

CRYOGENIC PROCESSES ON SHELF AND COAST OF ARCTIC SEAS

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MODELING OF COASTAL DYNAMICS OF THE LAPTEV AND EAST SIBERIAN SEAS
IN THE SECOND HALF OF THE HOLOCENE

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Two mathematical models of the Laptev and East Siberian seas coastal dynamics – multifactor model and multiplicative phenomenological model – have been developed and used for evaluation of their coastal retreat rate during the Holocene. Thermo-erosion affecting their ice-rich coasts occurred most intensely during the Subboreal period (from 10 to 20 m/year) in the Holocene and in the Early Middle Ages (8–15 m/year). Average rate of the east Siberian seas coastline retreat caused by coastal permafrost degradation ranged for the most part between 2 and 6 m/year over 500 years BP. However, it has drastically increased to 8–19 m/year in the last 40 years. Modern climatic conditions and retreat rates of the ice-rich coasts are found to be close to those existing during the Atlantic and Subboreal optimums of the second half of Holocene, when the mean air temperature anomalies reached 2 °C and more during thawing season (July through September), in the absence of multiyear ice in the Siberian seas.

Coastal dynamics, mathematical modeling, multifactor and multiplicative models, average air temperature in thawing season, multiyear sea ice

INTRODUCTION

Numerical modeling of the Arctic coastal dynamics in the Holocene can be a valuable contribution to the study of the permafrost zone evolution on the Siberian seas shelf, and particularly helpful in timing of the episodes of coastal permafrost strata flooding by the sea in the context of accelerated coastal thermo-erosion. Results of the Holocene coastal dynamics modeling are also critical for efficient calculation of the present-day temperature field and current locations of the upper and lower boundaries of permafrost in the coastal zones of the Arctic shelf. The modeling allowed for correlations between contemporary coastal processes and climatic conditions, given their variability, for example, over the last 5 thousand years. Alternatively, prognostic models were developed by Yu.A. Pavlidis and I.O. Leontiev [2000] for the eastern Arctic sector, to complement the discussed model [Grigoriev et al., 2006]. Their methodology is primarily applicable to the sandy shores of the East Siberian Sea in the vicinity of Cape Billings. This in fact is a mathematical model of the sandbar accumulation dynamics.

This model, however, is not capable to quantitatively evaluate dynamics of the thermoabrasion shores, composed mainly of ice-rich fine-grained silty sediments. The authors are not familiar with any

other models that incorporated the eastern Arctic seas ice-rich shores' response to the interplay of natural factors (climatic, permafrost, geological, morphological), to be quantitatively estimated. The East Siberian seas coastal dynamics during the second half of the Holocene was estimated using two numerical models: a modified multivariate mathematical model [Grigoriev et al., 2006] and a new multiplicative phenomenological model. The models reproduce the changing climate-driven dynamics of the permafrost coasts, taking into account permafrost-geological and coastal geomorphic conditions.

The novelty of this modeling approach consists in the substantiated and quantitatively formulated relationship between major climatic drivers affecting the coastal thermoabrasion development, primarily, the frequency of shoreward storm winds and air temperature during thawing season (July, August, September) in the coastal regions of Russia's eastern Arctic seas. The proposed Holocene coastal dynamics modeling for the Siberian seas and its results appear to be unique, given that no analogous mathematical models have been found by the authors either in Russian or foreign literature. Notably, the application of either of these models separately to the study of coastal processes intensity in the Holocene would not

allow to compare the results with any other data due to a lack of observational data, whereas concomitant application of both models stipulates more accurate appraisal of the erosion rates along the permafrost-bearing coastline at any specified time.

STUDY REGIONS

Several coastal regions selected for the modeling were allocated in the western and eastern parts of the Laptev Sea and in the western part of the East Siberian Sea for which the long-term measurements of coastal retreat rate are available (Fig. 1). The investigated coasts are composed of Late Pleistocene ice complex and Holocene lacustrine-thermokarst sediments. The ice complex is largely represented by thick ice wedges visible in the coastal outcrops from the outer surface of coastal cliff to its base and are likely to extend to a depth of 10–15 m below the sea water edge.

The width of ice wedges varies from 3 to 7 m and more. The distance between the wedge axes is 8–12 m. The mineral component is represented by heavy and light silty sand-loam, often with interlayers of light clay-loam and sometimes by silty sands.

The lacustrine-thermokarst complex is composed mainly of heavy and, to a lesser extent, medium and light silty clay-loams intruded by ice wedges. The width of the ice-wedges in the upper part is predominantly 2–3 m. Ice wedges 1.0–1.5 m and reaching 4 m in width are not rare. Their thickness reaches 5–8 m. Polygonal relief is widely developed in the coastal zone, with quadrangle polygons whose size vary mainly from 7 to 15 m and occasionally up to 20 m or more, prevailing among them.

