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CRYOGENIC PROCESSES ON SHELF AND COAST OF ARCTIC SEAS

MODERN CLIMATE CHANGE AT HIGH LATITUDES AND ITS INFLUENCE ON THE COASTAL DYNAMICS OF THE DMITRIY LAPTEV STRAIT AREA

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The long-term data series of the ice coverage condition of the Arctic sea during the whole period of observations (from 1935–1940 to 2014) have been analyzed. It has been shown that the last decade is characterized by a sharp drop in the ice cover area in all seas. The data provided by the ocean meteorological stations confirm the increase in air temperatures over the same period. This is accompanied by a significant increase in the rate of coastal retreat and the rates of thermal denudation of icy coasts. The ratio of the rates of thermal denudation and thermal abrasion on the eroded ice complex has been estimated.

Area of the sea ice cover, coastal processes, remote sensing data, ice complex, alas complex, thermal abrasion, thermal denudation

INTRODUCTION

The factors that influence coastal development may be divided into two main groups: geological-geomorphological factors and hydrological-climatic factors. Other conditions being equal, the first group of the factors influences variations of coastal retreat, depending on the coast's height and the structure of the coast cross section determined by the tectonic conditions of the coast and the geological history of the territory. The second group of thermal marine erosion includes duration of the ice-free period, the existence of currents, the strength and direction of the winds and fetches, the sum of positive air temperatures, the character of snow accumulation, the radiation and heat balance of surface exposures, and the peculiar features of the surface runoff in the coastal zone. Certain values of coastal retreat are the result of the combined effect of the above factors.

This paper focuses on continuation of the previously conducted studies of coastal development of the Lyakhovsky Islands, based on comparison of the coastline position and of the brows of thermal cirques shown on aerial photographs of 1951 and Landsat 7 ETM+ images obtained in 1999–2001 [*Pizhankova and Dobrynina, 2010; Pizhankova, 2011*].

As new Landsat 8 survey data appeared (2013), it became possible to trace down changes in the retreat rates of the icy coasts in the eastern sector of the Russian Arctic zone in time, while the increase in the retreat values recorded over the recent decade and a half demanded consideration of the hydrological and climatic factors to explain the increase.

THE INVESTIGATION PROCEDURE

The remote survey data provided for the years of 1951, 1999–2001 and 2013 were used for investigating the coastline of the Bolshoy Lyakhovsky and Oygos Yar islands (Fig. 1). The techniques of superposition of images of different age and scale were similar to those applied previously and were performed by using ScanEx Image Processor 3.6.9 software. Digitization of the coastline, of the thermal cirque brows and the necessary measurements were conducted in the GIS-medium MapInfo [*Pizhankova and Dobrynina, 2010; Pizhankova, 2011*].

The data on the area of the ice cover of the sea and the climatic characteristics were obtained from the electronic archives of the Arctic and Antarctic Research Institute (AARI) (http://www.aari.nw.ru/projects/ECIMO/) and the All-Russia Research Institute for Hydro- and Meteorological Information – the World Data Center (ARRIHMI–WDC) (http://aisori.meteo.ru/ClimateR).

The data on the ice coverage were analyzed, and the plots were made for the Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea, as well as for their parts for the whole period of monthly and annual observations; i.e. the entire array of data was used. The data were used both in the absolute expression (thousand km^2) to compare the ice cover of different seas, and in percentage, which is convenient to understand the ice cover dynamic in time for each sea. The ice cover of the seas is different and varies differently in the summer season. August was chosen for comparison, as in the earlier time (June–July)

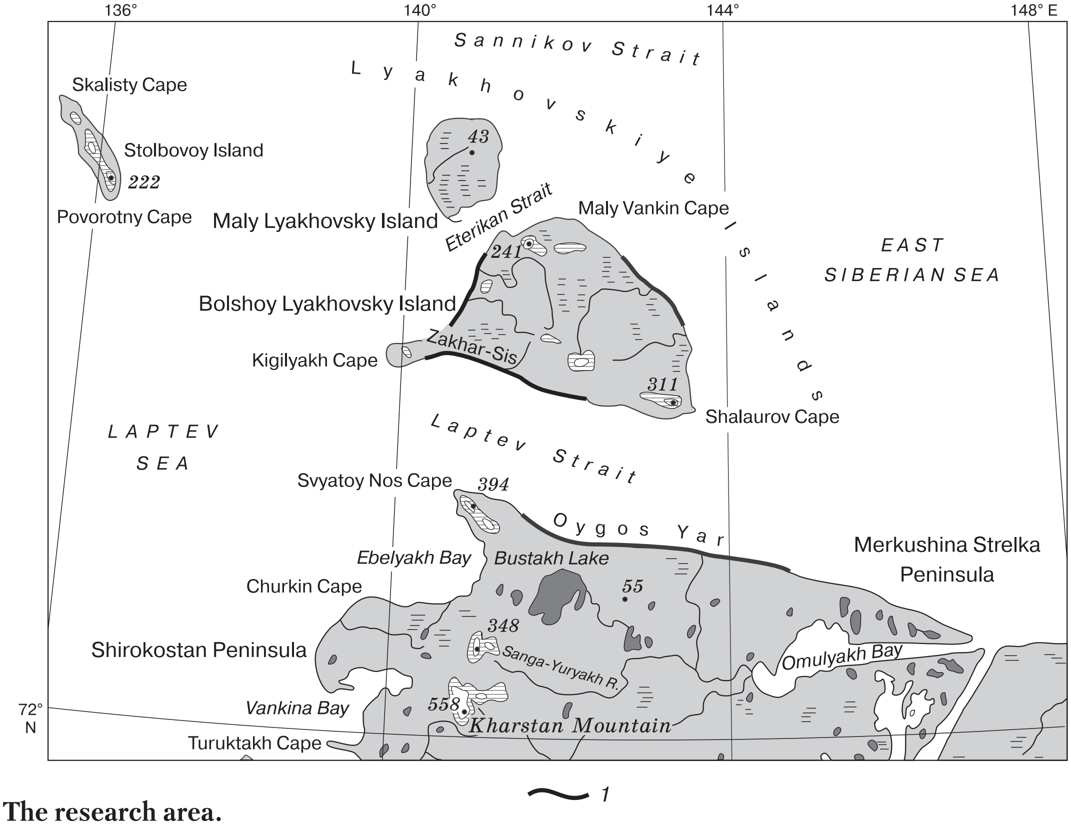

Fig. 1. The research area.

1 – segments of retreating shores for which medical measurements were made.

parts of the seas do not have open water at all the 100 % ice cover), whereas in the later time (September) they may be completely free from the ice (0 % ice cover); these facts make it difficult to compare the ice cover in the long-term sense. To investigate current regularity of changes in the sea ice cover, the data were averaged for the five-year period.

The main meteorological parameters (the mean annual and mean summer air temperatures and the total annual precipitation) were processed for the most northern coastal hydro- and meteorological stations (HMS): HMS Dikson, E.K. Fedorov HMS (Chelyuskin Cape), Kotelny HMS, and Wrangel Island HMS. Plots were built for the dynamic of the mean annual air temperatures, with the data averaged for the five-year period. Using the daily records of the air temperatures of HMS Kotelny, sums of the positive values of the air temperatures over all the years of observations were calculated.

ANALYSIS OF THE ICE COVERAGE CONDITIONS IN THE RUSSIAN ARCTIC SEAS

The relation between the coast retreat rate and the duration of the ice-free period is evident. It is possible to make indirect evaluation of changes in the open water period by analyzing the ice cover of the sea, considering the indirect correlation of these periods.

The ice coverage conditions of the Arctic are characterized by certain rhythms. *L.A. Zhigarev* [*1997*] provides the data of *P.M. Borisov* [*1970*] suggesting a 20-years' fluctuation in the ice cover of the seas in the Northern Hemisphere. This author also points out the existence of short-term (100, 30 years and less) cycles.

While studying the history of sea voyages in the Arctic seas, *V. Itin* [*1936*] made a conclusion about the existence of a period of ice cover variation equal to 30 years, while *L.A. Zhigarev* [*1997*] used these conclusions to build ice cover curves for the Kara and Chukchi Seas, which are asymmetric harmonicas with the ice sea cover rises every 4–5 years and a depression during 24–25 years.

