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HYDROMETEOROLOGICAL FORCING OF WESTERN RUSSIAN ARCTIC COASTAL DYNAMICS: XX-CENTURY HISTORY AND CURRENT STATE

ABSTRACT. The Arctic coasts in permafrost regions are currently quickly retreating, being extremely vulnerable to the ongoing environmental changes. While the spatial variability of their retreat rates is determined by local geomorphological and cryolithological aspects, their temporal evolution is governed mainly by hydrometeorological factors, namely, wave action coupled to thermoabrasion (thermodenudation), are active during ice-free period. We define the combined wave and thermal action as "hydrometeorological stress", and analyze its components and evolution, confirming it by known natural and remote sensing observations of coastal retreat rates. We estimated changes in the main hydrometeorological factors in the XX and XXI centuries for several sites on the coasts of the Kara and Barents Seas basing on observation and ERA reanalysis data. The term of hydrometeorological forcing is intended as an increment of the hydrometeorological stress, occurring because of changes of the hydrometeorological factors. Our results show that the current thermodenudation forcing amounts 15-50% of the 1979-1988 mean level and thermoabrasion forcing is equal to 35-130%. We detected 1989 (1993) – 1997 and 2005 – 2013 as periods of extreme hydrometeorological stress, as far as both thermodenudation and thermoabrasion were in a positive phase. It was also revealed that the hydrometeorological stress of the recent 10 years was apparently unprecedentedly high at the Barents-Kara region: the previous Arctic warming of the 1930-40s caused high thermoabrasion rates due to longer ice-free period despite cold summer temperatures, while, the latest ongoing warming shows previously unseen simultaneous increase in both thermodenudation and thermoabrasion.

KEY WORDS: western Russian Arctic, climate change, hydrometeorological factors, hydrometeorological stress, hydrometeorological forcing, coastal dynamics

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INTRODUCTION

At the beginning of the century, awareness has risen that changes in coastal systems are forced by large-scale processes and act over relatively long (decadal) timescales (Hanson et al. 2003). The persisting climate change allowed to trace changes in coastal dynamics caused by evolving hydrometeorological conditions. Such changes were described at arctic coasts with permafrost (Grigoriev et al. 2006, Günter et al. 2015, Jones et al. 2009, Rachold et al. 2005, Vasiliev et al. 2011, Ogorodov et al. 2016) and others summarized in (Lantuit et al. 2013) and tropical coasts (e.g., Livingston, 2014). One of the most intriguing topics is the behavior of Arctic coasts, as in most cases they are composed by continuous permafrost and contain ground ice; therefore, they may dramatically react to temperature growth. Indeed, in the last 15-20 years, increase of coastal retreat rates relatively to previous average values have been recorded in different Arctic regions (Günter et al. 2015, Jones et al. 2009, Vasiliev et al. 2011, Grigoriev et al. 2006, Vergun et al. 2013). Such increase might have been caused by the latest warming, more precisely, by the latest climate change, as not only temperature has been growing, but the whole land-ocean-atmosphere system has been changing, including winds and sea ice conditions, which, in their turn, influence sea coasts. Still, tracing the hydrometeorological effect on Arctic coastal dynamics is a difficult task, as studies of coastal dynamics are subject to several major challenges.

Challenges in studies of coastal dynamics: lack of observation data

The coasts of Russian Arctic (contrarily to the European Arctic and most part of the Canadian and US Arctic) are remote and difficult to access. They are rarely visited, the main purpose being oil and gas infrastructure construction and operation. Research activity in field is usually limited to short time periods. Fieldwork timeframes are determined by engineering and production requirements and are difficult to adjust to scientific tasks. Therefore, coastal dynamics observations are irregular both spatially and temporally: coasts are observed in different months (not at the end of ice-free period, as preferable), sometimes not every year, with varying methods which are hard to compare. There is in fact no regular network for coastal observations, as polar hydrometeorological stations are not authorized to conduct coastal retreat rate measurements. Hydrometeorological data produced by these stations is hard to process for several reasons. Firstly, the network of stations is extremely scarce, the resolution ranging from 100 to 500 km. Secondly, the network of stations with long-term observations (not less than about 30 years, Fig. 1) is even more scarce. Thirdly, there are lots of temporal gaps due to a variety of reasons, referred both to data operation problems and periods with no observations, caused, in turn, by both economical and natural reasons (insufficient funding, understaff, fires and severe weather conditions). Finally, some of the data (like ice and sea level data) are of hard access, as they are of special usage according to regulations of the Russian Federation. The only way to obtain reliable and complete characterization of hydrometeorological conditions is to use modelling data, like reanalyzes.

In coastal retreat rate studies, satellite imagery provides both good spatial and temporal coverage, however, it also faces several issues: 1) old-data imagery are of low resolution (7-10 m) and do not allow to detect the coastline with sufficient accuracy; 2) there is a problem in detecting the coastline itself (the position of the cliff edge, usually designated as the coastline, can in many cases be hard to recognize); 3) unfavorable weather conditions like sea ice and clouds make interpretation impossible.

In situ sediment transport measurements (like, for example, acoustic backscatter measurements of suspended sediment transport) are not used in the Russian Arctic. Estimations of changes in the coastal dynamics are usually based on measuring the position of the cliff edge in field at numerous cross-sections referenced to the State geodetic network or using remote sensing data. Coastal retreat rates depend greatly on local geocryological, (ice content, presence of ice bodies), lithological (grain size, texture) geomorphological (height of the coastal bluff, etc.) conditions. At different sections they vary by the scales of 1-10 m. Therefore, it is challenging to combine annual in situ measurements with estimations of coastal dynamics on a long-term scale. As reported in (Aagard et al. 2004): «A significant problem in current coastal research is the understanding of linkages between morphological phenomena occurring on different temporal and spatial scales. Morphodynamic processes in the nearshore typically exhibit nonlinear behavior and consequently, phenomena which occur on short temporal (event) scales as, e.g. observed during field experiments have generally been difficult to upscale to provide an understanding of the long-term behavior of the coast on the time scale of seasons or decades».

