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RUSSIAN ARCTIC COASTAL DYNAMICS HYDROMETEOROLOGICAL FORCING: HALF-CENTURY HYSTORY AND CURRENT STATE

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Abstract

The Arctic coasts are dynamically active and vulnerable to environmental changes. The dynamics of Arctic seashore and underwater slope composed of dispersive permafrost ground is determined mainly by hydrometeorological factors, namely, waves and wave currents action coupled to thermal abrasion, which are active during ice-free period. The combined wave and thermal action together with ice and sea level conditions is called here "hydrometeorological stress". Within climate change, the hydrometeorological stress at the Arctic coast is changing together with coastal retreat rate. In this study coastal dynamics hydrometeorological factors evolution in the second half of the XXth century and also the current conditions are analyzed for several sites in the Kara and Barents Seas. The term of hydrometeorological forcing is intended as an increment of hydrometeorological stress, appeared due to hydrometeorological factors change. It is shown that thermodenudation forcing amounts 15-50% of 1979-1988 mean level and thermoabrasion forcing – 35-130%. The last one in fact cannot be considered significant. Still, all the thermoabrasion (wave energy) components like ice-free period duration and storms frequency demonstrate the same evolution, like thermodenudation variations. This means that the periods 1989 (1993) – 1997 and 2005 – 2013 are characterized by extreme hydrometeorological stress, as far as both thermodenudation and thermoabrasion processes were in positive phase. In 1979 – 1988 and 1998 – 2004 both were in negative phase. The sparse coastal retreat rate data distilled from literature and field works come out in favor of this variations.

Key words: hydrometeorological factors, hydrometeorological stress, hydrometeorological frcing, coastal dynamics, climate change

1. Introduction

In the beginning of the century there was formed the awareness that changes in coastal systems are forced by large-scale processes and are realized over relatively long (decadal) time scales (Hanson, 2003). The persisting climate change gave a show to trace the changes in coastal dynamics due to evolving climatic conditions. Lots of publications appeared devoted to coasts with discontinuous permafrost (Allard, 2004; Grigoriev, 2006; Jones, 2009; Vasiliev, 2011; Shabanova, 2013) and tropical coasts (for example Livingston, 2014). The most intriguing is the Arctic coasts behavior as in most cases they contain ice which may react considerably to temperature growth and dramatically factor into coastal dynamics. And coasts do react: several publications have recorded the increase of the latest 15-20 years coastal retreat rate in different Arctic regions if compared to the previous period (table 1). This coastal retreat rate increase might be referred to the latest warming, more precisely to the latest climate change, as not only temperature grew, but the whole land-ocean-atmosphere system altered, including winds and sea ice conditions, which have their impact on coasts. Still it is challenging to trace the hydrometeorological effect to Arctic coastal dynamics (but we do and here the attempt is presented) as there are several obstacles in coastal dynamics studies.

1.1 *Coastal dynamics studies obstacles: observation data lack*

The coasts of Russian Arctic (as against the European Arctic and as well as the most part of Canadian and US Arctic) is pretty much remote and of difficult access. They are usually visited if only for special cases

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like oil and gas infrastructure constructions. Scientific purposed visits are usually conducted for a short period of time. The working timeframes are determined by production tasks and are hardly adjusted to scientific challenges. That is why coastal dynamics observations are sporadic in space and time: coasts are observed in different months (not at the end of ice-free season which is preferable), even not every year, with hardly comparable means and methods. The regular coastal net of observations is absent in fact: polar hydrometeorological stations are not authorized to conduct coastal retreat rate observations. The hydrometeorological data produced by these stations is of hard operation by several reasons. Firstly, there station net is extremely scarce: by about 100-500 km resolution. Secondly, the net of stations with long-period (by about 30 years) observations (figure 1) is even more scarce. In third, there are lots of gaps in time-series due to the variety of reasons, referred both to data operation problems and inaction periods, caused, in turn, to both economical and natural reasons (like insufficient funding, understaff, fires and severe weather conditions). And at last, some of the data (like ice and sea level data) are of hard access, as they are of special usage according to Russian Federation regulations. The only remedy in hydrometeorological conditions characterization is to use modelling data, like reanalysis.