The studies conducted in the Research Institute of Arctic and Antarctic [*Frolov et al., 2007*], showed that changes in the ice cover of the Arctic seas and in the mean annual air temperatures in the 20th–early 21st century are characterized by cyclic fluctuations lasting about 60 years (the largest range of variation), 20 and 10 years. A significant negative linear trend of the ice cover is typical of the western seas (Greenland, Barents, and Kara Seas), accounting for the cy-

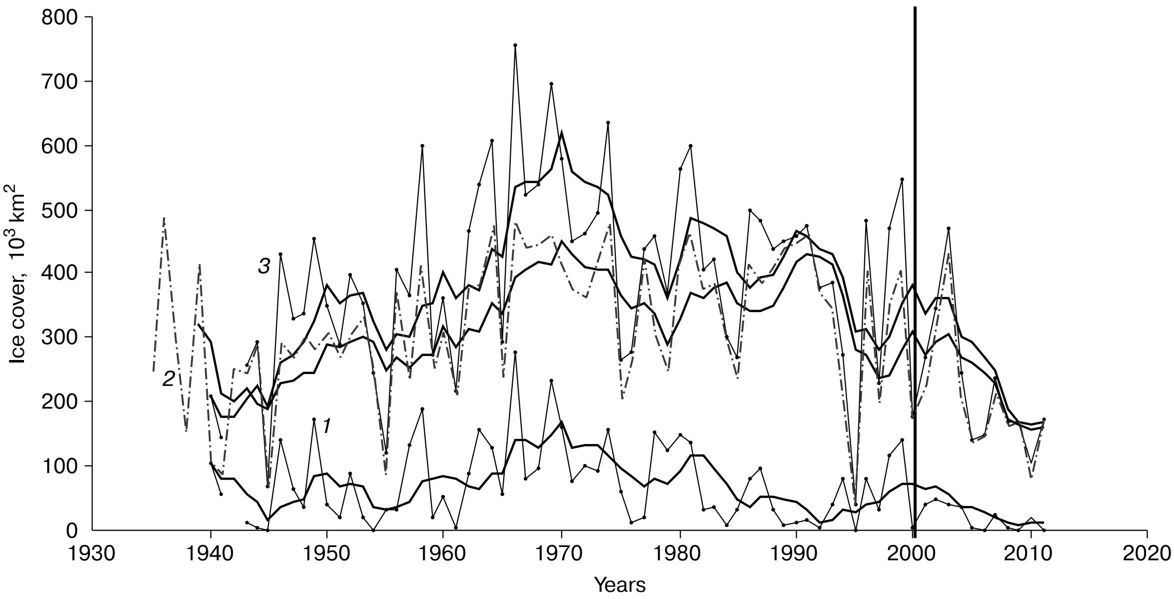

Fig. 2. Ice cover dynamics of the Kara Sea and of its parts (August) and the trend curves based on averaging results for a five-year period:

1 – the southwestern part, *2* – the northeastern part, *3* – the whole sea.

clic 60-years' variations. No definite trend is observed for the eastern seas (Laptev Sea, East Siberian Sea, and Chukchi Sea), with the ice coverage varying around the mean value (except for the recent years). Variations in the ice coverage in this region are characterized by high year-to-year fluctuations, while the 60-year cycle is less clearly expressed.

According to *V.F. Zakharov* [*1971*], the ice cover patterns reveal the cycles with the periods lasting 2–3, 4–5, 6–7, 7–9, 9–10, 11, and 18–19 years.

In order to understand the changes in the ice cover of the Arctic seas and their parts, the data on the Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea were analyzed from the beginning of the observations (1930–1940s) to 2014, contained in the electronic archives of the AARI (http://www.aari.nw.ru/projects/ECIMO).

The maximum ice coverage of the Arctic Ocean – 83 % of the total area of the ocean – is in April, while the minimum – 53 % of the total area is in September [*Zakharov, 1971*]. In accordance with the mean annual data, the ice coverage in May is 100 %; in June it is 93 %, in July it is 80 %, in August it is 57 %, in September 40 %, in October 78 %, and in November it reaches 100 % in the Siberian Arctic waters [*Zakharov and Malinin, 2000*].

The results of data processing demonstrate that the ice cover develops differently not only in the seas but also in parts of the seas.

For the southwestern part of the Kara Sea with the cycle period of 10 years, the ice coverage increases to reach its maximum in the mid-1960s (Fig. 2). The difference in the ice cover values from year to year does not exceed 50–60 %. For the northeastern part of the Kara Sea, the ice cover had a maximum value in 1960s, followed by a small decline in the late 1970s, a rise in the late 1980s – early 1990s, and drops to the minimum value in 1995. It generally retains the above average values from 1960s to 1990s. The difference in the ice cover values reaches 55–85 %.

The ice coverage of the Laptev Sea is lower than that of the Kara Sea and does not have the significant maximum records of the late 1960ies, deviating by not more than 60 % from the mean value (Fig. 3). Only the eastern part of the sea shows signs of certain rhythmicity, with a period close to 7–9 years with the blurred maximum values in the mid 1970ies. The influx of heat due to the runoffs of the Lena and Yana Rivers accounts for the lower ice coverage in the eastern part of the sea compared to the western one.

The ice coverage area of the East Siberian Sea is the largest among all the seas considered. Its western part has evident extreme records with a period of 15–20 years and a clearly observed extreme minimum in the late 1980s – early 1990s (Fig. 4). The total difference among the ice cover values in the neighboring years does not exceed 50 %. The difference among the ice cover values of the eastern part of the sea does not normally exceed 30 %, without any rhythmicity observed.

The Chukchi Sea has the smallest ice coverage area. High records were obtained for its southwestern part in the early 1940s, mid-1950s, and early 1980s, the lowest records were shown in the 1960s (Fig. 5).

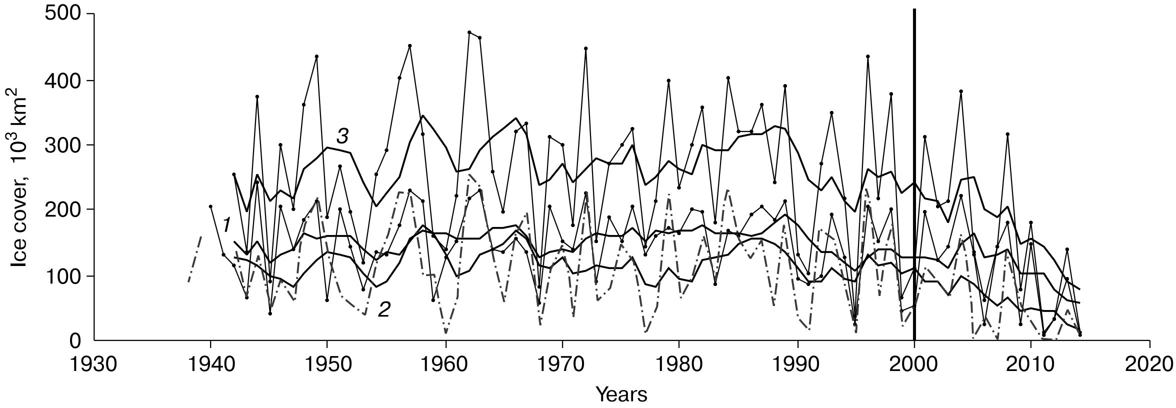

Fig. 3. Ice cover dynamics of the Laptev Sea and of its parts (August) and the trend curves based on averaging results for a five-year period:

1 – the western part, *2* – the eastern part, *3* – the whole sea.