Considering difficulties in direct observations of coastal destruction, one of the promising approaches is assessing not the retreat rates themselves, but the driving climatic factors of coastal dynamics. Such factors are easier to characterize, as data on hydrometeorological conditions can be obtained for much longer time periods and larger spatial extent, as they don't depend on high-resolution imagery availability and fieldwork measurements. In the present study, we aim to characterize and estimate the climatic-induced potential of coastal dynamics, determined as the quantitative expression of hydrometeorological impact on coasts. The mentioned potential varies from year to year and the coasts may experience it completely or not depending on their inner factors (grain texture, ice content, etc.). In this way, research of coastal dynamics obtains a way forward through estimation of its factors and their variability.

Hydrometeorological factors of the Arctic coastal dynamics

Coastal dynamics of the Russian Arctic are determined by two related processes. Ground ice in permafrost melts due to heat energy coming to the cliff from warm air and sea water. This process is called thermodenudation. After the sediments melt, they are removed by direct wave action, which is called abrasion. The interaction of these two processes, when permafrost simultaneously thaws and is carried away by waves is called thermoabrasion, being the main mechanism of destruction for most of the retreating coasts in the cryolithozone. The intensity of thermoabrasion therefore depends on two main hydrometeorological parameters: temperature and wind-wave energy.

The thermal factor regulates the amount of heat, due to which permafrost exposed in the coastal cliffs, melts. It generally depends on air and water temperature, and the number of days with positive temperature, during which the processes of thawing are active.

The wind-wave energy, determining the intensity of mechanical abrasion, depends on a greater number of environmental conditions. Because most waves in the Russian Arctic seas are wind-generated, wind conditions play a crucial role in the wave energy flux formation. Wind speed, wind direction and frequency are therefore important parameters. It has been shown, for instance, that storms provide the largest contribution to the total amount of wind-wave energy (Popov, Sovershaev, 1982). Because during most of the year the Arctic seas are covered by ice, waves can execute their mechanical action only in the relatively short ice-free period. Consequently, the yearly wave energy flux providing abrasion is determined by the ice-free period duration. In its turn, the ice-free period duration depends on the Arctic sea ice cover conditions, likely related to global temperature and local (regional) weather conditions (wind directions and heat transfer). The length of the wave fetch is also important, and it generally also depends on the extent of the ice cover, as, during the summer, distance from the sea ice rim to a certain coastal point can change every day. In this way, Coastal dynamics depends on hydrometeorological processes of different scales, from global to local.

Climate change of the latest decades results in changes of all described conditions: wind, ice and thermal. In the present study, we aim to estimate thermal and wave-energetic impact on coastal retreat rates at several key areas of the Yamal Peninsula characterized by different permafrost and lithologic conditions. By doing this, we will be able to assess the importance of each of the mentioned hydrometeorological factor and quantify their impact on the retreat rates for a better understanding of coastal dynamics and their evolution through time.

Hydrometeorological stress and hydrometeorological forcing

The retreat rate *Rr* of an Arctic thermoabrasional coast composed by permafrost is determined by a combination of hydrometeorological forces, called here hydrometeorological stress or potential *F*:

$$Rr = \gamma F(f_1, f_2, ... f_N) = \gamma F(T, WE(n, p, x), ...) \quad (1)$$

$$[\gamma] = m / J \quad (2)$$

where $f_1, f_2 ... f_N$ are CD (coastal dynamics) hydrometeorological factors, including air temperature *T* , wind-wave energy *WE* depending, in its turn, on the ice-free period duration *n*, wave fetch *x* and shoreward storm frequency *p*. Here, *y* is a parameter of sensitivity. It is equal to 0 for rocky coasts or coasts with no permafrost, and is appositive numeric value for frozen sediments, depending on their ice content (the greater the ice content is – the higher is *y*). For specific local conditions (for example, the areas which contain ice bodies like ice wedges or tabular ground ice), *y* may be extraordinarily high as such types of coasts may dramatically react to HM (hydrometeorological) forcing. Today, quantitative estimation of this sensitivity parameter remains subject to future studies. We use *y* for quantitative description of the different reaction of coastal areas to hydrometeorological forcing, as their behavior shows great spatial variability: in the same year, some coasts retreat significantly when others may stay almost stable.

The hydrometeorological stress (potential) consists of two parts: 1) mechanical part, being the energy, coming to the coast from shoreward waves and called the wind-energetic potential of coastal dynamics, – and 2) thermal part, being the energy transmitted to the coasts from the atmosphere (CD thermal potential).

Hydrometeorological forcing is an increment of the hydrometeorological stress (potential), appearing due to changes of hydrometeorological factors. It can be divided into CD thermal forcing (F_T), caused by changes in temperature conditions, and CD mechanical forcing (F_{WE}), caused by wind-wave energy changes.

