has been an increase in the wave energy potential at all key areas in the last decades. The highest values are typical for Varandey, where the ice-free period is the longest. The lowest values were observed at Lorino, despite its relatively long ice-free period compared to the other sit in the eastern Russian Arctic, Cape Maliy Chukochiy. One of the explanations is that Lorino faces to the east, and has a relatively short wave fetch; besides, the prevailing westerly winds are directed seawards and do not generate waves affecting this coast.

THE TOTAL HYDROMETEOROLOGICAL FORCING OF COASTAL EROSION

To estimate the total hydrometeorological forcing of coastal dynamics, depending on both the thermal and wave energy factors, the values for the air thawing index *(I_t)* and wind-wave energy *(WE)* were normalised by their standard deviations, and the total effect was calculated as their sum according to (Shabanova et al., 2018):

$$TE = WE_t + It_t.$$

Varandey area experiences the highest forcing, because of high values of both the air thawing index and the wave energy potential. It has considerable fluctuations; because of that, coastal erosion at Varandey occurs in shifts: very high rates during extreme storms and particularly warm years, followed by several years of little or no coastal erosion. An example of it can be year 2010, when the coastline moved landwards by up to 20 m (Sinitsyn et al., 2020), after which erosion rates did not excced 0.5 m/yr for several years.

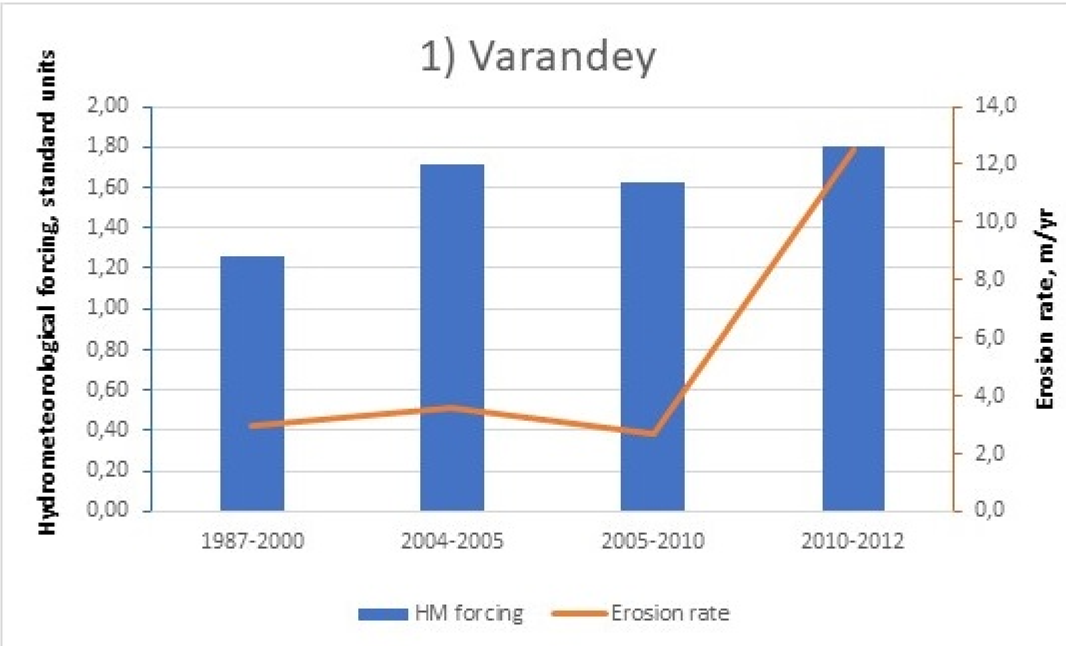


The other three key areas have similar values of TE: Lorino has higher air thawing index but lower wave energy, compared to Baydaratskaya Bay and Cape Maliy Chukochiy, making their total effect comparable to these sites. On the graphs, periods of relatively high forcing for those three key areas can be selected: 1988-1991, 2005-2007 and 2015-2017. Extremes for Varandey do not coincide with the rest of the key areas.
Generally, the total hydrometeorological forcing on the Russian Arctic coasts has increased since the 1980s, approving the assumption that changing climate leads to higher impact on the Arctic coasts.

CORRELATION WITH EROSION RATES

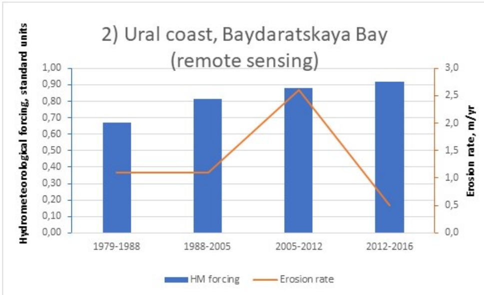
To check whether there changes in the hydrometeorological forcing are reflected in rates of coastal erosion at key areas, average values of the total hydrometeorological forcing for the time periods coincinding with observation on coastal erosion rates. The vaues were then compared.

