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Permafrost Coasts of Pechora and Kara Seas in Transition: Environmental Forcing Change

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ABSTRACT

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Two-thirds of the coastline along the Pechora and Kara Seas consists of ice-rich permafrost deposits. The dynamic of these coasts is forced mainly by the change of natural environment induced by the global warming. Environmental forcing changes in key areas along these coastlines have been calculated and analyzed. Across all considered sites, the sum of positive air temperatures has increased statistically significant for the period 1979-2021, with a trend of 7-28°C·day/year. Wind-wave energy potential for the destruction of thermal-abrasion shores also increased statistically substantially at all high-sea sites, ranging from 20-50% over 40 years. Rising temperatures are reshaping the Arctic coastline, with even greater changes anticipated in this century due to diminished sea ice and thawing permafrost. Reduced sea ice coverage leads to more open water, facilitating stronger wave generation by winds and thereby intensifying wave-induced erosion along the coasts of Pechora and Kara Seas. Analysis of multitemporal aerial and space images, along with field observations has revealed a significant increase in erosion rates of coasts featuring bluffs composed of ice-rich sediments, about 1.3-1.5 times higher, as well as the onset of erosion of many accumulative marsh coasts that had previously remained stable throughout the 20 century.

ADDITIONAL INDEX WORDS: *Arctic, permafrost, climate change, coastal dynamics.*

INTRODUCTION

Two-thirds of the coastline along the Pechora and Kara Seas consists of ice-rich permafrost deposits that are weakly resistant to thermomechanical effects. Sea ice conditions play an important role in coastal dynamics in the circumpolar Arctic, as shown in studies by Overeem *et al*. (2011) and Ogorodov *et al*. (2016). Most of the erosion of the coastline occurs during the relatively short ice-free period. The rapid reduction of sea ice in the Arctic in the 21st century, as reported by Cavalieri and Parkinson (2012), Stroeve *et al*. (2012) and Onarheim *et al*. (2018), has led to an increase in the duration of this ice-free period in Arctic Ocean waters (Peng *et al*., 2018; Sochnev *et al*., 2019; Bliss *et al*., 2019). The increase in the duration of the ice-free period in the coastal zone intensified thermoabrasion processes, leading to faster changes in the shoreline position (Irrgang *et al*., 2022). Moreover, the reduction in the area of sea ice cause an increase in wave height (Stopa *et al*., 2016). There is a clear spatial (regional) and temporal (interannual) variability in wave activity and wind speed (Surkova *et al*., 2015). The reduction in sea ice cover and the extension of the ice-free period (Shabanov *et al*., 2024) occur against the backdrop of a rapid rise in air temperature in the Arctic, known as Polar Amplification.

Under the conditions of modern climate changes in the Arctic (Overland *et al*., 2019), which are well-aligned with global changes (Savo *et al*., 2016) and growing climate trends for the Northern Hemisphere (Serreze *et al*., 2009), the listed processes lead to an increase in the rates of thermodenudation and mechanical abrasion independently (Kazhukalo et al., 2023). The impact of thermal and wave energy factors on the dynamics of permafrost coasts is becoming increasingly significant (Baranskaya *et al*., 2020, 2021). Higher air and sea temperatures, along with a possible increase in precipitation, are leading to more intense thawing of frozen soil. At the same time, the increase in the frequency of storm winds, the lengthening of the ice-free period, and the rise in sea level are increasing wave impact on the shores. Collectively, changes in hydrometeorological conditions create unusual circumstances that require study and adaptation for successful and sustainable development in the Arctic Ogorodov et al. (2023).

METHODS and DATA

The study of environmental forcing changes in the Pechora and Kara Seas was conducted for 22 key site (Figure 1), where

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coastal observations are carried out, and active resources development is conducted. For each site, annual characteristics of the ice-free period duration, air thawing index, wind-wave effect and total hydrometeorological effect for the period 1979-2021 were calculated.