In the present study, we introduce the term «coastal dynamics hydrometeorological forcing» on the analogy of the radiative forcing used in climatology and IPCC reports (IPCC, 2001; Myhre et al. 1998). The increment Δf_i in *i* factor of coastal dynamics provokes coastal dynamics ΔF_i hydrometeorological forcing Δf_i, which, in its turn, leads to coastal retreat rate change ΔRr_i, associated with this factor with the specific sensitivity to this factor y_i:

$$\Delta f_i \rightarrow \Delta F_i \rightarrow \Delta Rr_i \quad (3)$$

$$\Delta Rr_i = \gamma_i \Delta F_i \quad (4)$$

$$\Delta Rr = \sum_{I}^{N} \gamma_i \Delta F_i \quad (5)$$

CD hydrometeorological stress, as well as coastal retreat rate, is always positive for coasts composed by permafrost and can be characterized, for example, by its mean value during a certain period of interest. In these terms, hydrometeorological forcing is considered as a deviation of the current HM stress from the mean value, resulting in changing coastal retreat rates.

CD hydrometeorological stress is close to the term of "environmental forcing" used in literature (Forbes, 2011; Günter, 2013 et al.; Lantuit et al, 2013). Still, we use namely the term «hydrometeorological stress» in the present study, attempting, first of all, not to mix it with the term "forcing", widely used in climate change research and, secondly, aiming to emphasize the hydrometeorological aspect of the object under investigation.

RESEARCH AREA

In the present study, we focus on the western and central Russian Arctic coasts. We are continuing and extending previous work done for Pechora Sea coasts (Varandey area) and Western Yamal coasts (Marresalya and Baydaratskaya Bay areas) (Vergun et al. 2013; Ogorodov et al. 2016). To be able to compare measured monitoring data to the results of hydrometeorologic factors' estimations, we mostly took sites with long-term field monitoring data showing natural observations on coastal retreat rates, mostly gathered by the Laboratory of geoecology of the North, MSU since the 1980s until present.

We also expand the research area over the northern part of the Barents-Kara region, adding Frantz-Joseph Land and several Kara Sea islands (Belyi and Vize islands) (Fig. 1).

MATERIALS AND METHODS

Estimation of the thermal potential of thermodenudation

The thermal potential of thermodenudation is estimated by the air thawing and freezing indexes (I_{at} and I_{af} , respectively) showing the number of positive/negative °C·days per year (Andersland and Ladanyi, 2004). A similar parameter called degree days thawing was used in Günter et al. 2015. These indexes are the evaluations of the annual amount of heat added to or extracted from the ground and permafrost during warm and cold periods, respectively. For their calculation, we used both observation and reanalysis data since 1979. It is assumed that I_{at} can be reliably calculated if there are observations for 90% of summer days (June–September). The same applies for winter temperatures: we need not less than 218 (of 243) daily means for January–May and October–December. Several tests with years of complete data (1979–2013) showed that in the case of missing data, the underestimation of the values of I_{at} and I_{af} is approximately equal to the percentage of missing days. This allows

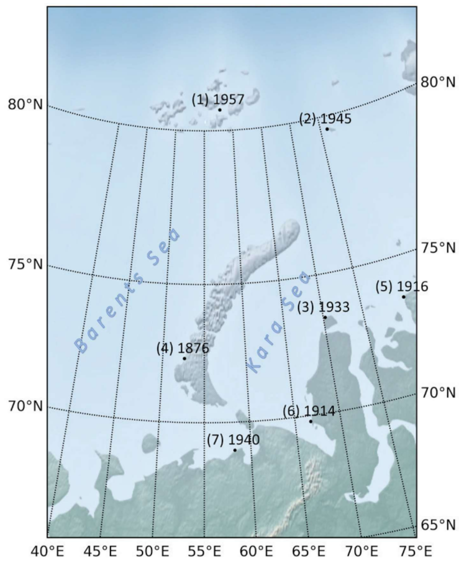

Fig. 1. Research area and hydrometeorological long-term observation stations (the year when observations started indicated in green): (from North to South) 1) Krenkelya Hydrometeorological Observatory (Heiss island); 2) Vize Island; 3) Popova station (Belyi Island); 4) Malyie Karmakuly (Novaya Zemlya arch.); 5) Dikson island; 6) Marresalya (Western Yamal); 7) Varandey (Pechora Sea coast)

us to reconstruct I_{at} and I_{af} for the years with missing data by dividing the accumulated value by the percentage of present daily means.

Along with observational data, ERA Interim (Dee et al. 2011) and ERA 20C reanalyzes (Poli et al. 2016) were used. Reanalysis data were compared to observational data (Table 1). Mean I_{at} differences amount 15-16% (relatively to mean values) for both reanalyzes. I_{af} means differ by 16% for ERA Interim and 27% for ERA 20C. Reanalyzes samples are corrected for these errors. The root mean square error of corrected samples and observational data does not exceed 12% for , and the correlation coefficient amounts 0.87-0.89. The variance of the observational data is by 20-30% higher than for reanalyzes' data.

For I_{af}, the RMSE (root mean square error) is much lower compared to the summer temperatures and amounts 4-5% of the mean value. Correlation between reanalyzes and observations reaches 0.94-0.96. The observation variance is by 8% lower than the variance of the values reproduced by ERA.

Ice-free period duration assessment

Daily sea ice concentration data were analyzed using the 12.5 km resolution product of Norwegian and Danish meteorological Institutes (EUMETSAT, 2014), following the study by Günter et al. 2015, where another 25 km resolution product of NASA was used with application to Buor Khaya Bay. With its help, open water days (OWD), which are equivalent to the ice-free period duration (IFP), were calculated for the period of 1979-2014 (35 years).