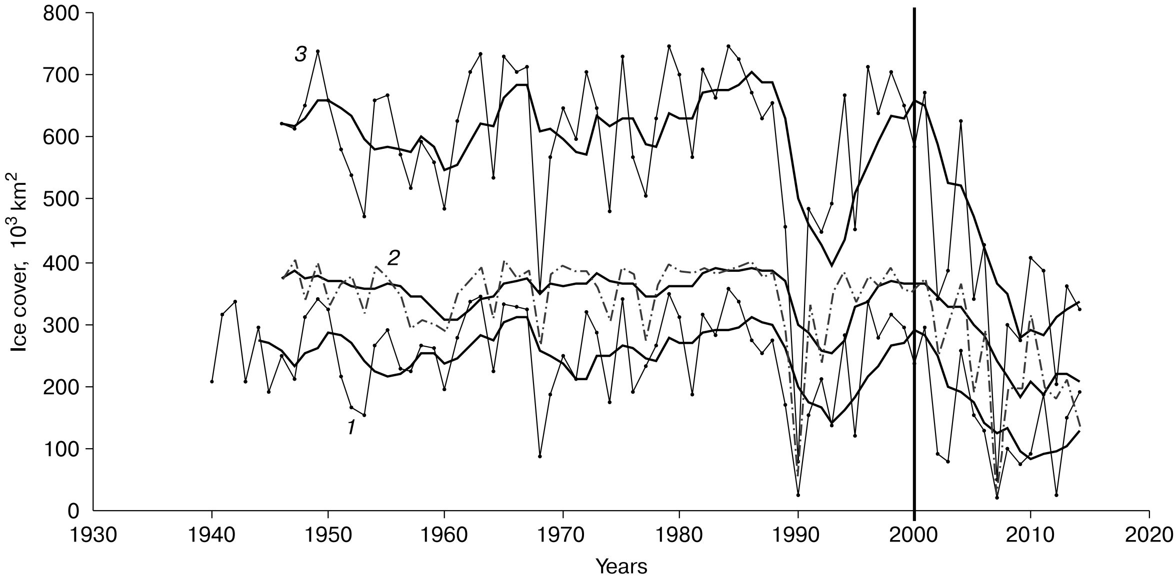

Fig. 4. Ice cover dynamics of the East Siberian Sea and of its parts (August) and the trend curves based on averaging results for a five-year period:

1 – the western part, *2* – the eastern part, *3* – the whole sea.

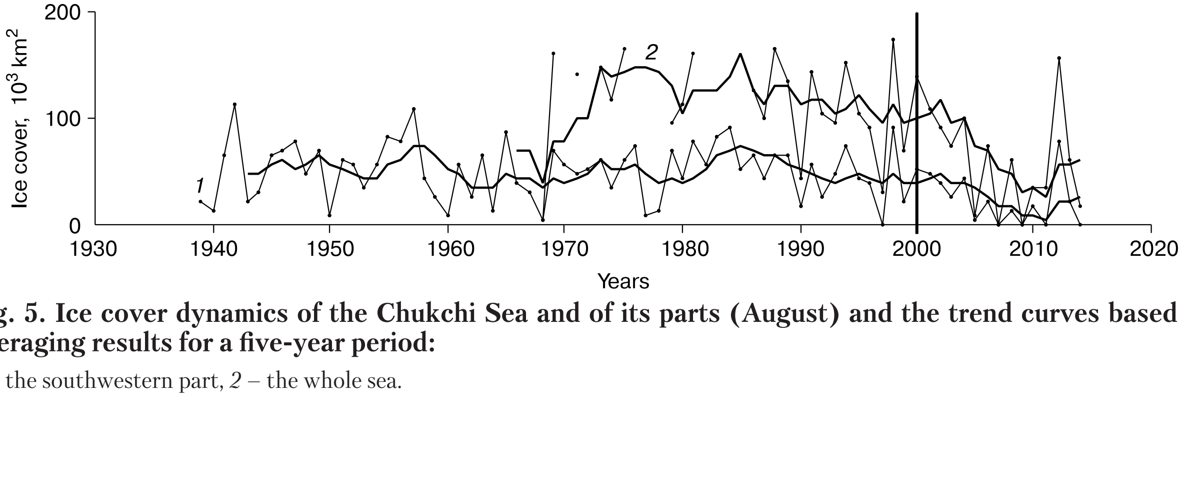

Fig. 5. Ice cover dynamics of the Chukchi Sea and of its parts (August) and the trend curves based on averaging results for a five-year period:

1 – the southwestern part, *2* – the whole sea.

Table 1. **Mean annual values (August) of the ice cover of the Russian Arctic seas for the periods before 2000 and 2000–2014**

Arctic seas	Ice cover, thousand km^2		Ice cover, %	
	Before 2000	2000–2014	Before 2000	2000–2014
Kara Sea	398.5	201.5	48	24
southwestern part	74.4	15.1	22	5
northeastern part	322.8	186.2	65	38
Laptev Sea	269.3	155.4	50	29
western part	152.1	102.2	61	41
eastern part	117.8	52.5	41	18
East Siberian Sea	606.5	378.7	79	49
western part	253.9	138.3	70	38
eastern part	352.7	240.7	87	59
Chukchi Sea	117.1	64.2	32	17
southwestern part	51.1	24.7	29	14
Total	1391.4	799.8	52	30

As a rule, the total difference among the ice cover values does not exceed 50 %. Observations over the ice cover of the entire sea started in the late 1060s of the 20th century, with significant time gaps. The annual August data have been available only since 1986.

Analysis of the data shows that before 2000 all the cycles, except for the evident maximum record of the ice cover of the Kara Sea, are expressed very slightly: the ice cover varies around the mean value characteristic of the period from the beginning of the observations to 2000. Sustained and rather sharp reduction of the ice cover to the values below the mean figure is characteristic of all the seas in the period after 2000.

This can be seen quite well from Table 1 and Figure 6, which show the mean values of the ice cover area of the Arctic seas and their parts in the periods from the beginning of the observations to 2000 and in the period of 2000–2014. Their comparison shows that the ice cover area of the Arctic seas of Russia has reduced 1.5–2.2 times, having reached the maximum records in the southwestern part of the Kara Sea (4.9 times).

ANALYSIS OF THE CLIMATIC FACTOR DYNAMICS

The thermal and circulating characteristics of the climate are the main climatic factors influencing the coastal development of the Arctic seas. The air temperature in the littoral zone and on the islands is closely connected with the ice cover of the seas.

The mean annual air temperature varies along the sea coasts from west to east from −11.3 °C (Dickson Island, Kara Sea), to −14.5 °C decrease in the eastern margin of the Kara Sea (Cape Chelyuskin) and in the Laptev Sea (Kotelny Island) to −11.0 °C increase (Wrangel Island, Chukchi Sea) (Table 2) [*Bulygina et al., 2014a*]. The influence of the Pacific Ocean is manifested both in the reduction of the ice cover of the Chukchi Sea, compared to the more western seas (Fig. 5, Table 1), and in the rise of the air temperature (Fig. 7, *a*, Table 2).

Fig. 7 shows the air temperature change curves for the entire period of observations made at all the main hydrometyeorological stations. The temperature curves are based on the data from HMS Dickson, which has the longest period of observations beginning from 1917 and from Fedorov HMS. The lowest mean annual air temperature refer to the late 1950s–early 1970s (Fig. 7, *a*). They correlate with the high ice coverage of the Kara Sea in this period, while the high temperatures of the 1940s correlate with the low ice coverage (Fig. 2).

For more eastern stations, the extremum values of the air temperatures are not distinct (Fig. 7, *b*). The ice coverage of the Laptev Sea, East Siberian Sea, and Chukchi Sea do not have evident extreme values, except for the minimum value of 1990 recorded in the East Siberian Sea (Fig. 4).

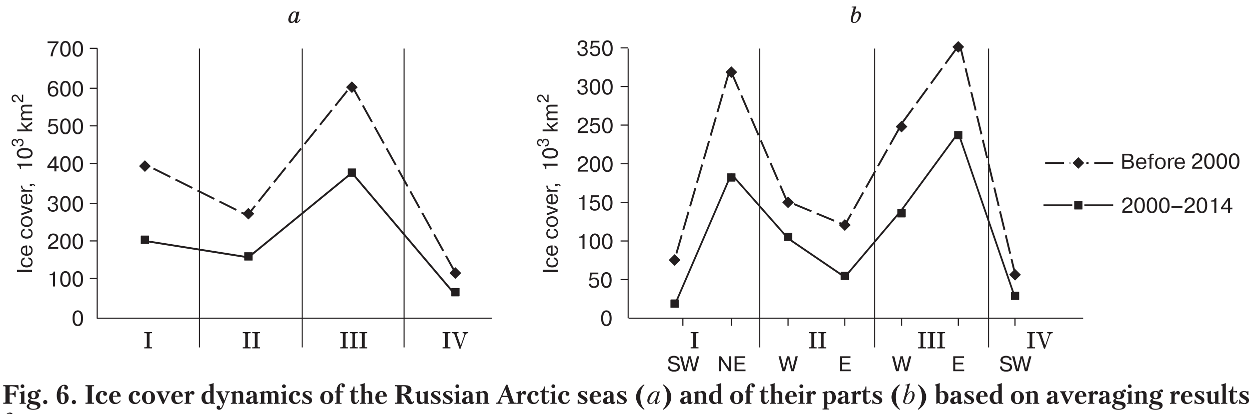

Fig. 6. Ice cover dynamics of the Russian Arctic seas (*a*) and of their parts (*b*) based on averaging results for August.