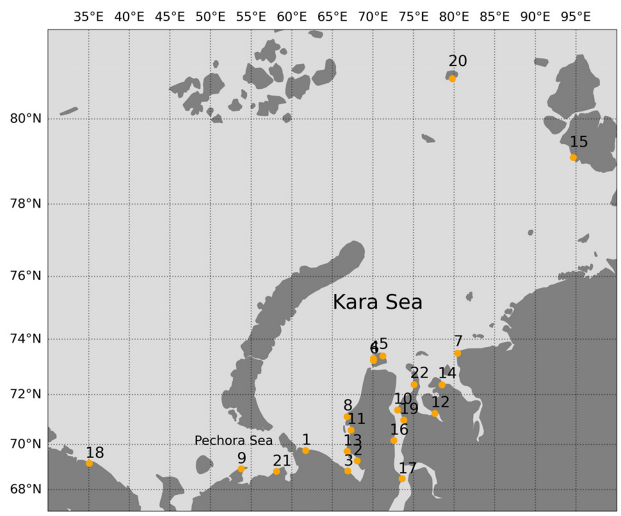

Figure 1. Study area. Numbers indicate locations of geographical objects or in situ measurements at stationary polar sites: 1—Amderma, 2—Baybay east, 3—Baybay west, 4—Beliy, 5—Beliy east, 6—Beliy west,7—Dikson, 8—Harasavey, 9—Hodovaricha, 10—Horansalya, 11—Kruzenshtern, 12—Mamont, 13—Marresalya, 14—Mongocheyacha, 15—Severnaya Zemlya, 16—Seiacha, 17—Snow Yar, 18—Teriberka, 19—Terminal Utro, 20—Ushakov Island, 21—Varandey, 22—Yavay.

To assess the impact of the thermal component, the air thawing index was calculated based on the ERA-5 reanalysis data (Hersbach *et al*., 2020) of air temperature. The air thawing index is the accumulated annual sums of positive daily mean air temperatures, measured in degree-days (Andersland and Ladanyi, 2004).

The observed changes in ice conditions in the seas were investigated using the ice-free period, the duration and limits of which were obtained from satellite data of sea ice concentration from the US National Snow and Ice Data Center (NSIDC), Climate Data Records array, ID: G02202, Version 4 (Meier *et al*., 2021). The ice-free period was identified using the threshold 15% method and a modified threshold method adapted for coastal zone data of the Russian Arctic seas (Shabanov, 2022; Shabanov and Shabanova, 2020).

To assess the wind-wave energy impact on the shores, the Popov–Sovershaev method was used (Popov and Sovershaev, 1982). According to their formula, the wind-wave energy flux is equal to the product of the third power of the wind speed of the wave-dangerous direction, the wave fetch along this direction, taking into account the frequency of wind of a given speed and direction within the ice-free period.

The obtained values accumulate for all storm wind speeds (starting from 6 m/s) and wave-dangerous directions:

$$E = \sum_{j=1}^{M} \sum_{i=1}^{N} E_{i,j} \qquad (1)$$

where

$$E_{i,j} = 3 \cdot 10^{-6} \cdot V_{i,j}^{3} \cdot x_j \cdot p_{i,j} \cdot n \qquad (2)$$

Here, $V_{i,j}$ is the wind speed at a height of 10 m above sea level (m/s) of a given level (more than 6 m/s, by index i from 1 to N gradations with a step of 1 m/s) and direction (by j from 1 to M of wave–dangerous directions in a step of 22.5°), $p_{i,j}$ is the frequency of this wind (of the given speed and direction) during the ice–free period; x_j is the corresponding actual or maximum fetch (km) along the given direction j, n is the duration of the ice–free period (in seconds). In later publications (Shabanova et al., 2018), it was proposed to call this accumulated scalar quantity wind-wave energy potential.

The speed and direction of the surface wind at a 10 m height were obtained from ERA-5 reanalysis data (Hersbach *et al*., 2020).

To assess the combined effect of thermal and wave-energy factors, the total hydrometeorological potential of thermoabrasion was calculated. The methodology described in the work (Shabanova *et al*., 2018) was used. Annual anomalies (deviations from the long-term mean) of the air thawing index and wind-wave potential were normalized to the regional average. The series of the air thawing index are normalized to 500 degree-days, and the series of wind-wave potential are normalized by 500,000 tons/year. The resulting dimensionless series were summed for each coastal site.