All sea ice concentration satellite products are affected by large uncertainties over low sea ice concentrations and open water in coastal zone. Nevertheless, it appeared possible to detect the start and end dates of ice-free period. In the Barents-Kara region, the start of the ice-free period and the freeze-up are usually expressed in abrupt changes on the annual curve of sea ice concentration. These changes can be objectively detected. The ice-free period duration, derived from satellite data by the described method, was compared to observational data for Varandey and Marresalya stations. The accuracy of the method is 12 days on the average (5 days at the beginning of the period and 7 days for the freeze-up). In three of the 35 cases it reached 40-55 days which can be considered as a large uncertainty. Despite that, the interannual variability features and trends are similar for both observational and satellite data. In this way, although the described data and methodology should be used with care for precise detection of the ice-free period duration, it shows good results for revealing long-term trends and general features of the main factors of coastal dynamics evolution.

The assessment of coastal dynamics' wind-wave-energetic potential: Popov-Sovershaev method

The wave energy (WE), tentatively called «wave-energy flux», was calculated according to the Popov–Sovershaev method (Popov and Sovershaev, 1982, Ogorodov, 2002). The method is based on the wave processes theory and applies correlations between wind speed and parameters of wind-induced waves. WE is expressed as the mass of water coming to the coastline per ice-free season (tons/yr). In the Popov–Sovershaev method, the wave energy flux (tons/yr) is proportional to the wind speed (*V*) to the power of three, to the ice-free period duration (*n*), wave fetch (*x*) and frequency of wave-generating winds (*p*).

For deep-water conditions, when the sea floor does not affect wave formation, the wave energy flux per second (for 1 m of wave front) at the outer coastal zone

$$WE = 3\times10^{-6}V^3x \qquad (6)$$

boundary is calculated using the equation: where *V* is the real wind speed of a chosen direction measured by anemometer at 10 m above sea level [m/s], *x* is wave fetch [km] along the current wind direction. The dimension of the coefficient corresponds

Table 1. Comparison of the ERA Interim and 20C reanalyzes' data with observational data for the three stations in the Kara and Barents Seas: means, variances, systematic deviations (SD), RMSE (root mean square error) values of corrected to SD (standard deviation) values and correlation coefficients. A) Air thawing index I_{at} ; B) air freezing index I_{af}

Station	Mean values			SD – systematic deviation		Variance values			RMSE of SD-corrected		Correlation coefficient	
	Obs	Interim	Clim	Int-Obs	Clim-Obs	Obs	Interim	Clim	Int-Obs	Clim-Obs	Int-Obs	Clim-Obs
	mo	mi	mc	mi-mo	mc-mo	do	di	dc	ri	rc	ci	cc
Marre-salya	672	780	577	108	-95	155	136	108	56	76	0.95	0.89
				*0,16**	*0,14**				*0,08**	*0,11**		
Popova	413	329	457	-84	44	104	74	88	59	50	0.82	0.87
				*0,20**	*0,11**				*0,14**	*0,12**		
Varan-dey	874	977	691	102	-183	186	153	139	83	100	0.89	0.84
				*0,12**	*0,21**				*0,10**	*0,12**		
Mean	**653**	**695**	**575**	**42**	**-78**	**148**	**121**	**112**	**66.7**	**75.9**	**0.89**	**0.87**
				0.16*	***0.15****				***0.11****	***0.12****		

** proportion of observation mean value (mo)*

Station	Mean values			SD – systematic deviation		Variance values			RMSE of SD-corrected		Correlation coefficient	
	Obs	Interim	Clim	Int-Obs	Clim-Obs	Obs	Interim	Clim	Int-Obs	Clim-Obs	Int-Obs	Clim-Obs
	mo	mi	mc	mi-mo	mc-mo	do	di	dc	ri	rc	ci	cc
Marre-salya	-3283	-3606	-3951	-323	-667	427	494	467	155	131	0.95	0.96
				*0,10**	*0,20**				*0.05**	*0.04**		
Popova	-3818	-3419	-4305	399	-487	400	397	415	85	166	0.98	0.91
				*0.10**	*0.13**				*0.02**	*0.04**		
Varan-dey	-2605	-3334	-3891	-730	-1286	398	441	441	113	135	0.97	0.95
				*0.28**	*0.49**				*0.04**	*0.05**		
Mean	**-3235**	**-3453**	**-4048**	**-217**	**-813**	**408**	**443**	**441**	**118**	**144**	**0.96**	**0.94**
				0.16*	***0.27****				***0.04****	***0.05****		

** proportion of observation mean value (mo)* to the dimensions of *p/g*, where *w* is density [t/m^3], and *g* is gravitational acceleration [m/s^2]. Thus, *WE* has dimension of tons per second:

$$\frac{t}{m^3} \bullet \frac{s^2}{m} \bullet \frac{m^3}{s^3} \bullet m = \frac{t}{s} \quad (7)$$

For the whole ice-free period, the wave energy flux is equivalent to the water mass coming to the coast expressed in tons.

Wave directions, wave fetches and depths were obtained from digital elevation model ETOPO1 (Amante and Eakins, 2009). The frequency of wave-generating winds was calculated for the time of the ice-free period. For wind data, ERA Interim reanalysis was used. The Popov–Sovershaev method is based on wave processes theory, and applies correlations between wind speed and parameters of wind-induced waves. Wind speeds from 6 m/s and higher were used, as it had been shown in (Popov and Sovershaev, 1982) that the effect of weaker winds (velocities <6 m/s) is negligible for geomorphological coastal studies. The ice-free period duration was determined with the help of satellite imagery data, as shown in 2.2.