I – Kara Sea; II – Laptev Sea; III – East Siberian Sea; IV – Chukchi Sea.

Table 2. **Main meteorological characteristics for the coastal hydrometeorological stations of the Arctic seas**

Hydrometeorological station	Mean air temperature, °C			Mean precipitation, mm		
	Entire period	Before 2000	2000–2012(13)	Entire period	Before 2000	2000–2012(13)
Dickson (73°50′ N, 80°40′ E)	–11.3	–11.4	–10.2	370.3	357.1	401.2
Fedorov HMO (77°72′ N, 104°30′ E)	–14.5	–14.8	–13.2	217.9	232.7	173.8
Kotelny (76°00′ N, 137°87′ E)	–14.5	–14.8	–12.9	161.6	166.7	148.3
Wrangel Island (70°98′ N, 178°48′ E)	–11.0	–11.3	–9.4	154.9	160.7	139.7

Over the recent decade and a half, the mean annual air temperature rise has been observed. For example, at HMS Kotelny the mean air temperature before 2000 was –14.8 °C, while the mean annual air temperature for the recent 14 years is –12.9 °C (Table 2), so the mean annual air temperature increment in regard to the period before 2000 is 1.9 °C. The mean summer air temperatures have the same posi-

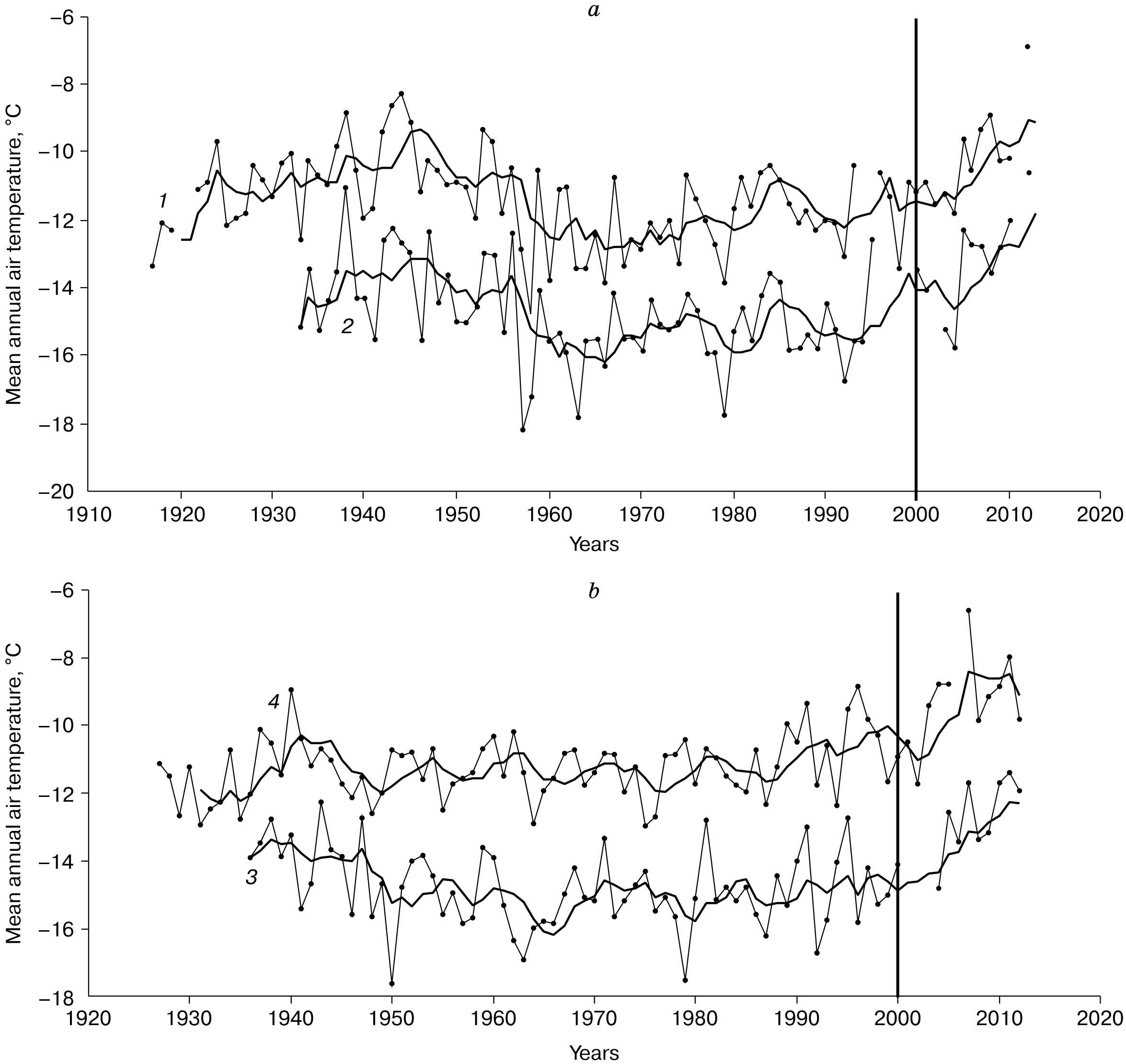

Fig. 7. Changes in the mean annual air temperatures recorded at HMS Dickson (line *1*), Fedorov HMO (line *2*), Kotelny HMS (line *3*), Wrangel Island HMS (line *4*) and curves for the five-year period.

tive trend: according to the data recorded at HMS Kotelny, the air temperature in July and August of 2000–2013 grew to differ from the mean air temperature in the preceding period by 1 °C (the average air temperature for the period of 1933–1999 is equal to 2.2 °C, in the period of 2000–2013 it is 3.2 °C). For the ice-free period (July–September), this difference was 1.2 °C with the mean annual air temperatures in the periods under study being 0.9 and 2.1 °C.

The sums of the positive air temperatures for all the years of observations were calculated according to the daily data recorded at HMS Kotelny [*Bulygina et al., 2014b*]. The average sum for the period of 1936–1999 was 184.9 °C, and for the period of 2000–2013 it was 254.2 °C. The difference between the average sums for the recent 14 years and for the preceding period is 69.3 °C.

The total annual precipitation rate somewhat decreases (except HMS Dickson) [*Bulygina et al., 2015*]; however, it is too early to speak about serious trends. Unfortunately, the monthly data on the amount of precipitation has been available only since the late 1960s of the 20th century; therefore, it is difficult to make any conclusions yet.

OTHER NATURAL FACTORS AFFECTING COASTAL DYNAMICS

In addition to the above mentioned factors, the following phenomena affect the dynamics of the considered segment of the Arctic coastal zone: the wave action (most active in storms and fetches; longshore currents; fluctuations in the sea level during wind-effected phenomena; the character of snow accumulation depending on the wind regime; and the water warming river runoff. For the shores composed of the Ice Complex deposits, which are eroded with thermal cirques formed, the sums of positive air temperatures, solar radiation, the character of snow accumulation, and exposition of the shore are most important.

The most significant variations in the dynamics of the coastal processes are caused by the geological and tectonic structure of the coastal zone composed of the rocks directly affected by sea. In the areas of the steady uplift these rocks contact the Pre-Quaternary rocks, which are resistant to abrasion. They are characterized by the presence of steady segments of the shore and by accretion of the shores [*Pizhankova and Dobrynina, 2010*]. These territories are often located next to the region of *alternating-sign movements* with a tendency for elevation. In this case, the thickness of the Quaternary cover does not normally exceed 50–60 m, and the roof of the bedrock is close to the Earth surface. As the distance from the areas of ablation increases (in *alternating-sign movements* with a trend for lowering), the thickness of the Cainozoic deposits increases up to 100–300 m [*Dorofeev et al., 1999*], and the steady segments of the shore are replaced by eroding shores. A large part of the shore of the eastern sector of the Russian Arctic is composed of ice-rich rocks of the Ice Complex (IC) and Alas Complex (AC), manifested on the relief by plains with the absolute elevations of 10–40 m and lower, as well as of marine and alluvial-marine deposits, forming terraces with the elevations usually not lower than 4 m. The latter are characterized by higher-temperature and less thick permafrost. The areas with a trend for lowering are known for the merger of alas areas into thermokarst plains. The area occupied by them can reach 60 % or more. Depending on whether the IC and AC bottom is above or below the sea level, the shore retreat rates vary. In the first case, the shore retreat rates for the southern shore of Bolshoy Lyakhovsky Island proved to be 0.7–2.1 m/year lower than in the second case [*Pizhankova and Dobrynina, 2010*].