In the Anabar-Olenek sector of the Laptev Sea, the height of the investigated coastal cliffs varies from 15 to 20 m; ice content of sediments composing the coast ranges from 35 to 50 %. The height of the coastal cliffs reaches 20–30 m at some sites in the eastern sector of the Laptev Sea; ice content of sediments reaches 40–60 %. In the Kolyma-Indigirka sector of the East Siberian Sea, the height of the studied shores does not exceed 12–30 m, while ice content of sediments ranges between 30 and 70 %. The depth of the sea at the waves acceleration lines averages 8–10 m within the study areas. The average wind speed during storm is 12–13 m/s. The distance between the coastline and the multi-year ice boundary is subject

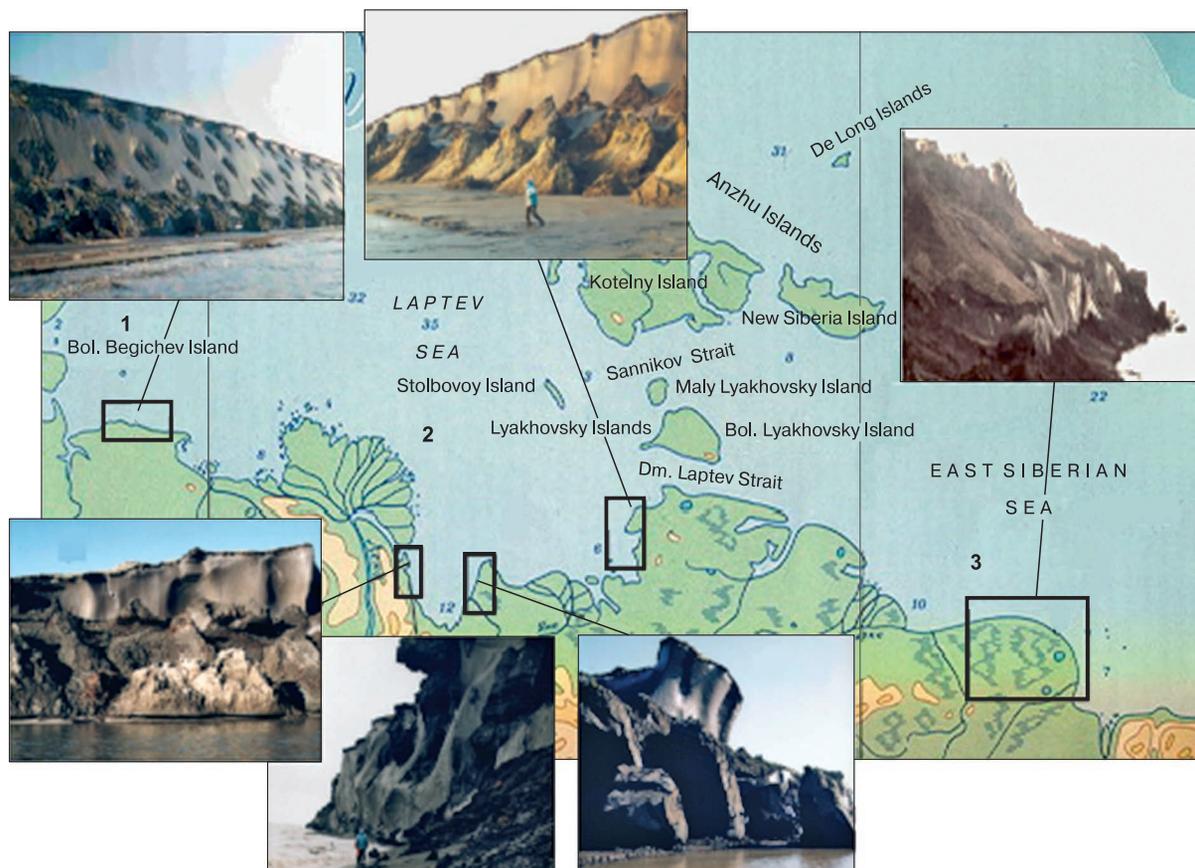


Fig. 1. Study regions:

1 – Anabar-Olenek sector; **2** – regions in the eastern sector of the Laptev Sea; **3** – Kolyma-Indigirka sector. Insets show type ice-rich coasts of the East Siberian seas (photograph by M.N. Grigoriev).

to spatial and temporal variations (from 40 to 700 km). The provided quantitative characteristics are sourced from the available database [Grigoriev, 2008] and publications [Razumov, 2002, 2003].

PHYSICAL SUBSTANTIATION OF THE MODELS AND THEIR MATHEMATICAL REPRESENTATION

Multifactor mathematical model. An important role in the “atmosphere–sea–coastal permafrost” system is played by the mean air temperature variations in thawing season whose impact on coastal permafrost is the most destructive compared to other major natural drivers of coastal thermal abrasion processes: the drift ice edge dynamics, duration of the ice-free period, the frequency of shoreward storm winds, as well as the permafrost-geological and geomorphic features of the coastal zone, both onshore and offshore [Razumov, 2002]. Enhanced heat fluxes in parallel with the increasing mean summer temperature, on the one hand, promote entropy of coastal cryogenic complexes making their resistance against the sea effect lower due to the higher average temperature of sediments within the layer of annual fluctuations and prompted thereby cliff segmentation along the thawing ice wedges. On the other hand, hydrodynamic impact of the offshore sea on the coast tends to grow due to the increasing frequency of shoreward storm winds and the expansion of the open water surfaces, along with the duration of the ice-free period and, therefore, of the persistence of thermoabrasion processes.