The observed changes in hydrometeorological characteristics were estimated using linear trends for 1979-2021 period. Linear trends were estimated by the least-squares best fit and tested with the original two-tailed t-test for the null hypothesis of no trend against the alternative of a trend significant at the 5% level or less.

RESULTS and DISCUSSION

For the study of environmental forcing changes based on NSIDC satellite data and ERA-5 reanalysis data, annual values of ice-free period duration, air thawing index, wind-wave potential and total hydrometeorological potential were calculated for 22 sites (Figure 1) for the period 1979-2021. Based on the obtained time series, an analysis of the spatial-temporal features of environmental forcing changes for the Pechora and Kara Seas was conducted.

Thermal Potential, Thawing Index

The average long-term values of the air thawing index in the studied sites range from 375 to 1340℃-days. The average value for 22 sites is 580℃-days. Accumulated positive average daily temperatures during the period 1979-2021 show statistically significant trends of increase with a slight slowdown in the rise in 1995-2002 (Figure 2, 3). Trends range from 62 to 162°C days /decade. On average, for 22 sites, the trend is 105°C days/decade. This corresponds to 7-28%/decade or 19%/decade for the averaged trend relative to the long-term mean value for 1979-2021. All these trends are statistically significant at a significance level of 0.01.

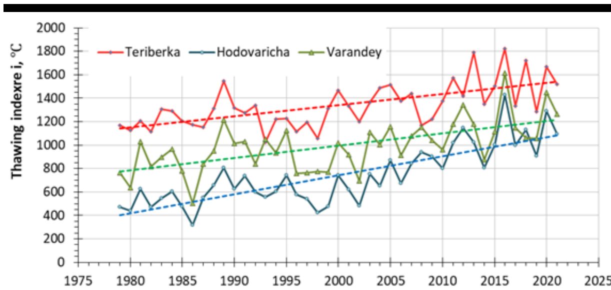

Figure 2. Air thawing index change according to ERA-5 dataset at key sites in the Pechora Sea.

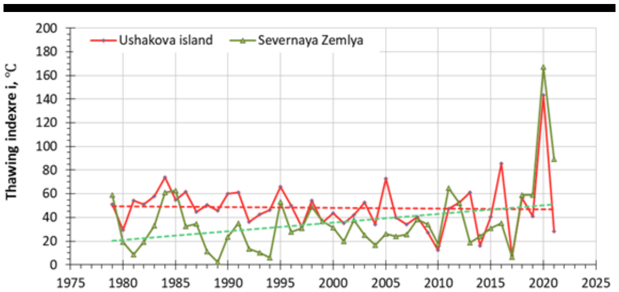

Figure 3. Air thawing index change according to ERA-5 dataset at the northern sites in the Kara Sea.

The increase in the air thawing index is due to both the extension of the warm period (the period with positive average daily surface air temperatures) and the increase in the intensity of warming (warm days become warmer). Thus, the warm period in all sites increased by 3.5–6.5 days (on average by 5 days). On Severnaya Zemlya it increased by 15 days, on Ushakov Island the changes are statistically insignificant. The average temperature of a warm day (a day with a positive average daily temperature) increased by 2.4°C (~50%) during the period from 1979 to 2021: from 3.4 to 5.8°C. Notably, this characteristic remained stable with an average value of 4°C until 2007. Since 2008, years have appeared when the average warm day was significantly warmer than usual. The long-term average annual mean for the last 14 years has become 1.5°C higher than in the previous period, reaching 5.5°C (Figure 4).

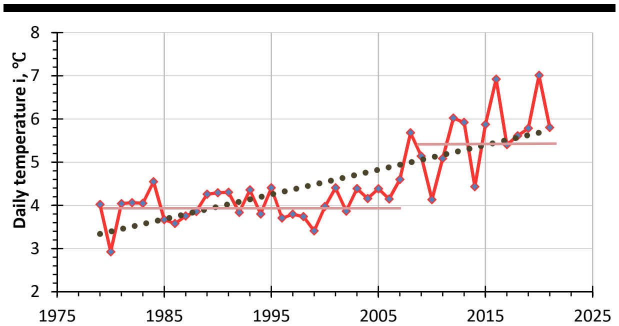

Figure 4. Warm day daily temperature change according to ERA-5, averaged over 22 sites in the Pechora and Kara seas.