LONG-TERM VARIABILITY OF THE SHORES REVEALED BY MULTITEMPORAL REMOTE SENSING DATA

The use of multitemporal remote data of different time periods has allowed changes in the position of the coastline to be traced down throughout its length, covered by aerospace images (Fig. 8–10), and the value of reduction in the coastal area and the shore retreat rates to be assessed (Table 3). Comparison of satellite images (SI) made in 1999–2001 and in 2013 has shown that the retreat rates of the shores of Bolshoy Lyakhovsky Island and Oygos Yar exceeded the values of the preceding 50-year period by 1.3–2.9 times.

The values of the retreat rates throughout the length of the shore can be shown graphically, by dividing the coastal zone into segments corresponding to different types of the onshore cross-section structure, namely: those composed from the surface by Alas or Ice Complexes, alluvium, or alluvial-marine deposits. The longest segments occupied by the Alas Complex were divided into shorter ones, approximately of the same length. The measurement results for each of such segments are shown in Fig. 11, 12.

In accordance with different morphostructural positions of the coast, variations in the shore retreat rates are observed. For Bolshoy Lyakhovsky Island, three morphostructural regions are identified: in accordance with these regions, the retreat rates change from minimal rates (0–0.5 m/year) in the areas of persistent elevations (Kigilyakh Peninsula, Shalaurov Cape) to maximal values, which are 5–7 m/year for the period of 1951–2001 and 10–13 m/year for 2001–2013 in the areas with a tendency for subsiding. For the latter, the differences in the cryolithological onshore cross-section structure of the shore cross section are attributed to the position of the sea

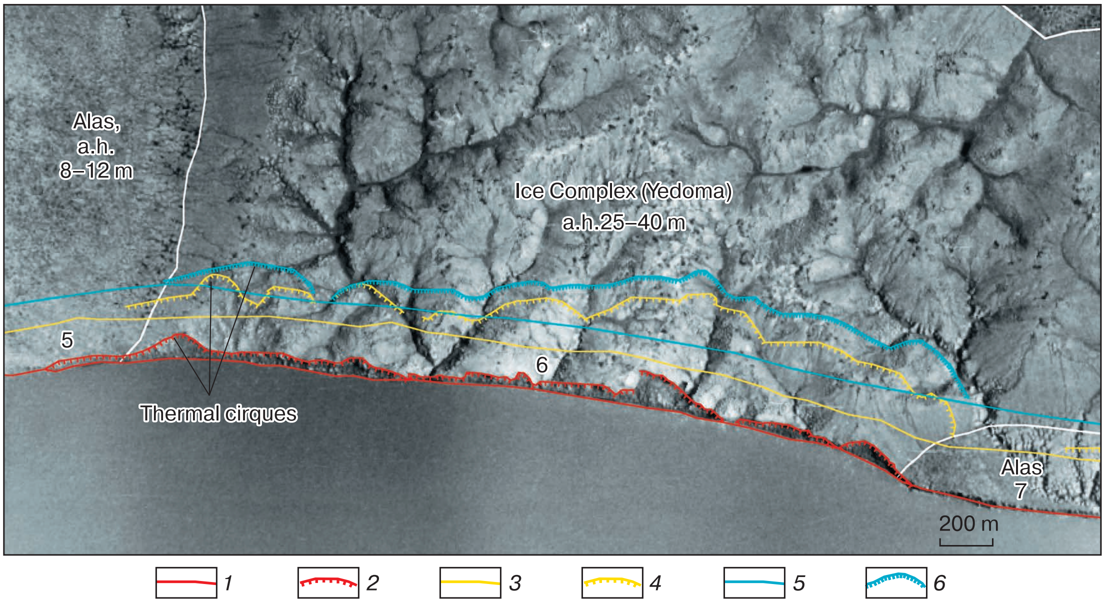

Fig. 8. Coastal dynamics of the southern shore of Bolshoy Lyakhovsky Island (an air photo of 1951).

5–7 – numbers of segments for which the retreat rates have been calculated (Fig. 11, *a*). The coastline: *1* – 1951; *3* – 2001; *5* – 2013. The position of the edge of the thermal cirques: *2* – 1951; *4* – 2001; *6*– 2013.

level in relation to the base of icy deposits of the ice and alas complexes, which is reflected on different shore retreat rates (Table 4).

In the tectonic structure of Oygos Yar, there are also areas of steady uplifts (the erosion remnants of Cape Svyatoy Nos), areas of alternating movements with a trend for elevation (fringing the former ones) and the areas with a tendency for subsiding. In Fig. 12, the plot made for dedicated segments from west to east (from Cape Svyatoy Nos to Merkushina Strelka) demonstrates the character of changes in the retreat rates, in accordance with which the boundaries of the above morphostructures may be indicated. The maximal shore retreat rates for Oygos Yar were

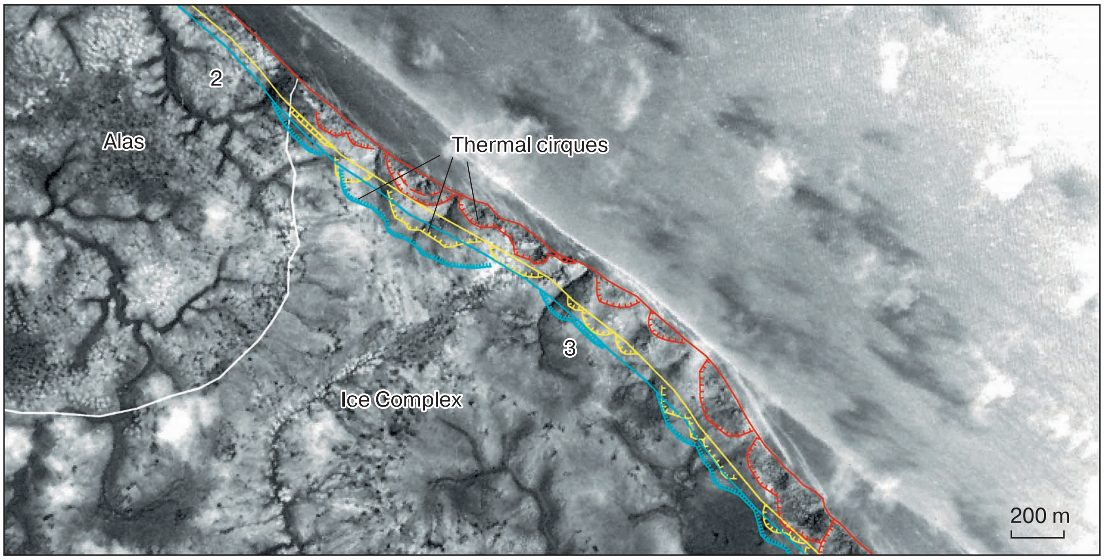

Fig. 9. Coastal dynamics of a part of the northeastern shore of Bolshoy Lyakhovsky Island (air photo of 1951).

2, 3 – numbers of segments for which the retreat rates have been calculated (Fig. 11, *c*). See Fig. 8 for explication of the symbols.

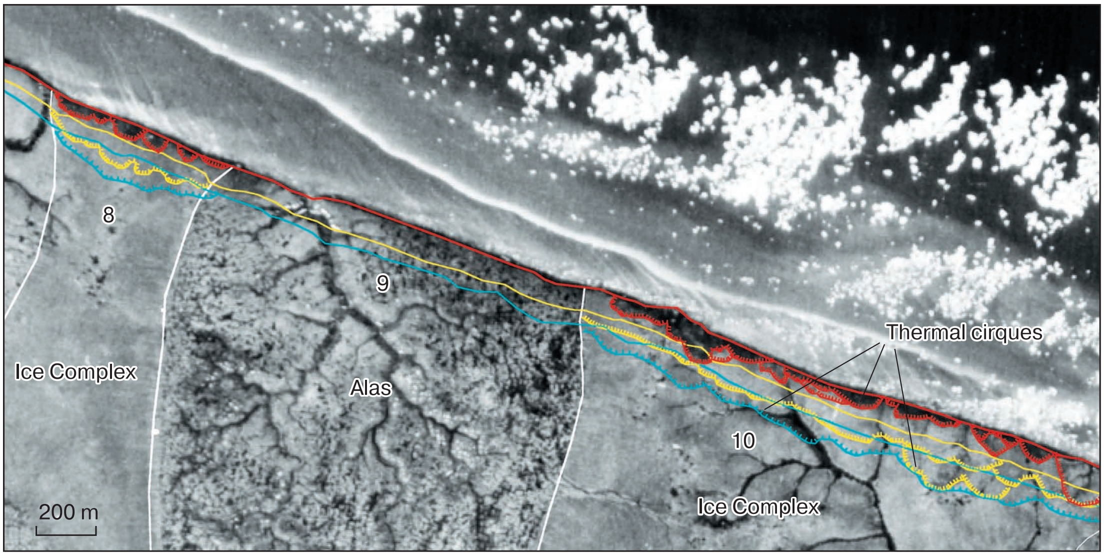

Fig. 10. Coastal dynamics of a section of the shore of Oygos Yar (1951).