Changes in the coastal stability due to the degradation of ground ice, in duration of ice-free time and the drift ice edge position controlled by the fluctuations in the thermal constituents of climate, are cumulatively responsible for on average 70 % of the total variability of coastal permafrost retreat rates. The individual contribution of destructive storms to the evolving thermoabrasion processes is estimated by the authors to be about 20 %. Intensity of the abrasion-accumulation processes in the coastal zone governed by the sea floor morphology and the sea depth at the waves acceleration lines accounts for about 10 % of the contribution of major factors to the thermoabrasion processes [Razumov, 2002, 2003].

In this model, climatic variations and spatial inhomogeneity of the permafrost-geological characteristics are the main forcings influencing the Arctic coastline retreat rates. Mean air temperature in thawing season represents a universal indicator of coastal cryogenic processes activation, which impacts thermoabrasion rate indirectly, through all the above discussed main factors contributing to the formation of coastline features. The activity of coastal cryogenic processes is mathematically expressed by the equation

for the coastal thermoabrasion rate $v_a = v_a(D, R)$ with the solution given below [Grigoriev et al., 2006]

$$v_a = D/R. \quad (1)$$

Here D (destroy) is the sea capacity for coastal destruction (an indicator of the sea abrasion activity, dimensionless value), depending on duration of the ice-free period, the drift ice edge dynamics and the frequency of shoreward storm winds (these three factors are coupled with the air temperature during thawing season), as well as on the sea depth at the waves acceleration line; R (resistant) is the coasts capacity to resist the sea impacts, or the resistance coefficient (year/m) that depends on temperature, ice content and mechanical composition of the shore sediments, height of the coastal cliffs and the mean air temperature in thawing season.

The considered model includes the equation which relates the frequency of shoreward storm winds to the sum of horizontal components of the tidal forces calculated for the forecast until middle of the 21st century. The literature sources known to the authors do not provide any methodologies or data for calculations of these forcings to span intervals of time of several thousand years in the second half of the Holocene, and therefore such model if not modified is not capable to quantify the Holocene coastal dynamics. The model was thus updated by the authors for the frequency of storms based on the following assumption: in the eastern Arctic, storm activity offshore is functionally related to the mean air temperature in thawing season. The analytic solution for the system of canonical equations as discussed in [Grigoriev et al., 2006, p. 88] allowed the authors to obtain a formula describing this relationship:

$$p = \exp\left[0.7 + (\bar{T} + \Delta T)/2.8\right],$$

$$T = \bar{T} + \Delta T,$$

where p is frequency of shoreward storm winds with a speed of more than 10 m/s, %; T is the mean air temperature of the thawing season in the calculated time interval (years), °C; \bar{T} is climate norm of the air temperature in thawing season, defined as the average value for the 1961–1990 base period (standard reference period in climatology) [Alekseev et al., 2010]; ΔT indicates air temperature anomalies during thawing season as deviation of the air temperature in thawing season from its climate norm within the estimated time intervals. The obtained formula is used for the first time in modeling the dynamics of permafrost coasts, and the proposed multifactor model for coastal dynamics in the Holocene differs from the model variant [Grigoriev et al., 2006] that was used to predict the coastal dynamics for the 21st century. Given that the model was updated by the authors with other modeling tasks posed, the values for sea abrasion

activity and coastal resistance coefficient were also changed.

Multiplicative phenomenological model is based on dependence of the coastal erosion rates on the interplay of two factors: frequency of shoreward storm winds with speed exceeding 10 m/s and the mean air temperature in thawing season. This interrelation resulted from analysis of the measurement data at key sections of the Laptev and East Siberian Sea coasts and synchronous observations at the coastal meteorological stations [Grigoriev *et al.*, 2006].

The relationships between the coastal permafrost dynamics and air temperature in thawing season T (Fig. 2, *a*) and frequency of the shoreward storm winds p (Fig. 2, *b*) appear relatively weak. These are characterized by the normalized correlation coefficients equal to 0.74 and 0.75, respectively. Notably, the erosion rate along ice-rich coasts is very closely related to the pT product with the normalized correlation coefficient being about 0.99. This relationship is approximated with high reliability by a linear dependence (Fig. 2, *c*):