In coastal retreat rate study the satellite imagery are of insightful support, however, there are some sticking-points in its operation: 1) the old-data imagery are of low resolution (7-10 m) and do not allow to detect the coastline with sufficient accuracy; 2) there is the problem of coastline detection itself (the bench crest is usually designated as coastline which sometimes is dimly recognized); 3) unfavorable weather conditions like sea ice and clouds interfere recognition.

The in situ measurements of sediment transport (for example, acoustic backscatter measurements of suspended sediment transport) in Russian Arctic is not used. The coastal dynamics assessment is conducted here usually by observing the bench crest retreat during the fieldwork (using the number of cross-sections tied to benchmarks) or using satellite images. Still coastal retreat rate is in great dependence on local geocryological conditions including ice content, ice bodies presence, grain texture, coastal bluff height and so on. It varies from place to place on scales of 1-10 m. That is why it is challenging to cross over the annual in situ measurements to coastal dynamics long-period description. This is what Brian Greenwood writes in his paper (Greenwood, 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».

Taking the complexity of coastal dynamics direct research into consideration, not the coastal retreat rate itself, but the driving factors are under study. Hereby the coastal dynamics potential is characterized – the quantitative expression of hydrometeorological impact on coasts. The mentioned potential varies from year to year and the coasts may exhaust it completely or not depending on their inner factors (grain texture, ice content and so on). That is how the coastal dynamics research is translated into its factors description.

1.2 *Arctic coastal dynamics hydrometeorological factors*

Russian Arctic coastal dynamics is determined by two interrelate processes. The sediments are decomposed trough ice melting due to heat energy transmission to the coast from warm air and sea water. This is called thermodenudation process. It prepares the ground material for further removal by wind-wave energy. This process is called abrasion. The whole complex of sediment pretreatment by thermodenudation and removal by abrasion is called thermoabrasion. Thermoabrasion is driven by hydrometeorological factors.

As far as Russian Arctic seas waves are mostly wind-generated, wind conditions are crucial in wave energy flux formation. Shores are affected by waves during the ice-free period. The seasonal shore retreat rate is determined by wave energy flux coming to the shoreline and the amount of heat, making the ground ice melt. Wave energy flux depends on ice-free period duration. Storms provide the largest contribution to total amount of wind-wave energy. Ice-free period duration is connected to polar ice cap conditions which is likely related to global temperature and by and local (regional) weather conditions (wind directions and heat transfer). That is how coastal dynamics is bounded to different scales of processes from global to local.

Climate change of the latest decades results both in wind, ice and thermal conditions changes. The current investigation aims to assume thermal and wave-energetic impact on coastal retreat rate in different permafrost and sediment composition conditions of the Yamal Peninsula.

1.3 *Hydrometeorological stress and hydrometeorological forcing*

That said, arctic coastal retreat rate Rr is determined by hydrometeorological forces, called here hydrometeorological stress or potential F:

$$Rr = \gamma F(f_1, f_2, .. f_N) = \gamma F(T, WE(n, p, x), \dots) \tag{1}$$
$$[\gamma] = m/J, \tag{2}$$

where $f_1, f_2, .. f_N$ are CD hydrometeorological factors like air temperature T, wind-wave energy WE depending, in turn, on ice-free period duration n, wave fetch x and shore-sided storm frequency p. Here γ is sensitivity parameter and is equal to 0 for non-dispersive coasts, and is positive for loose frozen ground being in dependence to its ice content (the more ice – the higher γ). For specific local conditions (for example, the areas which contain ice bodies like ice wedges or embedded ice) γ may be extraordinarily high as such type of coasts may react to HM forces much more prominent. Up to the moment we are not prepared well to assess quantitatively sensitivity parameter. Here we introduce γ for quantitative description the differences in the reaction of different coastal areas to hydrometeorological forces, as their behavior is very mosaic: in the same year some coasts retreat significantly when the others may stay almost stable.