8–10 – numbers of segments for which the retreat rates have been calculated (Fig. 12). See Fig. 8 for explication of the symbols.

3.0–3.5 m/year for the period of 1951–1999 and 5.5–6.5 m/year for 2000–2013.

Retreat of the shores composed from the surface of an Ice Complex on the southern and northeastern shores of Bolshoy Lyakhovsky Island and Oygos Yar occurs with thermal cirques and thermal terraces formed (Fig. 8–10). The total length of the shores for which such thermal denudation forms are characteristic is 24.9 km for Bolshoy Lyakhovsky Island, or nearly 70 % of the shores composed of the Ice Complex, for OygosYar – more than 90 %. The total length of the shores composed of the Ice Complex for Oygos Yar does not exceed 20 % of the entire length of the eroding shore.

The study of the thermal denudation landforms and their comparison for different sections of the shores and different period of remote sensing (Table 5, Fig. 13, 14) have shown the following. Significant differences both in their morphology and in the quantitative parameters have been observed. Characteristic for the southern shore of Bolshoy Lyakhovsky Island is merging of thermal cirques, with scalloped

Table 3. **Characteristic of the retreating shores of Bolshoy Lyakhovsky Island and Oygos Yar**

Shore type	Years	Bolshoy Lyakhovsky Island									Oygos Yar		
		Southern coast			Northeastern coast			Western coast					
		S	*L*	*v*	*S*	*L*	*v*	*S*	*L*	*v*	*S*	*L*	*v*
Shores composed by IC from the surface (h = 20–30 m)	1951–2000	4.3	25.4	3.4	1.7	12.4	2.7	2.0	7.9	5.1	1.5	20.0	1.5
	2001–2013	2.2	25.2	7.2	0.5	12.6	3.5	0.8	8.0	8.6	1.0	19.1	4.3
Shores composed of AC from the surface (h = 8 m)	1951–2000	7.5	42.9	3.5	1.2	12.3	1.9	2.3	12.1	3.7	10.9	84.0	2.6
	2001–2013	3.8	41.8	7.6	0.4	9.6	3.2	1.4	12.0	9.9	5.5	85.1	5.4
Shores composed of alluvium (h = 4 m)	1951–2000	0.5	2.7	3.3	2.0	10.3	4.0	–	–	–	–	–	–
	2001–2013	0.3	2.5	9.4	0.7	9.7	6.2	–	–	–	–	–	–
Shores composed of marine and alluvial-marine deposits (h = 3 m)	1951–2000	–	–	–	–	–	–	5.3	26.5	4.0	–	–	–
	2001–2013	–	–	–	–	–	–	2.0	14.4	11.6	–	–	–
Retreating shore in total	1951–2000	12.2	71.0	3.4	4.8	35.0	2.7	4.3	20.0	4.3	12.4	104.0	2.4
	2001–2013	6.4	70.0	7.7	1.6	32.0	4.2	2.3	20.0	9.4	6.5	104.2	4.4

Note for Table 3, 4. h – mean shore height, m; S – area of the coast eroded by sea water, km^2; L – shore length, km; v – mean shore retreat rate, m/year.

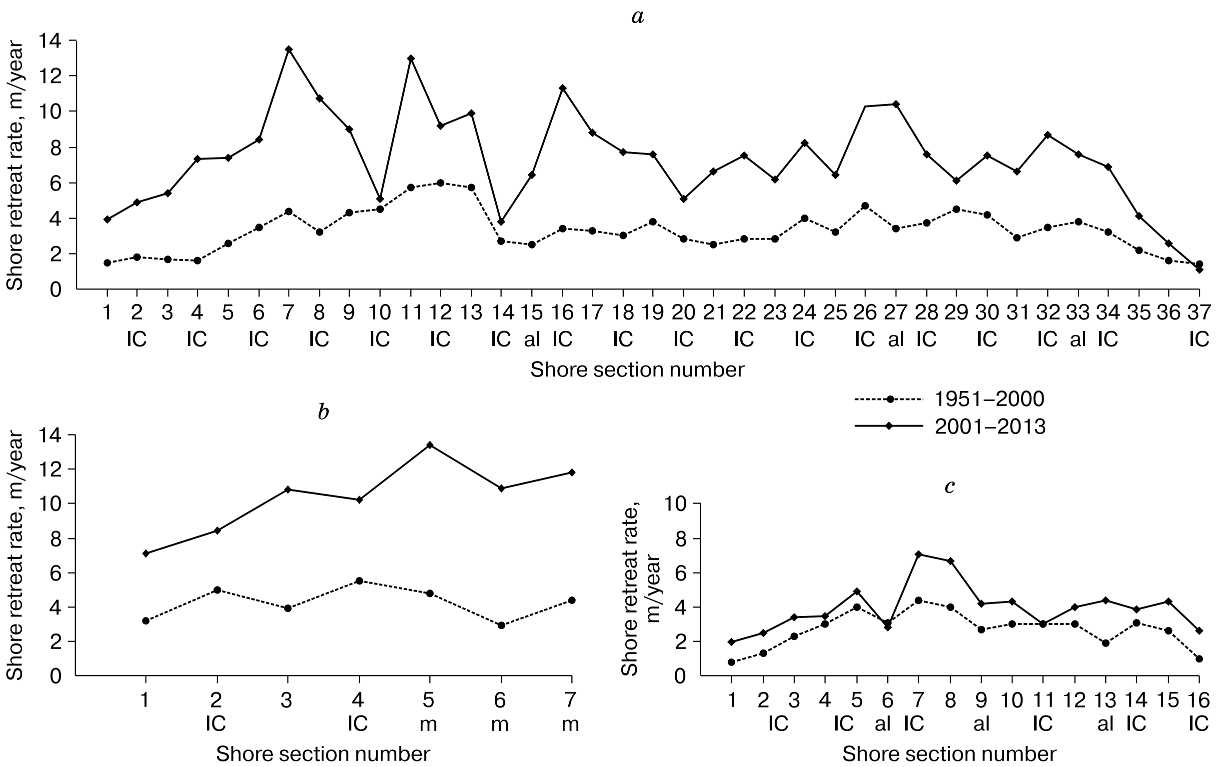

Fig. 11. Changes in the retreat rates for different shores of Bolshoy Lyakhovsky Island.

Shores: *a* – southern, *b* – western, *c* – northeastern. 1–37 – segment numbers; IC – segments of the Ice Complex; al – segments of alluvial deposits; m – areas of marine and alluvial-marine deposits; no letter indications – areas of the Alas Complex. The length of the shores: *a* – 70 km, *b* – 48 km, *c* – 32 km.

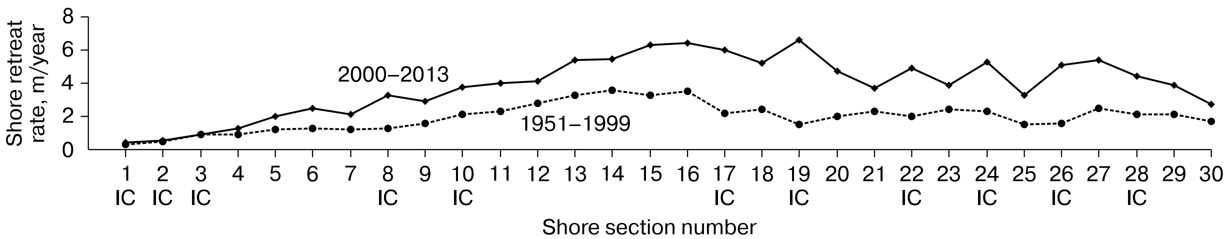

Fig. 12. Changes in the retreat rates for different segments of Oygos Yar.