$$v_a = 0.2 + 0.206p(\bar{T} + \Delta T). \quad (2)$$

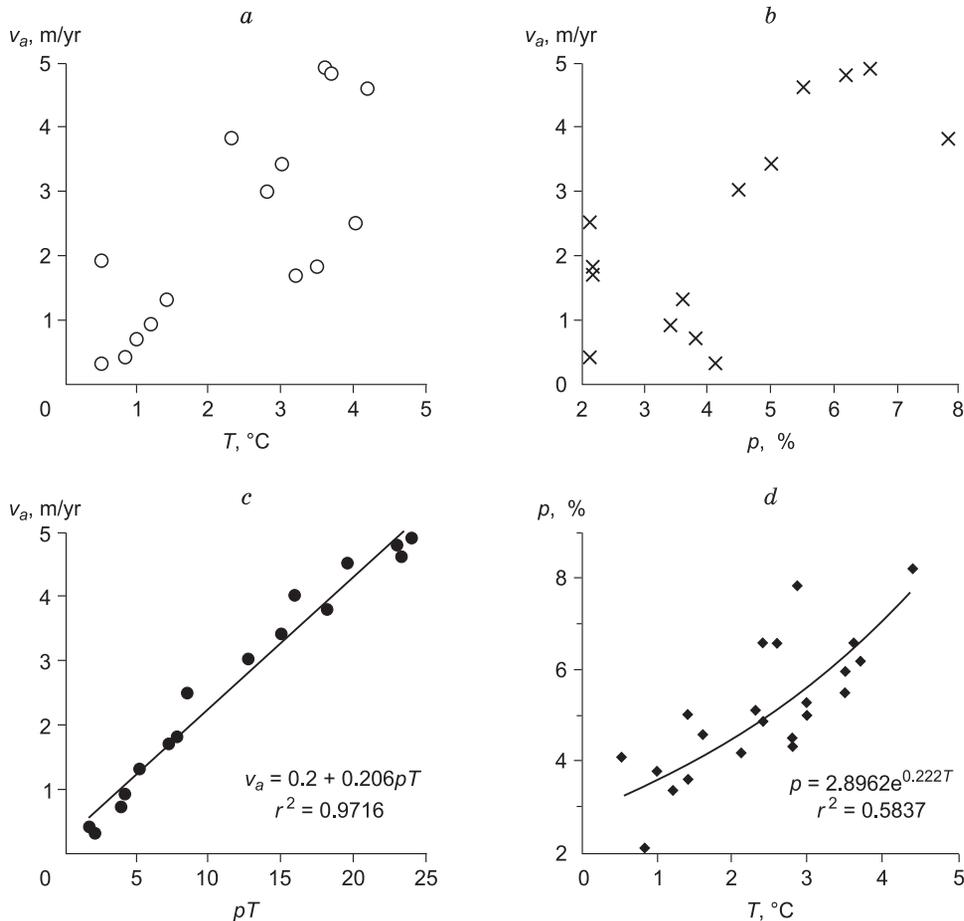


Fig. 2. Dependence of retreat rate of ice-rich coasts v_a on: mean air temperature in thawing season T (*a*), frequency of shoreward storm winds p (*b*), pT (*c*) product, and relationship between frequency of shoreward storm winds and mean air temperature in thawing season (*d*).

The correlation coefficient between p and T is 0.62. Despite the weak coupling, the frequency of storms during the warming of the thawing season obviously tends to change (Fig. 2, *d*) and is approximated by the equation below

$$p = 2.9 \exp[0.22(\bar{T} + \Delta T)].$$

The phenomenological model of the coastal dynamics is based on approximations related to the spatial heterogeneity of permafrost-geological and geomorphological conditions on the Arctic coast. Equation (2) reproduces averaged rates of retreat of the coasts on average 15–20 m high and composed by sandy-loamy sediments whose volumetric ice content averages 50 %, under different climatic conditions. At the same time, sediments composing the icy shores in the study areas vary from silty sands and sandy silts to heavy silty clay. Volumetric ice content of sediments varies from 30 to 70 %, the height of sea cliffs ranges from 12 to 30 m.

For each section of the coastline whose permafrost and geological structure differ from those of adjacent areas, it would be critical to find an analogous

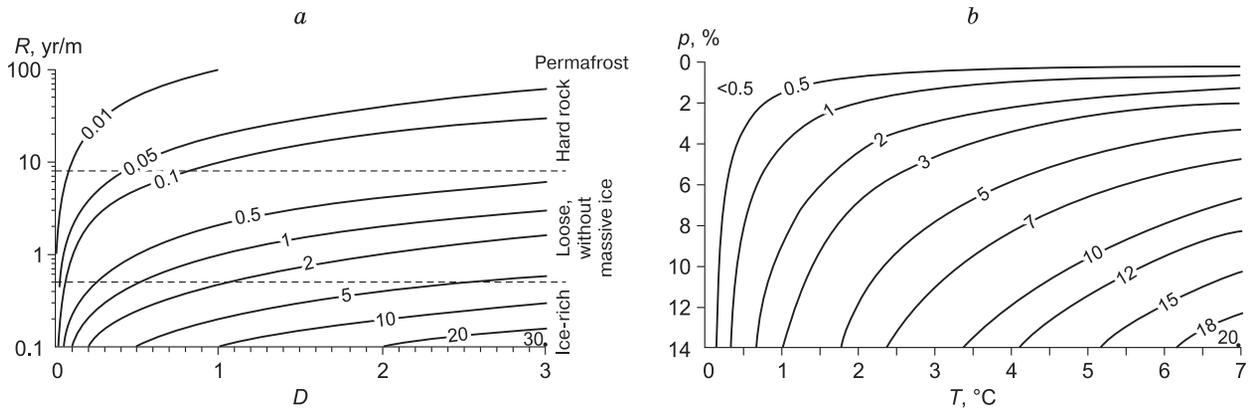


Fig. 3. Multifactor mathematical DR-model of coastal dynamics (a) and multiplicative phenomenological pT -model of ice-rich coastline dynamics (b).