Objective periodization: residual-mass curve method

The residual mass curve method was used to detect periods of increased and decreased hydrometeorological stress. The RM-curve method provides the relative intensity of the parameter to its long-term mean value. The RM-curve method is commonly used in hydrology. Modular coefficients are calculated as the relation of current annual value X_i to the long-term mean value :

$$K_i = \frac{X_i}{\bar{X}} \quad (8)$$

The deviation of K_i from one is positive if the current value is higher than the mean value and negative if it is lower than the mean. If K_i are positive for several subsequent years, the accumulating K_i will result in the growth of the sum $\sum_1^i K_i$ (ascending branch of the $\sum_1^i K_i$ curve).

When the period of low values begins, the curve starts to descend. The bend of the curve gives evidence of the end or beginning of the period with high or low values. To compare temperature and wave-energy curves anomalies $(X_i / \bar{X} - 1)$ can be divided by the variation coefficient C_v with the purpose to equalize the scales of fluctuations:

$$X\_N_i = \frac{X_i I \bar{X} - 1}{C_v} = \frac{X_i - \bar{X}}{\delta} \quad (9)$$

where δ is the standard deviation and "N_i" in X_N means "normalized by standard deviation". The RM-curve values are calculated through accumulation:

$$X\_RM_i = \sum_1^i X\_N_i \quad (10)$$

This method has limitations related to the dependence of result on the mean values of the studied parameters. The method is suitable for cyclic processes where the oscillation magnitude is constant during several periods of oscillation. If the oscillation with the outstanding magnitude occurs, the mean value moves much higher/lower than the usual value. In such case, it is harder for the deviation $X_i - \bar{X}$ to reach positive/negative values and the determination of high-value/low-value period becomes difficult. However, the ascending/descending branch of the RM-curve does not occur in this case, the derivative of the curve noticeably changes if there are the up-trend/down-trend values in the original series and the high/low-value period may be detected using the RM-curve derivative analysis.

RESULTS

The retreat of the Arctic coasts in the XX century

In the last years, many reviews of coastal erosion rates in the Arctic appeared (Lantuit et al. 2013, etc.). For comparison with the variability of hydrometeorological parameters, we collected literature data covering long time intervals (Table 2), allowing to divide it into periods, similarly to the large-scale oscillations of the coastal dynamics' hydrometeorological factors.

In the Arctic, coastal retreat rates were increasing and decreasing at different times in different regions. Generally speaking, periods of heightened erosion rates occurred from about 1985 to 1995 and from 2002 to present; low values were noted from about 1995 to 2002. In the recent years, some of the coasts experienced accelerated erosion. The Kara Sea coasts also started retreating faster, as it was noticed during field monitoring and with the help of remote sensing data in the Varandey area (Pechora Sea), and on the coasts of the Baydaratskaya bay, Kara Sea (Ogorodov et al. 2016). In the Kharasavey region, the years 2006-2016 are characterized by 1.5-3 times higher retreat rates compared to 1964-2006 mean (Belova et al. 2017). At Muostakh island (Laptev Sea), the 2010-2012 mean coastal retreat rate reached 4.1±2.0 m/year, which is 2.3 times faster than the historical (1951-2012) mean (Günter et al. 2015).

Both authors notice that the highest acceleration is observed at sites with high ground ice content in the frozen sediments and underline the role of thermodenudation.

It is also remarkable that in the Eastern Siberian Seas the period of 1935-45 was characterized by high retreat rates (Grigoriev et al. 2006). For other Arctic seas, there is little known about this period as observations were not yet conducted on a regular basis back in the 1930s-1940s. We will further suggest an explanation to the increased coastal retreat rates at that time.

Evolution of the hydrometeorological stress in 1979-2015

Thermal stress evolution

The process of thermodenudation is determined by thermal conditions, above all, by summer temperatures, leading to thawing of the permafrost. The XX-century evolution of I_{at} gives evidence that the latest warming of the 1990s-2000s was high, but comparable to previous increases of the 1950-60s and 1920s (Fig.2A). 1922, 1923 and 1924 in sense of I_{at} are still record warm.

An unusual aspect of the current warming is that since the 1980s, both summer and winter temperatures have evolved in-phase, which had never been observed before. The latest warming is often compared to the previous great Arctic warming of 1930-40s which was expressed in the rise of the mean annual temperatures. Some stations' historical maximums are still related to the period of 1940-1945, and the current warming has not still managed to break these records. However, the analysis of the air freezing and air thawing indexes shows that the warming of 1930-40s is provided

Table 2. Coastal erosion rates in different Arctic regions and periods (XX-XXI cent.): literature data

Reference	Region	Method	Erosion rates, m/year (averaged for the indicated periods)				
Jones, 2009	Alaska, Beaufort Sea	Satellite images		1955-79 6.8	1979-2002 8.7		2002-07 13.6
Vasiliev, 2011	Western Yamal, Kara Sea	Direct field observations		1978-81 ~1.2	1988-1992 1.7-3.5	1997-2002 ~1	2006-10 ~2.5
Grigoriev, 2006	Eastern Siberian Seas	Literature sources and others	~1935-45 ~ 6-7	~1955-65 ~3	~1985-1995 ~5-6	The beg. of 2000s ~2	