1–30 – segment numbers; IC – segments of the Ice Complex; no letter indications – segments of the Alas Complex. The length of the shore is 107 km.

Table 4. **Characteristic of the retreating segments of the southern coast of Bolshoy Lyakhovsky Island with varying structure of the shore cross section**

Shore section	Years	Coast Zakhar-Sis*			Coast located in the east of the River Zimovye**		
		S	*L*	*v*	*S*	*L*	*v*
Shores composed of IC from the surface	1951–2000	1.2	5.9	4.0	2.9	17.0	3.4
	2001–2013	0.6	6.0	8.5	1.4	16.9	7.1
Shores composed of AC from the surface	1951–2000	4.4	16.5	5.0	1.4	8.8	3.2
	2001–2013	2.2	16.3	11.4	0.7	8.9	6.7

* Above and below the sea level composed of IC and AC.

** IC and AC underlying by less icy deposits above the sea level.

Table 5. **Dynamics of the coastal processes proceeding on the IC segments**

Parameters measured on the basis of remote data (total mean values)	Years	Bolshoy Lyakhovsky Island			Oygos Yar
		Southern coast	Northeastern coast	Western coast	
The rate of the thermal cirque brow retreat in the most remote part from the shore, m/year	1951–2000	4.2	2.0	–	2.0
	2001–2013	7.0	3.8	–	3.6
Thermal abrasion rate in the places of the thermal cirque brow retreat, m/year	1951–2000	3.3	2.6	–	1.5
	2001–2013	7.4	4.2	–	3.6
Mean multi-annual thermal abrasion rate, m/years	1951–2000	3.4	2.7	5.1	1.5
	2001–2013	7.2	3.5	8.6	4.3
Total area of thermal terraces, km^2	1951	0.7	0.4	–	0.6
	2001	1.7	0.3	–	1.3
	2013	1.5	0.4	–	1.2

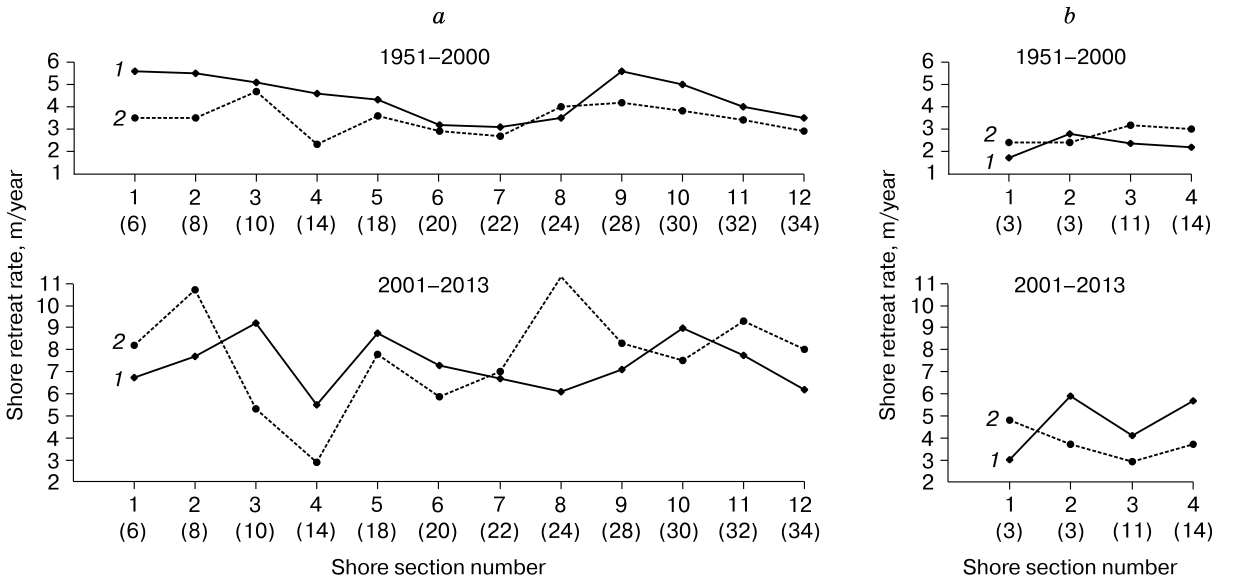

Fig. 13. Changes in the rates of thermal abrasion and thermal denudation of IC on different shores of Bolshoy Lyakhovsky Island in different periods of time.

Shores: *a* – southern shore, *b* – northeastern shore; *1* – retreat rate of thermal cirque brows in the part most remoted from the shore (average value for the parts); *2* – thermal abrasion rate at the sites of measuring the retreat rates of thermal cirque brows (average value for the parts). The figures in brackets indicate the number of the shore segment in the total numbering of the shore segments.

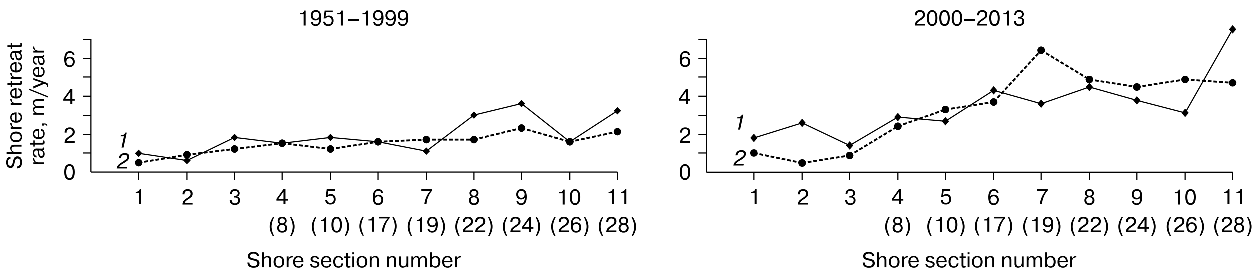

Fig. 14. Changes in the rates of thermal abrasion and thermal denudation of IC in different segments of Oygos Yar in different periods of time.

See Fig. 13 for explication of the symbols for Fig. 14.

forms formed. The northeastern shore and Oygos Yar had separated thermal cirques in 1951, which were merged in 2013.

On the western coast of Bolshoy Lyakhovsky Island no thermal denudation forms were found, which is attributed to high thermal abrasion rates. It is supposed that for this shore the thermal denudation and thermal abrasion rates are close [*Pizhankova, 2011*].

According to the remote sensing data, the highest retreat rate of the brows of thermal cirques is characteristic of the southern shore of Bolshoy Lyakhovsky Island. Its northeastern shore and Oygos Yar have equal thermal denudation rates but different thermal abrasion rates. In the first case, the thermal abrasion rate is higher than the thermal denudation rate, and this tendency continues in the recent decade. In the second case, the thermal abrasion rate in 1951–2000 was lower than the thermal denudation rate; currently they are equal. On the southern shore of the island, the thermal denudation rates in 1951–2000 exceeded the thermal abrasion rate 1.3 times; currently the thermal abrasion rates are higher than the thermal denudation rates.

Compared to 1951, in 1999–2001 the area of the thermal terraces more than doubled on the southern shore of Bolshoy Lyakhovsky Island and Oygos Yar; this parameter somewhat decreased in 2013. Reduction of the area of thermal terraces has been recorded for the northeastern shore of Bolshoy Lyakhovsky Island, and in 2013 their value approached the value of 1951 (Table 5).