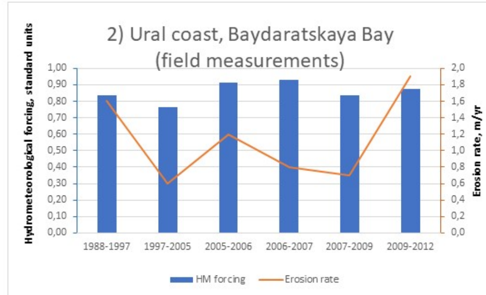
1) Varandey

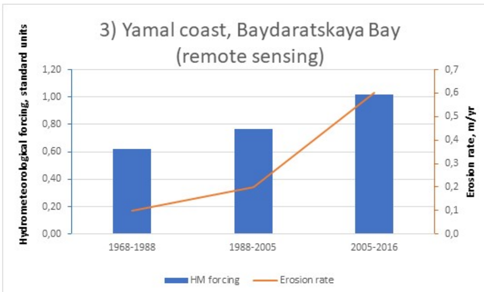


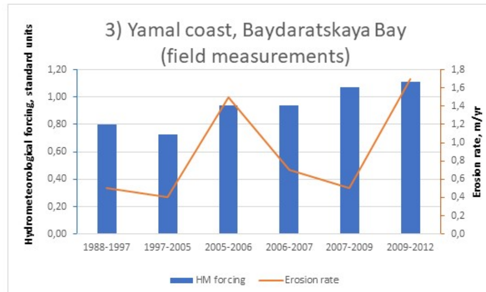
At Varandey, a link between the hydrometeorological forcing and the erosion rates is seen in the trends of the graphs. They both have maximums in 2004-2005 and 2010-2012. At the same time, the hydrometeorological forcing in 2010-2012 shows a relatively small increase, while erosion rates rise dramatically. This effect results from the previously mentioned short extreme storm surge in 2010, when most of the erosion happened, and much of the lowlands was flooded. Besides the weather and climatic reasons for such an extreme erosion event, some of the impact resulted from human activity: much of the dune belt was destroyed during sand excavation for construction on the settlement and oil terminal infrastructure. The dune belt previously had a barrier function and did not allow surges to penetrate inland.