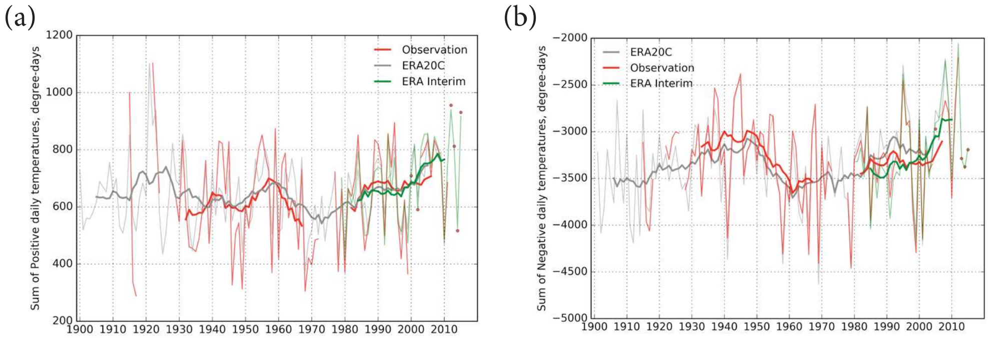

Fig. 2. Air thawing (I_{at})– a – and air freezing (I_{af}) – b – indexes at Marresalya station calculated using observational and reanalyzes' data. Bold lines show 11-year running mean values' evolution

by increased winter temperatures only (Fig. 2B), while summer temperatures were close to low values. Consequently, it is reasonable to expect higher thermodenudation potential to be more likely related to the 1950-60s, rather than to 1930-40 as previously expected.

The current thermodenudation potential is therefore unprecedented as it is provided by both high I_{at}, provoking weaker freezing in winter, and I_{at}, making the ice melt effectively in summer.

Within the latest 35 years, generally characterized by positive trends in I_{af} and I_{at} (on the average 17.3 and 5.7 degree-days per year respectively, see table 3), there were periods of heightened and decreased values of these two parameters. Residual mass curve analyses for 11 stations showed that 1988 – 1994 and 2004 – 2014 may be considered as I_{at} and I_{af} positive-phase, and 1995 – 2003 as a negative phase (Belova et al. 2017, Shabanova, Channellier, 2013).

Ice free period extension

The median value of the ice-free period duration in the Barents-Kara region increased by about 30 days (43% per 35 years) (Fig. 3). Such prolongation occurred, above all, due to earlier ice melt (by about 19 days). This agrees well with the results by (Günter et al. 2015) obtained for the Laptev Sea: the Buor Khaya Bay cleared up by 10 days earlier in 2010-2012 compared to 1992-2012 mean, and freezed up by 5 days later only.

Similarly, to I_{at} and I_{af}, the ice-free period duration evolution has three main features: 1) positive trend; 2) relatively low values in 1996-1999; 3) extremely high values after 2004. It is remarkable that the scatter of IFPD in different locations may reach 160-170 days for the same year; however, scatter disappears when negative and positive phases occur: in 1998-99 and 2009-2010 it was equal to 20 – 55 days. This gives evidence of the large scale of processes leading to the described IFPD evolution.

The most considerable changes of IFPD happened around Franz-Josef Land, where IFPD for some years was close to 10 days and in 2008 – 2013 was consistently higher than 70. For Franz-Joseph Land, the IFPD extension amounts 300-700%. It means that the coasts of these islands, previously almost unexposed to waves, now experience the action of thermoabrasion during at least two months every year. This inevitably leads to activation coastal erosion, marked in the natural observations of the recent years (Romanenko et al. 2015). Some field works were conducted here in 2012-2015. The benchmarks installed in 2012 allowed to reveal for the first time ever the coastal retreat rates for Aldger Island. It amounts to 1.7 m/year. Here the thermoabrasion is of great importance as it threatens lots of historical monuments of the archipelago with extinction or damage, thus impeding the activity of the national park «Russian Arctic».

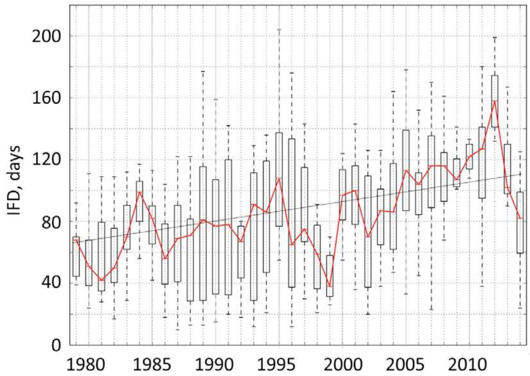

Fig. 3. Ice-free period duration at 11 stations of Barents-Kara region determined using EUMETSAT (EUMETSAT, 2014) satellite data product. "Boxes" show 25 and 75% quantiles, whiskers – the highest and the lowest values. The red line indicates the median evolution, the black line shows the trend of the median value

Marresalya ice observation data, available from 1929, reveal the IFPD maximum corresponding to the warming of 1930-1940s and the positive trend of 1985-2012. The period of 1960-1984 is characterized by a negative phase of IFPD.

Wave energy stress evolution

The wave-energy flux evolution partly follows the IFPD evolution as they are in linear dependence (Fig. 4). The difference occurs due to wave-dangerous wind frequency evolution. It appeared that NW winds frequency fluctuates similarly to I_{at}, reaching a local minimum in 1996 – 2002 and local maximums in 1988 – 1995 and 2003-2013, respectively. This gives the evidence that western coasts experience more intense wave-energy forcing compared to coasts with other orientation. Western coasts are characterized by positive WE trends: Marresalya's WE trend is significant at 0.05 significance level (see Table 3), while other coasts and all-stations-mean trends are positive, but insignificant even at 0.1 level.

In terms of mean values, the WE flux has increased by 70% compared to 1979 – 1988 mean. This increase is less than the within-sample variance, that is why the trend can't be considered significant.