Isolines show rate of coastal degradation v_a (m/year).

(2) equation with other numerical coefficients. However, given the limited amount of actual data on the rate of thermoabrasion, this condition appears not practical. To build the Holocene coastal dynamics simulations, the authors therefore used equation (2) obtained for the averaged permafrost-geological and geomorphic characteristics of the investigated eastern sectors of the Siberian seas coast. The multifactorial model thus takes into account spatiotemporal variations of climatic and permafrost-geological characteristics (Fig. 3, a). While in the phenomenological model, the coastal dynamics is associated with spatiotemporal changes in climatic characteristics under the spatially averaged permafrost-geological conditions (Fig. 3, b).

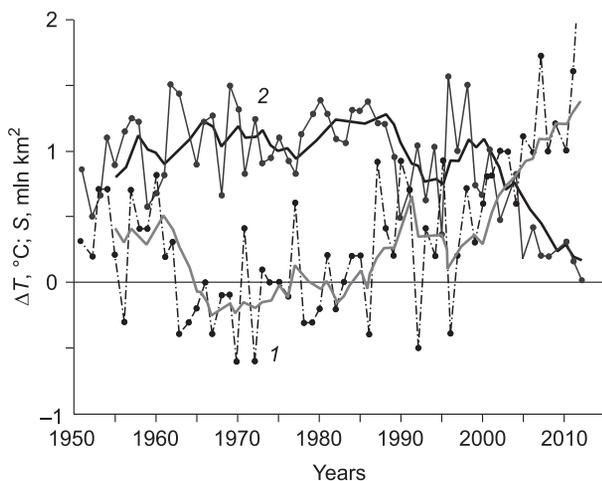


Fig. 4. Temporal variations of climatic characteristics in the East Siberian seas:

1 – anomalies in mean air temperature in thawing season $\Delta T, ^\circ\text{C}$; 2 – area of multiyear ice S , millions km^2 [Aleksseev et al., 2010; Schiermeier, 2012]. Bold lines delineate 5-year smoothing periods.

MODELING DYNAMICS OF ICE-RICH COASTS OF THE LAPTEV AND EAST SIBERIAN SEAS IN THE HOLOCENE

The presented models were used to estimate the coastal permafrost retreat rate under changing climate conditions of the Holocene. The assessment is based on the relationship between the coverage area or quantified multiyear ice in the marine Arctic (the Arctic Ocean with seas) and the air temperature anomalies during thawing season relative to its climatic norm assumed to be $3.9 ^\circ\text{C}$ for the marine Arctic and $3 ^\circ\text{C}$ for the East Siberian seas (Fig. 4). The term ‘amount of ice’ is common in oceanology, which indicates ice-covered area occupying a part of the offshore area as a percentage of the total offshore area. Sea ice immediately responds to interannual mean air temperatures variations in thawing season. Normalized correlation coefficient between the temperature anomalies and sea ice area for 45 synchronous value pairs equaled -0.824 . Given that the ice extent values are shifted 1–2 years forward and backward relative to air temperature anomalies, the absolute value of the correlation coefficient is reduced to -0.76 and -0.54 , respectively.

According to the calculations by M.I. Budyko, a $4 ^\circ\text{C}$ increase (relative to climate norm) in the summer air temperatures would lead to the Arctic Ocean multiyear ice breakdown in 4 years’ time [Borisov, 1970]. This value of temperature anomaly is taken as the boundary condition for complete disappearance of multiyear ice. The equations coupling the mean summer air temperature anomalies with the amount of multiyear ice (s , %) in the marine Arctic

$$\Delta T = 4 - s/13.6 \quad (3)$$

and in the East Siberian seas

$$\Delta T = 2.2 - s/22.3 \quad (4)$$

describe lines 1, 2 in Fig. 5, which were plotted by the authors using the data from Fig. 4. To evaluate