2) and 3) Baydaratskaya Bay



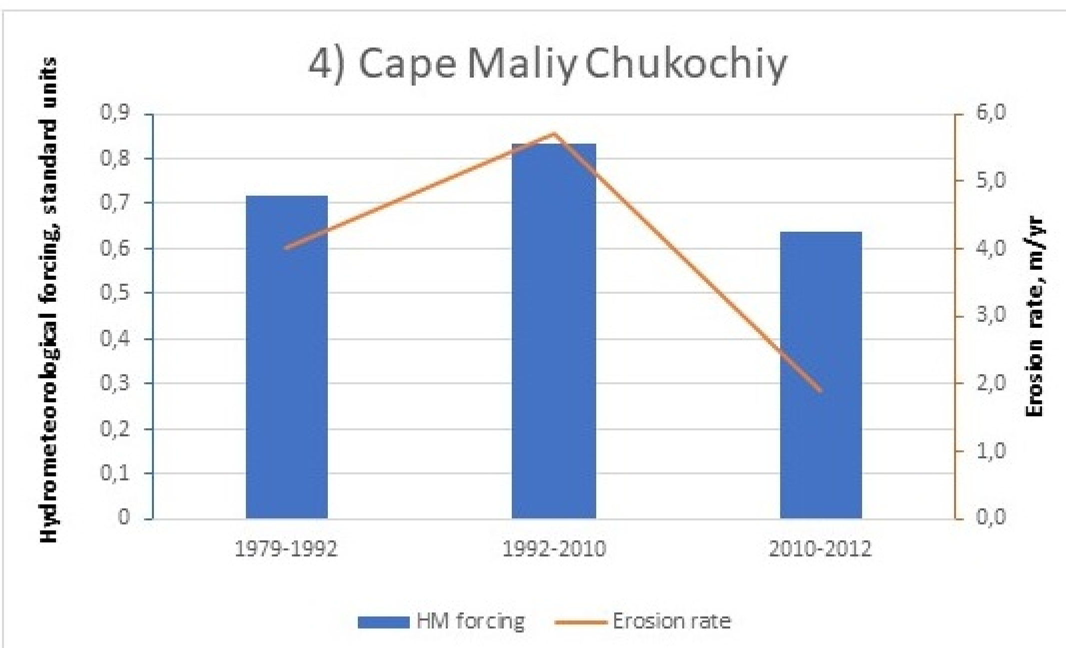






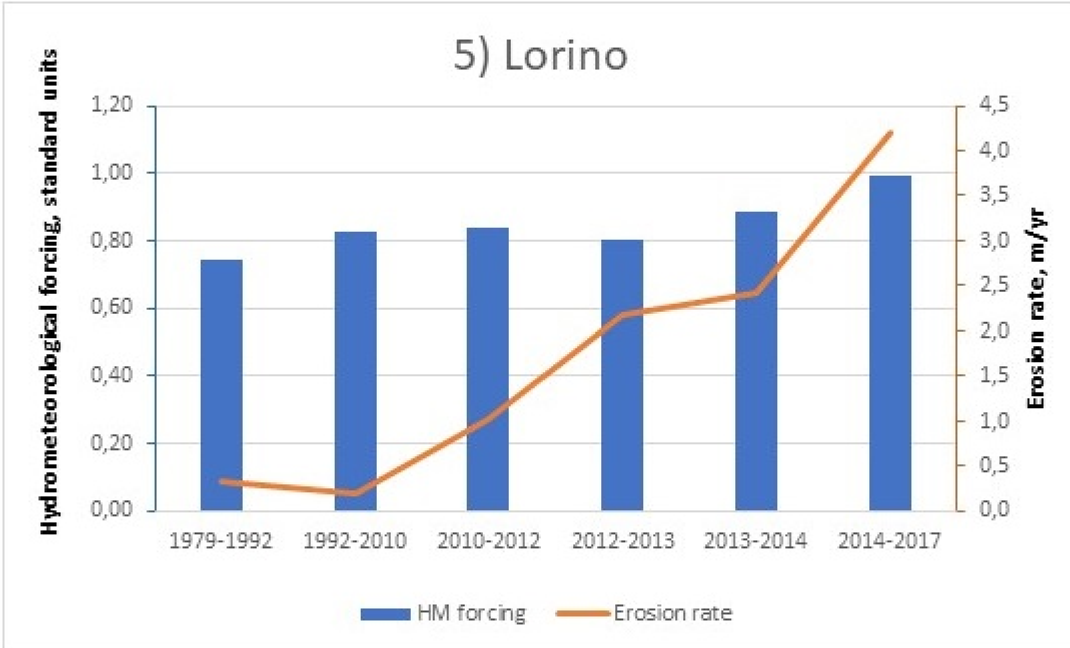
On the Ural and Yamal coasts of the Baydaratskaya Bay, relatively good correlation is seen in results both of field measurements along benchmark profiles and remotely sensed data interpretation. The two peaks of increased hydrometeorological forcing in 2005-2006 and 2009-2012 correspond to peak erosion rates. The peak of 2005-2006 is caused by climate factors only, while the other peak coincides with both the increased forcing and the construction of the underwater crossing of the pipeline "Bovananenkovo-Ukhta" built across Baydaratskaya Bay in 2009-2012. After its finish in 2013, the hydrometeorological impact remained high, but the erosion rates on the Ural coast became lower, according to the analysis of satellite imagery.

4) Cape Maliy Chukochiy



At Cape Maliy Chukochiy, where relatively long time periods of erosion rate observations are available, there is good correlation between erosion rates and the hydrometeorological forcing: the values of both parameters rose from 1979-1992 to 1992-2010 and then became lower in 2010-2012.

5) Lorino



At Lorino, both of the parameters experience an increase with fluctuations. The exact timing of there fluctuations does not fit for both parameters as precisely as for other sites. This partly results from the short time periods between observations: starting from 2010, observations were made every 2-3 years (Maslakov, 2019).

Analysis of all the key areas has shown significant agreement of the temporal variations in the hydrometeorological forcing and the rates of coastal erosion. The best agreement was obtained for areas with relatively long observational periods, mainly derived from remote sensing analysis. This implies that trends in the climate change have an influence on coastal erosion rate long-term trends, while short-term events can be influenced by the geomorphological and permafrost inconformity of the retreating coastal bluffs, human-induced disturbances and other local factors

DISCLOSURES

Studies on the variability of climate parameters were funded by the RFBR grant 18-05-60300 (S.Ogorodov, N. Shabanova). Studies on rates of coastal erosion were funded by the RSF grant 16-17-00034 (A.Baranskaya, A. Novikova). B.Jones was supported by US National Science Foundation award OISE- 1927553.

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