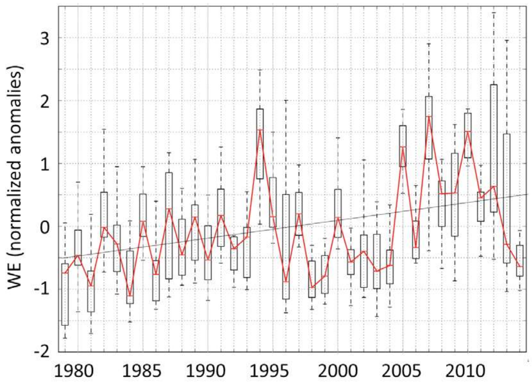

Fig. 4. Wave energy flux evolution at 11 stations of the Barents-Kara region expressed in anomalies divided by standard deviation. "Boxes" show 25 and 75% quantiles, whiskers – the highest and the lowest values. The red line indicates the median evolution, the black line shows the trend of the median value

Total hydrometeorological stress evolution

For the general estimation of the total hydrometeorological stress evolution, both thermoabrasional and thermodenudational potentials were analyzed. They have similar evolution with maximums in 1989 (1993) – 1997 and 2005-2013, respectively. The 1998 – 2004 period is characterized by low values of both potentials. The anomalies of both parameters normalized by standard deviation were summed to calculate total (combined wave-energetic and thermal) stress, equal to the overall hydrometeorological stress of coastal dynamics. Its evolution in 1979 – 2015 and periodization is shown in Figure 5. It has been revealed that up to 2014 the total stress has increased by about 100% if compared to the 1979 – 2014 mean value. Trends' characteristics of both thermodenudation, thermoabrasion and total HM stress are presented in Table 3.

DISCUSSION

During the last 35 years, total hydrometeorological stress has increased by about 100% for Yamal, Pechora Sea and Franz-Josef land regions. At that thermodenudation forcing amounts 15-50% of 1979-1988 mean level and thermoabrasion forcing is equal to 35-130%. The last one, however, cannot be considered significant in terms of statistics.

Table 3. Characteristics of hydrometeorological forces' trends at the Kara and Barents Seas stations based on data from 1979 – 2015. Trends which are significant at 0.01 level are marked by bold italics, at 0.05 level by italics

HM factor	Trend characteristic	Popova	Marresalya	Varandey	Mean
Air thawing index (I_{at})	Trend (°C·days/year)	5.5	4.3	7.3	5.7
	37-year increment (% of 1979 - 1988 mean value)	53	15	36	35
	37-year increment (% of 1979 - 2014 variance)	1.7	1	1.4	1.4
	p-value	0.0016	0.074	0.0116	0.028
Air freezing index (I_{af})	Trend (°C·days/year)	23.9	13.5	13.9	17.1
	37-year increment (% of 1979 - 1988 mean value)	22	26	19	22
	37-year increment (% of 1979 - 2014 variance)	1.7	1.1	1.2	1.33
	p-value	0.0016	0.073	0.031	0.035
Wave energy flux (WE)	Trend (tons/year)	4455	10763	8499	7906
	37-year increment (% of 1979 - 1988 mean value)	37	129	44	70
	37-year increment (% of 1979 - 2014 variance)	0.56	1.4	0.84	0.93
	p-value	0.34	0.014	0.16	0.17

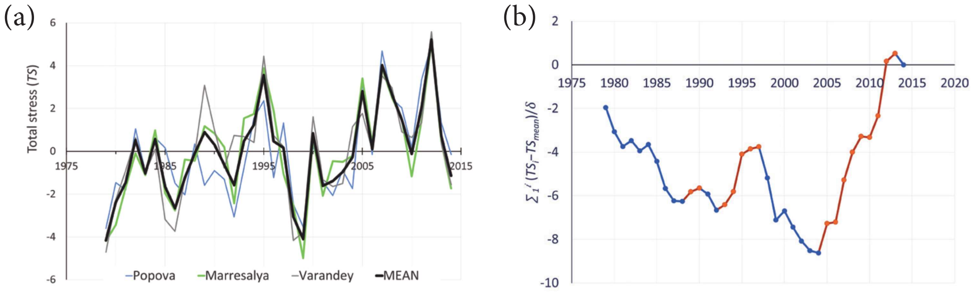

Fig. 5. a) Total hydrometeorological (combined wave energetic and temperature) stress at the Popova, Marresalya and Varandey coasts. b) Residual mass curve for the total stress, averaged among Popova, Marresalya, Varandey. Red dots and lines indicate ascending branches of RM-curve, blue dots and lines show descending branches

Still, all the thermoabrasion (wave energy) components, including the ice-free period duration and storms frequency demonstrate the same evolution as thermodenudation. Consequently, the periods of 1989 (1993) – 1997 and 2005 – 2013 are characterized by extreme hydrometeorological stress, as far as both thermodenudation and thermoabrasion processes were in a positive phase. In 1979 – 1988 and 1998 – 2004, both thermoabrasion and thermodenudation were in a negative phase. Scarce data on coastal retreat rates' evolution derived from literature and natural observations, confirm these trends in the evolution of the hydrometeorological factors.