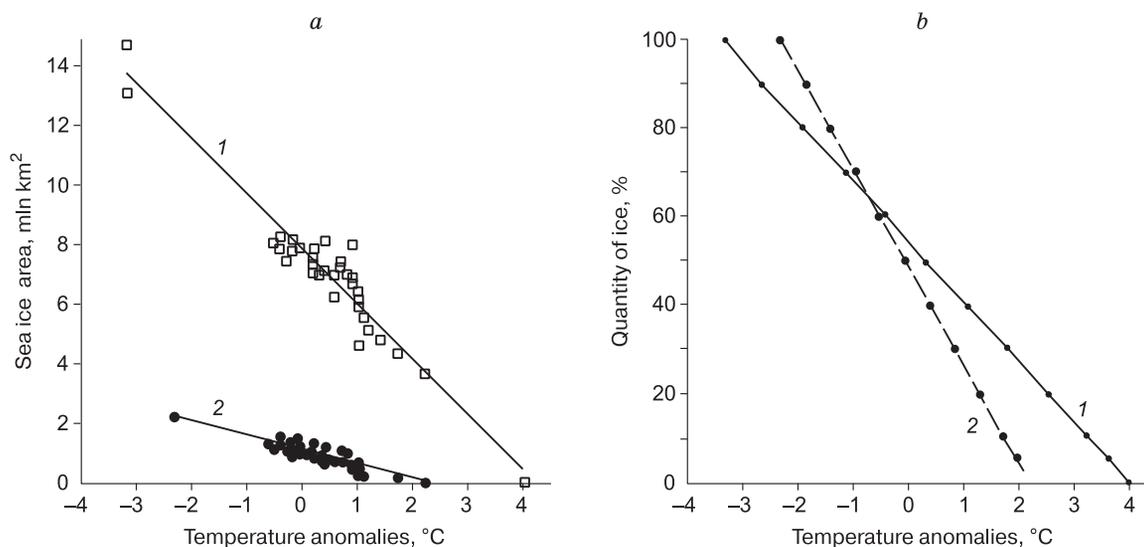


Fig. 5. Relationship between areal extent (a) and quantity (b) of multiyear ice in September with air temperature anomalies ΔT in thawing season:

1 – in Arctic marine waters; 2 – in the East Siberian seas.

temperature anomalies in the Late Cenozoic, the sea ice coverage was converted into the amount of ice due to the fact that sea-ice conditions existing in that time in the Arctic basin are translated into quantities of ice in the literature referred to by the authors.

Sea-ice situations of the late Neopleistocene-Holocene were restored according to the published data [Borisov, 1970; Chizhov, 1970; Schiermeier, 2012] (Fig. 6, a). Accordingly, the changes in air temperature anomalies during thawing season (Fig. 6, b) are calculated using formulas (3), (4) and prove to be consistent with the data after [Avenarius et al., 1978; Burashnikova et al., 1979; Bradley, 1999; Alekseev et al., 2010]. To quantify multi-year ice in the seas during postglacial transgression (Fig. 6, c), the sea level dynamics of the Laptev and East Siberian seas is derived from the published data [Holmes and Creager, 1974]. Results of the multifactor mathematical and multiplicative phenomenological models complemented by the estimated ΔT data enabled calculations of the retreat rate of ice-rich coasts over the period of the last 5 thousand years (ky) for the studied regions of the eastern Siberian seas (Table 1). A climate norm of the mean air temperature in thawing season, applied to estimation of the coastal dynamics using formulas (1), (2) was found to be 2.6 °C for the Anabar-Olenek sector of the Laptev Sea coast; 3.5 °C for eastern coast of the Laptev Sea, and 3 °C for western coast of the East Siberian Sea [Grigoriev et al., 2006].

The long-term observational data obtained at key sites of the coastal eastern Arctic seas allowed to estimate retreat rates of the ice-rich coasts in the Arctic regions in the 20th and early 21st century [Grigo-

riev et al., 2006; Razumov and Grigoriev, 2011; Are, 2012; Gunther et al., 2013]. According to these data, they varied from 2 to 9 m/yr during the period of 1940–1970s, from 2–6 to 10–13 m/yr in the 1970s through the early 2000s, and from 5–7 to 15 m/yr during the period of 2000s–2012. The calculation results of the both models generally agree with the actual data, except for the 2005–2012 interval with about 70 % of the calculated data included into the actual data set (Fig. 7, a). A comparative analysis of the medium (3–11 m/yr), minimum (less than 3 m/yr) and maximum (more than 11 m/yr) estimated and actual coastal degradation rates in the studied regions has shown (Fig. 7, b) that in the domain of minimal values, the estimated rate deviations range from 0.8 to 2.5 m/yr (on average, 2 m/yr), while in the range of maximum values, the deviation is from 1.5 to 4.5 m/yr, averaging 3 m/yr.

Significant deviations in the range of maximum and minimum values can be accounted for the following: the modeling helps to estimate rates of thermoablation averaged over time and coastline both in the range of medium values and in the domains of maximum/minimum values, whereas the actual data characterize coastal dynamics at specific measurement points and time intervals. Given that thermoablation develops very unevenly in space and time [Are, 2012], the rate of coastal retreat may differ by several times either in adjacent areas at the same specified time or in the same sector of the coast at different times. With only sparse actual data on maximum and minimum coastal permafrost retreat rates available for the studied Arctic region, the correct comparison with the modeling results would be very problematic. The me-