Ice-Free Period Changes

The air temperature is closely related to sea ice conditions and, importantly for coastal dynamics in the Arctic, to the ice-free period. The duration of the ice-free period increased for all the studied sites at a rate of 7-25 days/decade (7-19%/decade relative to the average long-term duration for the 1979-2021 period). Taking into account the fact that the standard deviation of the time series is 17-45 days, over last 40 years the increment of ice-free period duration is near 2-2.5 standard deviations.

Sea ice conditions are diverse in the Pechora and the Kara seas. Near Teriberka there is no seasonal sea ice cover, while for 1979-2007 period near Severnaya Zemlya the ice-free period was observed only 8 times. Since 2008, the waters there have been free of ice every year.

The most noticeable fluctuations of the ice-free period in the open sea coasts and bays occur together: the key minima and maxima of both graphs occur in the same year (Figure 5). In the bays, the increase in the duration of the ice-free period is on average twice as slow as in the open sea coasts: the average trend coefficient here is 10 days/decade, and in the open sea – 19 days/decade.

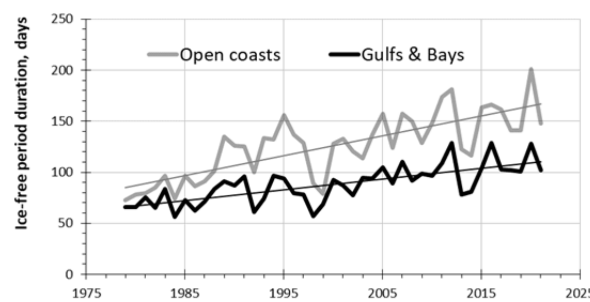

Figure 5. Ice-free period change according NSIDC data, averaged for grouped open sea coasts sites and gulfs & bays sites.

Wind-Wave Energy Potential

An analysis of the long-term variability of the wind-wave energy potential (WE) of coastal dynamics showed its noticeable and statistically significant growth in all the studied sites. This increase is primarily due to an increase in the duration of the ice-free period considered at the previous stage of research.

On average, the average amount of incoming wind-wave energy in the studied areas is 600 kilo tons/year (from 120 kilo tons/year up to 2200 kilo tons /year). By the end of the 1979-2021 period, WE increased by 700 kilo tons (Figure 6).

At the same time, the wind-wave energy potential is characterized by significant interannual variability: the average standard deviation is 265 thousand tons /year, that is, 50% of the long-term average. The increment over the studied period for an average of 22 sites is 140% of the time series.

Bays and gulfs are characterized by average values of wind-wave energy potential of 100-200 kilo tons/year. The average increment over 40 years was 110 kilo tons, that is, 50-100% of the average value. Thus, in the open sea areas of the coast, there is a faster increase in wind-wave effects than in gulfs and bays, and in the Pechora Sea – faster than in the Kara Sea.

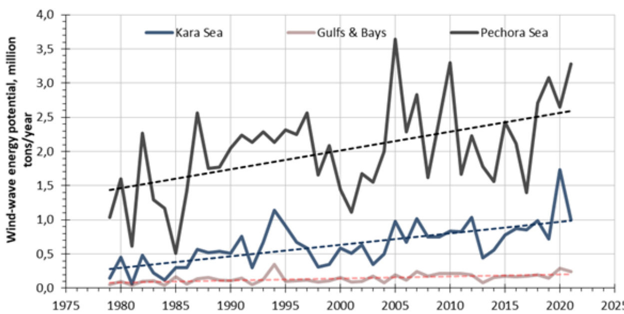

Figure 6. Wind-wave energy potential change averaged for grouped for gulfs & bays sites, the Pechora Sea and the Kara Sea sites.

Total Hydrometeorological Potential and Environmental Effect Change.

The analysis of the long-term variability shows a significant increase in the total hydrometeorological potential (TE) over the studied period (Figure 7, 8), which averages 215% of the time series.