DISCUSSION OF RESULTS

V.F. Zakharov [*1981*] provided data collected by different researchers relating to climate changes in the Northern Hemisphere and in the Atlantic part of Arctic. The data indicate that, in whichever direction

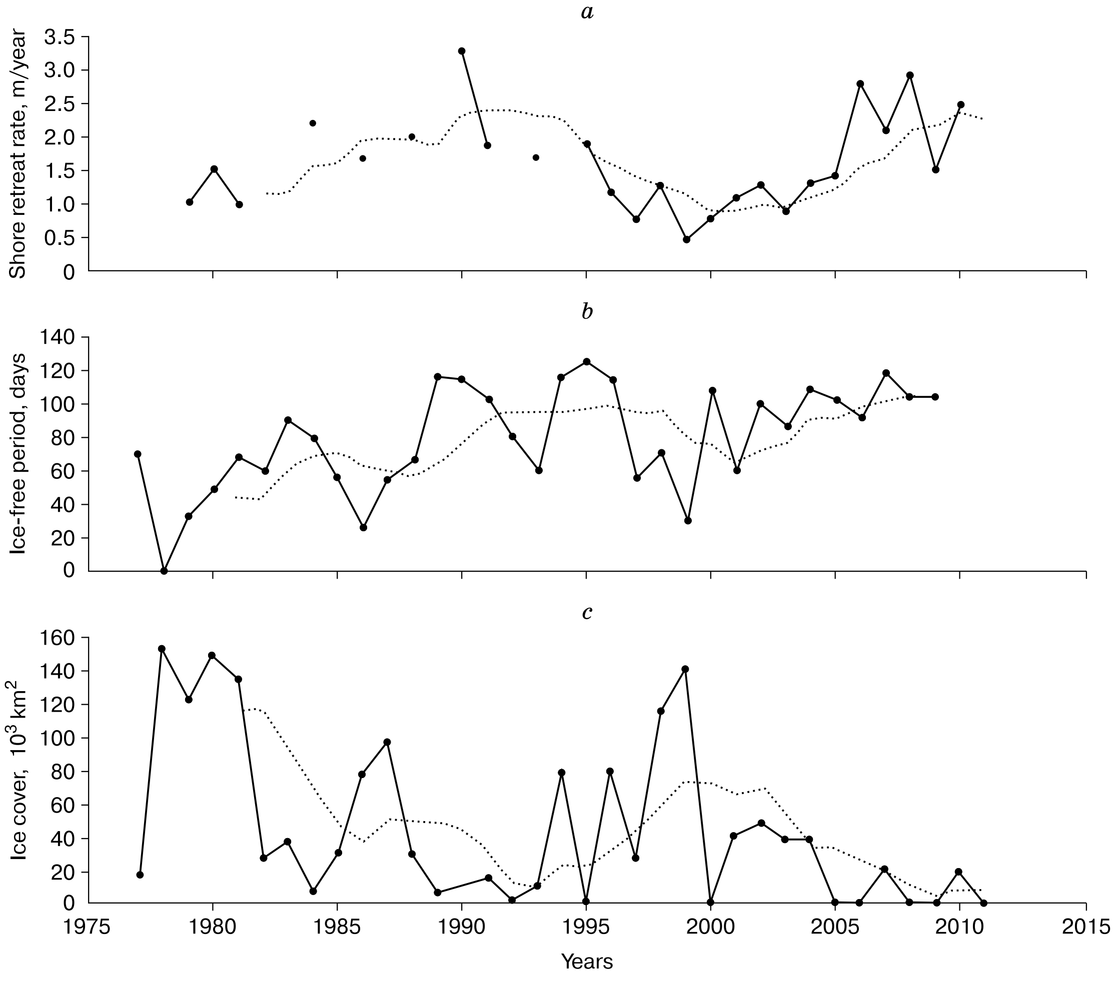

Fig. 15. Comparison of data on the shore retreat rates (*a*), duration of the ice-free period (*b*) and the ice cover of the southwestern part of the Kara Sea in August (*c*).

a – the data provided by [*Vasilyev et al., 2011*]; *b* – before 2002 according to [*Vasilyev et al., 2006*], after 2002 in accordance with the time of ice phenomena recorded at the Marre-Sale polar station (http://www.aari.nw.ru/projects/ECIMO/); *c* – data on the ice cover of the southwestern part of the Kara Sea (http://www.aari.nw.ru/projects/ECIMO/).

the climatic changes occur (cooling or warming), they are most intense in the extreme north of the Atlantic Ocean and in the adjacent Arctic districts. The data on the ice coverage conditions of the Russian Arctic seas provided in this study have confirmed this assumption and have demonstrated significant fluctuations of the ice coverage for the most western of all the seas – the Kara Sea (Fig. 2). The same tendency can be traced in the changes of the mean annual air temperatures (Fig. 7), which is confirmed by the secular trend data of the mean annual air temperature anomalies [*Zakharov, 1981*]. Moreover, this author insists that the ice cover and its behavior play the decisive role in changes of the thermal air regime: "The thermal conditions in the atmosphere are not the cause but rather the effect of the sea ice area changing in time" [*Zakharov, 1981, p. 71*]. The behavior of the ice cover of Arctic is explained by the change in the thermohaline structure of the upper layer of the ocean. Sea ice, the ocean, and the atmosphere form a single system functioning in the regime of self-induced oscillation, which results in the change of the upper ocean layer [*Zakharov and Malinin, 2000*].

Despite the numerous data and a rather long history of investigating the behavior of the Arctic sea shores, the results of measuring the shore retreat and its rates are quite contradictory. It is stated in some studies [*Vasilyev et al., 2006*] that there is no direct correlation between the retreat rate of the shore, the air temperature and duration of the ice-free period and that the correlation coefficient between them does not exceed 0.15 for the western coast of Yamal Peninsula. However, the integrated analysis of the curves of the shore retreat rates, of the duration of the ice-free period [*Vasilyev et al., 2011*] and the ice cover of the seas in August (http://www.aari.nw.ru/projects/ECIMO/) has shown that such correlation exists in the long terms (Fig. 15).

Reduction of the ice cover of all the Russian Arctic seas over the recent decade and a half and the resulting extension of the ice-free period with all the respective effects of it (increase of the total amount of wave energy, the length of the wave run-up, increase in the height of storm fetches [*Ogorodov, 2011*]), as well as growth of air temperatures cased acceleration of the destructive processes on the icy shores, which occupy a significant part of the eastern Arctic coast of Russia. This has been proved by comparing multitemporal remote sensing data for Bolshoy Lyakhovsky Island and the southern shore of the Dm. Laptev Strait.

The results obtained indicate more than double increase of the retreat rates of the shores composed of the icy rocks of the Ice and Alas Complexes, marine, alluvial-marine, and alluvial deposits. As earlier, the highest rates are recorded for the western and southern shores of Bolshoy Lyakhovsky Island, while the lowest rates are now characteristic of the island's northeastern shore. For Oygos Yar nearly triple increase of the shore retreat rates composed of Ice Complexes is characteristic, although in the previous 50 years period the retreat rates of these shores were much lower than for the northeast of Bolshoy Lyakhovsky Island (Table 3).

At the same time, somewhat lower but still significant growth of the thermal denudation rate of the Ice Complex, accompanied by formation of thermal terraces, is observed. The excess of the thermal abrasion rate over the thermal denudation rate suggests determinant influence of the reduction of the ice cover on the behavior of the shores under study. The growth of the absolute thermal denudation rates suggests noticeable influence of the rise in the air temperature and of the factors of the radiation and heat balance on destruction of the icy shores of the Laptev and East Siberian Seas.

Reduction in the sizes of thermal terraces and increase of the thermal abrasion rate compared to the thermal denudation rate on the eastern coast of Bolshoy Lyakhovsky Island, where formation of snowbanks along the shores prevents thermal abrasion, may indicate reduction in the winter precipitation amounts in the period preceding the survey. The growth in the sizes of thermal terraces observed there over the recent years indicates reduction in the impact of thermal abrasion on the coastal dynamics, on condition the character of snow distribution remains the same.

The spaciotemporal differences between the thermal abrasion rates and the thermal denudation ion rates are distinctly seen in the exposure of the Ice Complex of Oygos Yar (Fig. 14): at local reduction of the thermal abrasion rates the sizes of the thermal terraces increase, while the growth of the thermal abrasion rates causes reduction in the thermal terrace sizes.

CONCLUSIONS

1. In 2000–2014, reduction of the ice coverage and increase in the air temperatures was recorded for the Arctic seas of Russia (Kara, Laptev, East Siberian, and Chukchi Seas). In August, reduction in the ice coverage area of all the seas was on average 591,600 km^2, indicating 1.7-fold reduction compared to the period of 1940–1999. The mean annual air temperatures rose by 1.2–1.9 °C.

2. Changes in the climate and in the ice cover resulted in essential acceleration of the icy shores retreat rates in the eastern sector of Russian Arctic. The mean thermal abrasion rates recorded for the shores of Bolshoy Lyakhovsky Island and Oygos Yar of the total length of more than 250 km, increased 1.3–2.9 times to reach 9.9–11.6 m/year. The thermal denudation rates of the shores composed from the surface of Ice Complex increased 1.7–1.9 times to reach 7 m/year.

3. The growth of the Arctic shore retreat rates for the recent decade and a half allows measurements to be made based on medium-scale satellite images with acceptable accuracy. This makes it possible to study the behavior of the sea shores of considerable length on the basis of publicly available satellite images (Landsat 7, 8) made in the recent years.

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