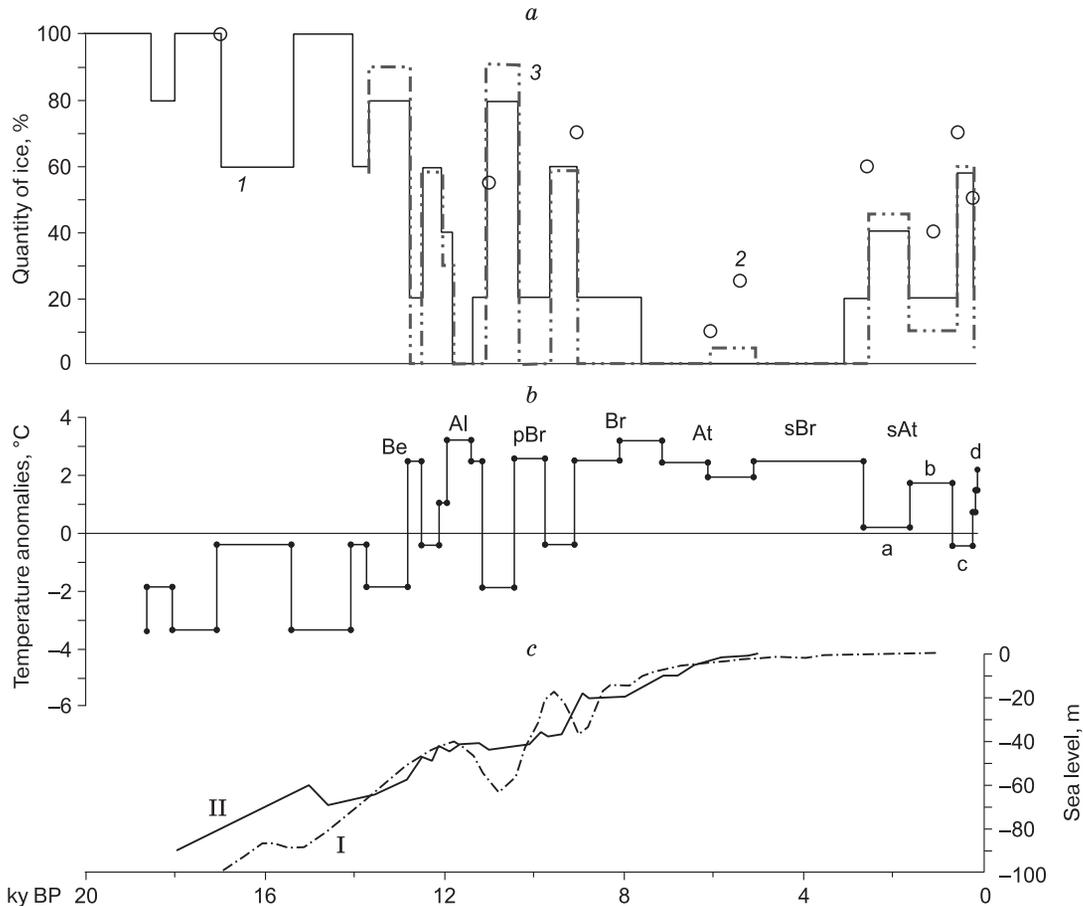


Fig. 6. Estimated changes in quantity of multiyear ice in Arctic marine waters in the Late Pleistocene–Holocene (a), variations of the mean air temperature anomalies in thawing season calculated by formulas (3), (4) based on variability in sea ice conditions (b), and the Laptev and East Siberian sea-level dynamics (c).

a: 1 – after [Borisov, 1970; Schiermeier, 2012]; 2 – after [Chizhov, 1970]; 3 – in East Siberian seas, derived from the formulas (3), (4) at different temperature anomalies; b: Be – Belling, Al – Allerød, pBr – Preboreal, Br – Boreal, At – Atlantic Period (sea-level reached the present-day marks), sBr – Sub-Boreal, sAt – Sub-Atlantic Period (a – Sedov-phase cooling, b – early Medieval Warm Period, c – Little Ice Age, d – recent warming). c: line I – after J. Curray, line II – after N. Mörner [Holmes and Creager, 1974].

dium values domain where more actual data are available allows more accurate comparison of the measured and calculated thermoabrasion rates. Moreover, absolute deviations of the calculated coastal retreat rates from actual rates vary within 0–2 m/yr, averaging 0.8 m/yr, while relative deviations vary from 0 to 18 %, averaging 8 %, which indicates a satisfactory level of reliability of the simulation results.

CONCLUSIONS

The coastal dynamics models developed by the authors show that from the beginning of sea-level stabilization at modern elevations (5–6 ky BP), the greatest activity of thermoabrasion of cryogenic coasts (from 10 to 20 m/yr) took place in the subboreal period. Another peak in the activation of thermoabrasion processes (8–15 m/yr) revealed by means

of modeling in the early Middle Ages, succeeded by a sharp decline these processes activity down to 1–2 m/yr in the Little Ice Age.

In the wake of the Little Ice Age, the average coastal retreat rate of the East Siberian seas increased gradually from 2 to 6 m/yr, which proved true for the last 500 years, with the ice-rich coasts retreat rate thus averaging 2–6 m/yr. However, the results of the performed simulation aided by the measurements indicate that in the last 40 years it has dramatically increased and reached 8–19 m/yr during the period of 2005–2012.