Hydrometeorological stress (potential) is presented here consisting of two parts: mechanical – the energy, transmitted to shore from shore-sided waves and called coastal dynamics wind-energetic potential, – and thermal – the energy transmitted to shore from the atmosphere (CD thermal potential). The term of hydrometeorological forcing is intended as an increment of hydrometeorological stress (potential), appeared due to hydrometeorological factors change: CD thermal forcing (F_T) – due to temperature conditions change; CD mechanical forcing (F_{WE}) – due to wind-wave energy changes.

By analogy with the radiative forcing used in climatology and IPCC reports (Smithson, 2002; Mayer, 1998) coastal dynamics hydrometeorological forcing is introduced here. The increment in i coastal dynamics factor Δf_i provokes the coastal dynamics hydrometeorological forcing ΔF_i, which in turn leads to coastal retreat rate change ΔRr_i, associated with this factor with the specific sensitivity to this factor γ_i:

$$\Delta f_i \rightarrow \Delta F_i \rightarrow \Delta Rr_i \tag{3}$$
$$\Delta Rr_i = \gamma_i \Delta F_i \tag{4}$$
$$\Delta Rr = \sum_1^N \gamma_i \Delta F_i \; . \tag{5}$$

CD hydrometeorological stress, as well as coastal retreat rate, is always positive for frozen dispersive coasts and can be characterized by certain level, for example, mean value for the research period. In these terms hydrometeorological forcing is considered as deviation of current HM stress from the mean value, as well as coastal retreat rate.

2. Research area

In this study we extend the research area over the Frantz-Joseph Land and some islands in the Kara Sea (Belyi and Vize islands). The previous studies are devoted to the Pechora Sea coasts (Varandey area) and Western Yamal coasts (Marresalya and Baydaratskaya Bay areas) (Overduin, 2014, Shabanova, 2016). The sites where coastal dynamics data exist are analyzed (mostly gathered by the Laboratory of geoecology of the North, MSU).

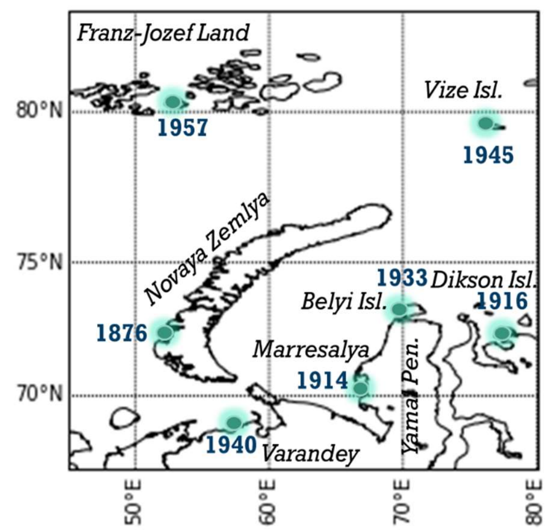

Figure 1. Research area and hydrometeorological long-term observation stations with start-observation year indication: (from North to South) 1) Krenkelya Hydrometeorological Observatory (Heiss island); 2) Vize Island; 3) Popova station (Belyi Island); 4) Malyie Karmakuly (Novaya Zemlya arch.); 5) Dikson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

Several islands of Franz Josef Land are described. Here modern processes have significantly changed the shape of coastlines. 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».

3. Methods and data

3.1 *Thermal potential of thermodenudation assessment*

The thermal potential of thermodenudation is assessed by 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). These indexes are the evaluations of the year amount of heat added to or extracted from the ground and the permafrost during the warm and cold periods, respectively. For calculations both observation and reanalysis data are used 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 non 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 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.