Generally, the fact that the ice-free period duration (IFPD) extension is followed by local temperature growth, is logical and can be easily predicted. It is also inevitable, that in this case, the wave energy flux increases as well, being a linear function of the IFPD. The new and unexpected result is that temperature and IFPD growth is accompanied by wave-dangerous winds frequency increase, provoking the record-breaking hydrometeorological stress for west-oriented coasts. Moreover, although, in theory, a link between summer temperatures and the ice-free period duration can be expected, our results are showing that during the XX century (at least, starting from the 1920-s), there was apparently no period when both summer temperatures (being is crucial for thermodenudation) and the ice-free period duration (important for thermoabrasion) simultaneously increased, the only exception being recent 15-year period. The Arctic warming of the 1930-40s was characterized by warm winters and long ice-free period, while summer temperatures were close to the local minimum. The local maximum of summer temperatures was observed in the 1950s, when there were less open water days. Contrarily to the warming of the 1930-40s, the current warming is expressed in both summer and winter temperatures increase together with the ice-free period growth. Figure 6 shows that before 1968, the IFPD and were negatively correlated and every year after 1967, positive linear linkage grew. Since 1989, the correlation coefficient exceeds 0.39, which is significant at 0.01 level. Since 2007, it has exceeded 0.65, which is statistically significant and means that in 1967 – 2007 (and after that), the IFPD and are linearly linked to each other to a considerable degree.

The mentioned facts lead to a disputable conclusion that as the latest warming differs from the previous one in its parameters and evolution, it should be caused by other reasons and mechanisms. Such idea may serve as indirect support to the anthropogenic explanation of the current warming. The conception also supposes that the latest warming "switched on" all the hydrometeorological forces of Arctic coastal dynamic (thermal, sea ice, winds), while previously (at least in XX century) they were "switched on" optionally and not simultaneously.

High hydrometeorological stress of the recent years is visibly expressed in an

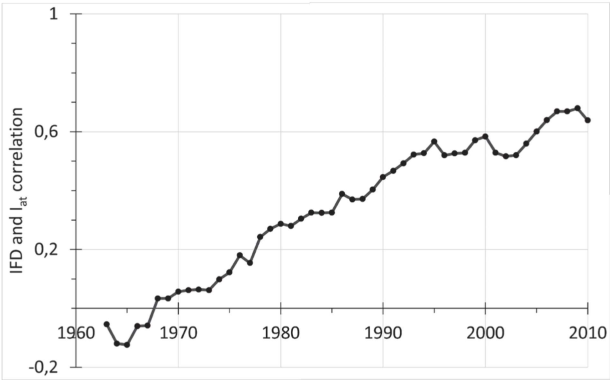

Fig. 6. Evolution of the correlation coefficient between the Air Thawing index (I_{at}) and the ice-free period duration (IFPD) at Marresalya station. The value for every year expresses the correlation of the samples over the previous 40 years (for example, in 2010 – for the period 1971-2010). This can be interpreted like a 40-year-running correlation coefficient

increase of the coastal retreat rates through the whole Arctic basin (Jones et al. 2009; Vasiliev et al. 2011; Günter et al. 2015; Belova et al. 2017). The intensification of thermodenudation process is confirmed by temperature data. The highest acceleration in coastal retreat is observed at the sites with ice-rich permafrost, which underlines the role of the thermodenudation process. The western coasts experience the highest HM forcing, as their thermoabrasion intensification occurs due not only to the IFPD prolongation, but also to an increase of wave-dangerous winds' frequency. Coasts of all orientation experience thermoabrasion and thermodenudation intensification due to climate change.

CONCLUSION

In this study the term of hydrometeorological forcing as distinct to hydrometeorological stress was intended and used for the assessment of the current Arctic coastal dynamics' state. Hydrometeorological stress sizes up the level of HM factors' exposure to coasts. HM forcing is an increment of HM stress appearing to change of coastal dynamics' HM factors'.

Annual sum of daily positive temperatures is used to assess thermodenudation forcing. Thermoabrasion forcing is determined through wave-energy flux calculation. Both thermodenudation and thermoabrasion factors evolution from 1979 to 2015 was analyzed together with ice-free period duration and wave-dangerous winds' directions frequency.

The variety of data is used in the study. Both observation and reanalysis data are used for thermal condition description. ERA Interim describes the "modern" period of 1979-2015 and ERA 20C was brought in to cover the whole XX-century (1900 – 2010). It is shown that ERA reanalyzes data are suitable for long-term interannual and interdecadal evolution of temperatures over the Barents and Kara regions. ERA Interim reanalysis wind data were also used for wave energy flux calculation.

We brought in the satellite data product (EUMETSAT, 2014) to determine the ice-free period start and end dates and duration and ETOPO1 digital elevation model for wave-energy flux calculation.

We revealed that thermodenudation forcing amounts 15-50% of the 1979-1988 mean level and thermoabrasion forcing is equal to 35-130%. The periods of 1989 (1993) – 1997 and 2005 – 2013 are characterized by extreme hydrometeorological stress, as far as both thermodenudation and thermoabrasion were in a positive phase. In 1979 – 1988 and 1998 – 2004, both thermodenudation and thermoabrasion were in a negative phase. Data on coastal retreat rates' evolution derived from literature and natural observations,

confirm these trends in the evolution of the hydrometeorological factors. It was also revealed that the hydrometeorological stress of the recent 10 years was apparently unprecedentedly high at the Barents-Kara region: the previous Arctic warming of the 1930-40s caused high thermoabrasion rates due to longer ice-free period despite cold summer temperatures, while, the latest ongoing warming shows previously unseen simultaneous increase in both thermodenudation and thermoabrasion.
To obtain more details on the evolution, characteristics and mechanisms of the hydrometeorological forcing in different parts of the Russian Arctic, more detailed data on coastal retreat rates are required. As field monitoring and remote sensing data analysis are quickly evolving, there is good perspective of revealing the nature and possible development of the current climate change and its impact on the vulnerable Arctic coasts.

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