The sites of Varandey and Hodovarikha have the greatest TE impact (Figure 7). The remaining sites are characterized by a comparable level of TE impact and a trend: directed growth after 2005, a short minimum in 1995-2003. Notably, since 2007, the value of TE for many of the studied sites has never dropped to the average level of the previous period 1979 – 2006, and sometimes does not reach the maximum values for those years. Ushakov Island and Severnaya Zemlya can be studied using the described method of estimating the total TE impact on the shores only conditionally. The level of the thermal factor here is much lower than in other regions (as considered in the previous stage: 20 – 140 degree days versus 200 - 1400 in other areas), resulting in very low TE values (near -30 and -20 on the scale of Figure 7).

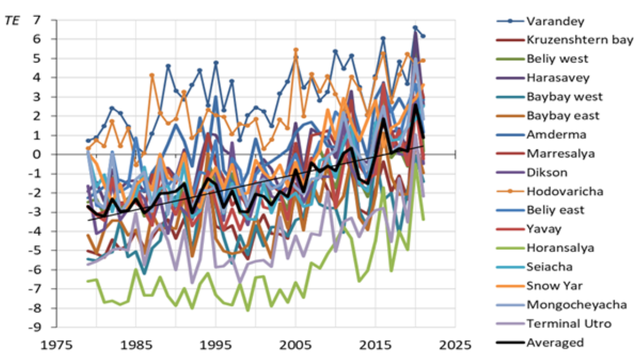

Figure 7. Normalized anomalies of total hydrometeorological potential (TE) change for sites in the Pechora Sea and the Kara Sea. Black line – averaged values.

The results indicate that the shores of the northern islands have been experiencing hydrometeorological stress annually since 2007 and this stress has been significantly increasing from year to year. In 2012, 2016 and 2020, the air thawing index values approached the mainland values (140-170°C days in 2020), so significant changes in coastal systems can be expected in the area.

The positive wind-wave anomalies generalized for all the considered sites in 2012, 2016 and 2020 are accompanied by high temperature anomalies (Figure 8). At the same time, temperature anomalies turn out to be twice as high as anomalies of mechanical (wind-wave) action, which may mean that the thermal factor is growing faster than wind-wave, which may indicate that the thermal factor is growing faster than wind-wave factor, which may affect coastal dynamics.

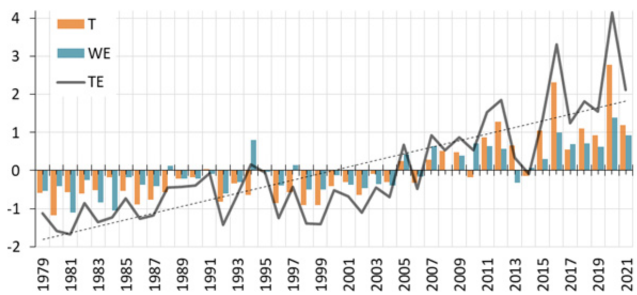

Figure 8. Anomalies relative long-term mean for 1979-2021 period Wind-wave energy potential (WE), Thermal effect (T) and Total hydrometeorological effect (TE), averaged for 22 sites in the Pechora and the Kara seas.

CONCLUSIONS

The calculated time series of wind-wave energy and thermal potentials of the dynamics of the Pechora Sea and Kara Sec shores, as well as the ice-free period duration for 1979-2021 period were analyzed and compared. We found positive statistically significant trends in all observed hydrometeorological parameters. The extension of the ice-free period, the rise of the air thawing index, and the increase in the wind-wave activity present new risks and challenges for economic activity and sustainable development in the permafrost coastal zone.

Based on the analysis of wind-wave characteristics, three groups of sites were identified according to the level of wind-wave impact: gulfs and bays, northern territories and open coasts. The highest rate of change is observed on coasts open to the sea, while the lowest in bays and bays. In these areas, ice melts in fresh waters later in spring and freezes in autumn earlier than in open salty waters, thereby restraining the rate of change. The TE impact on Arctic shores increases statistically significantly due to all components: the annual sum of positive daily average temperatures increases, and more wind-wave energy transferred to the shore. The increase in the wind-wave energy component is primarily due to the longer ice-free period. Rapid warming and subsequent thermal degradation supply so much material to the beach that it cannot be processed by waves, despite the extended ice-free period and increased incoming wind-wave energy.

The obtained estimates of environmental forcing change enhance the regional climate description in the key sites of the Pechora and Kara seas in Transition.

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