The current rates of the ice-rich coasts retreat was thus found to be higher than during the warming in the early Middle Ages, and are comparable to the rates of thermoabrasion in the climatic optimum of the subboreal period. Modern climatic parameters,

Table 1. Results of modeling ice-rich coastline degradation rate for Russia's eastern Arctic sector in the second half of the Holocene

Periods of climatic change (ky BP)	ΔT , °C	Region	T , °C	D	R , yr/m	$v(D, R)$, m/yr	$v(p, T)$, m/yr
Sub-Boreal (5–2.5)	2.5	1	5.1	2.25	0.160–0.220	14.1–10.2	10.4
		2	6.0	2.99	0.130–0.153	23.0–19.5	13.6
		3	5.5	1.73	0.113–0.175	15.2–9.9	11.2
Sub-Atlantic: Sedov-phase (2.5–1.5)	0.2	1	2.8	0.66	0.230–0.335	2.9–2.0	3.3
		2	3.7	1.09	0.206–0.243	5.3–4.5	5.2
		3	3.2	0.59	0.125–0.277	2.1–4.7	4.1
Early Medieval (1.5–0.5)	1.8	1	4.4	1.52	0.180–0.244	8.4–6.2	7.1
		2	5.3	2.25	0.150–0.176	15.0–12.8	10.4
		3	4.8	1.29	0.131–0.201	9.8–6.4	8.4
Little Ice Age (0.5–0.14)	–0.4	1	2.2	0.42	0.278–0.380	1.5–1.1	2.3
		2	3.1	0.56	0.233–0.274	2.4–2.0	3.9
		3	2.6	0.62	0.203–0.383	3.0–1.6	3.0
Recent warming (0.14–0): 1870–1970s	0.7	1	3.3	0.88	0.220–0.303	4.0–2.9	4.3
		2	4.2	1.39	0.187–0.220	7.4–6.3	6.5
		3	3.7	0.77	0.113–0.251	6.8–3.1	5.2
1970s–2005	1.0–1.5	1	3.8	1.32	0.200–0.260	6.6–5.1	6.2
		2	4.7	1.98	0.159–0.187	12.5–10.6	9.2
		3	4.2	0.98	0.102–0.227	9.6–4.3	6.5
2005–2012	1.5–2.2	1	4.5	1.82	0.170–0.225	10.7–8.1	8.4
		2	5.4	2.65	0.138–0.163	19.2–16.3	12.1
		3	4.9	1.34	0.089–0.197	15.1–6.8	8.8

Note. 1–3 regions of study are shown in Fig. 1; T – mean air temperature in thawing season; D – sea impact on coastal degradation; R – coastal resistance coefficient; $v(D, R)$, $v(p, T)$ – coastal thermoabration rates calculated on the basis of DR -model and pT -model, respectively.

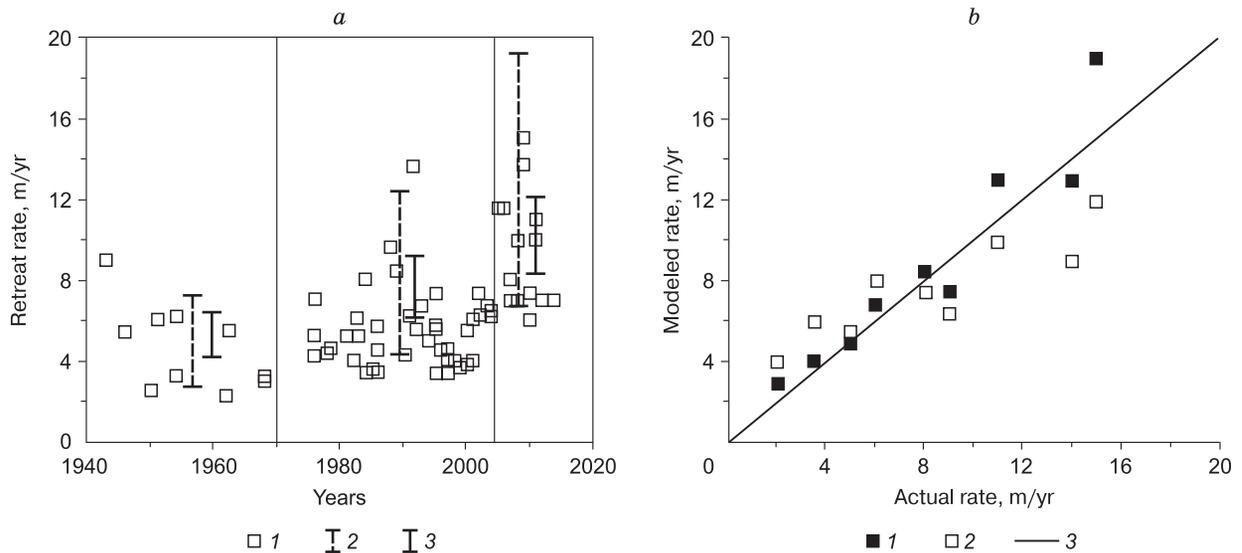


Fig. 7. Comparison of modelled and actual coastal retreat rates:

a: 1 – actual data [Razumov and Grigoriev, 2011]; 2, 3 – variation limits for modelled values (2 – in DR -model, 3 – in pT -model); b: 1, 2 – deviations between modeled and actual values (1 – in DR -model, 2 – in pT -model); line 3 – domain of equal values (modeled and actual).

including sea ice conditions, are close to those in the subboreal period of the second half of the Holocene when the mean air temperature anomalies in thawing season reached 2 °C and more, while multiyear ice did not survive on the Siberian seas.

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