The reanalysis data were compared to observation data. The result is presented in table 1. ERA Interim (Dee, 2011) and ERA 20C reanalysis (Poli, 2016).

Table 1. ERA Interim and 20C reanalysis data comparison to observation for the three stations in the Kara and Barents Seas: means, dispersions, systematic deviations (SD), RMSE values of corrected to SD values and correlation coefficient. A) Air thawing index I_{at}; B) air freezing index I_{af}

A)

Station	Mean values			SD – systematic deviation		Dispersion 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****		

B)

Station	Mean values			SD – systematic deviation		Dispersion 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)*

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

Wave energy (WE), tentatively called "wave-energy flux", was calculated according to the Popov–Sovershaev method (Ogorodov, 2002; Popov and Sovershaev, 1982). 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, ice-free period duration (n), wave fetch (x) and frequency of wave-generating winds (p).

Wave energy flux is calculated using the Popov-Sovershaev (1981, 1982) wind-wave energy method (Ogorodov, 2002). 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 flux per second (for 1 m of wave front) at the outer coastal zone boundary is calculated using the equation:

$$WE = 3 \times 10^{-6} V^3 x \tag{6}$$

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 3×10^{-6} coefficient corresponds to the dimensions of ρ/g, where ρ is density [t/m^3], and g is gravitational acceleration [m/s^2]. Thus, WE has dimension of tons per second:

$$\frac{t}{m^3} \cdot \frac{s^2}{m} \cdot \frac{m^3}{s^3} \cdot m = \frac{t}{s} \tag{7}$$

During the ice-free period the wave energy flux presents the mass of coming water in tons.

Wave directions, wave fetches and depths are obtained from digital elevation model ETOPO1. The frequency of wave-generating winds was calculated for the ice-free period. ERA Interim reanalysis is used for wind data. The Popov–Sovershaev method is based on wave processes theory, and applies correlations between wind speed and wind-induced waves parameters. Wind speeds from 6 m/s and higher used. It is shown in (Popov and Sovershaev, 1982) that the effect of weaker winds (velocities <6 m/s) is negligible in geomorphological work. The satellite imagery were operated to gather sea ice data and determine ice-free period duration.

3.3 *The objective periodization: residual-mass curve method*

Residual mass curve method was used to detect periods of heightened 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. The modular coefficients are calculated as the relation of current year value X_i to long-term mean value $\bar{X}$:

$$K_i = \frac{X_i}{\bar{X}}, \tag{8}$$

The deviation of K_i from one is positive if the current value is higher than mean and negative – if one is lower. If K_i are positive for several subsequent years, than 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 then the curve starts to descend. Break of the curve signalizes of the low-value/high-value period beginning/end. It is reasonable to get rid of the oscillation scale by dividing anomalies $(X_i/\bar{X} - 1)$ by variation coefficient C_v:

$$X\_N_i = \frac{X_i/\bar{X} - 1}{C_v} = \frac{X_i - \bar{X}}{\delta}, \tag{9}$$

where δ is standard deviation and "*Ni*" in X_N_i means "normalized by standart deviation". The RM-curve values are calculated through X_N_i accumulation:

$$X\_RM_i = \sum_1^i X\_N_i, \tag{10}$$

This method has limitations related to the dependence of result on the mean value of studied parameter. Method is suitable for cyclic processes where the oscillation magnitude is constant during several oscillation periods. If the oscillation with the outstanding magnitude occurs then it results in moving the mean value 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 is hampered. 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.

4. Results

4.1 *Arctic coastal retreat in XX century: literature analysis*

Literature analysis revealed that several coasts all over the Arctic displayed the increased and decreased retreat rates of coastal erosion in different times (table 2). Generally speaking, there were periods of heightened values in about 1985 – 1995 and after 2002 and low values in about 1995 – 2002. In recent years some coasts displayed accelerated erosion. The same was noticed during the field works at the Varandey area and the Baydaratskaya bay and Pechora Sea (Ogorodov, 2000, 2003).

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

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	

It is expectable, that ice-free period duration (IFD) extension is followed by local temperature growth. It is also inevitable, that wave energy flux increases as it is a linear function of IFD. The new and

4.2 ***Hydrometeorological stress evolution in 1979-2015***

Table 2. Hydrometeorological forces trends characteristics at the Kara and Barents Seas stations basing on 1979 – 2015 period data. Trends which are significant at 0.01 level are marked with ***bold italics***, at 0.05 – *italics*

HM factor	Trend characteristic	Popova	Marresalya	Varandey	Mean
Air thawing index	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 dispersion)	1.7	1	1.4	1.4
	p-value	***0.0016***	0.074	*0.0116*	*0.029*
Air freezing index	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 dispersion)	1.7	1.1	1.2	1.33
	p-value	***0.0016***	0.073	*0.031*	*0.035*
Wave energy	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 dispersion)	0.56	1.4	0.84	0.93
	p-value	0.34	*0.014*	0.16	0.17

Both thermoabrasion and thermodenudation potential were analyzed. All of them have similar evolution with maximum in 1989 (1993) – 1997 and 2005-2013. The 1998 – 2004 period is characterized by low values of thermoabrasion and thermodenudation potential. The normalized by standard deviation anomalies of both of parameters were summed to calculate total (combined wave-energetic and thermal) stress. Its 1979 – 2015 period evolution and periodization is presented on figure 2. If analyzing the trend of total stress, the increase amounts about 100% compared to 1979 – 2014 mean value.

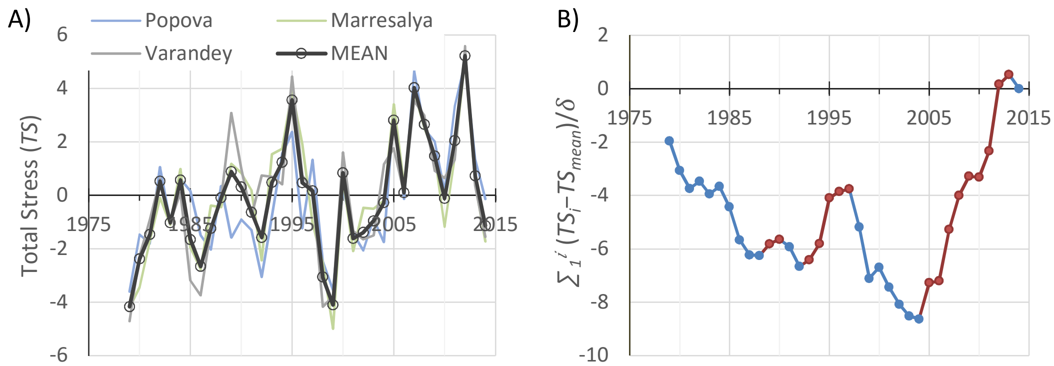

Figure 2. Total hydrometeorological (combined wave energetic and temperature) stress on the Popova, Marresalya and Varandey coasts. (A). B) Residual mass curve for the total stress, averaged among Popova, Marresalya, Varandey. Red dots and lines indicate ascending branches, blue – descending

5. Conclusion

Total hydrometeorological stress of Russian Arctic coasts has increased in recent 35 years by about 100% for Yamal, Pechora Sea and Franz-Josef land regions. Herewith thermodenudation forcing amounts 15-50% of 1979-1988 mean level and thermoabrasion forcing – 35-130%. The last one in fact cannot be considered significant. Still, all the thermoabrasion (wave energy) components like ice-free period duration and storms frequency demonstrate the same evolution, like thermodenudation variations. This means that the periods 1989 (1993) – 1997 and 2005 – 2013 are characterized by extreme hydrometeorological stress, as far as both thermodenudation and thermoabrasion processes were in positive phase. In 1979 – 1988 and 1998 – 2004 both were in negative phase. The sparse coastal retreat rate data distilled from literature and field works come out in favor of this variations.

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