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## Zoning of the Barents and Kara Seas by surface air temperature changes and variability. Natural climatic seasons

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**Abstract.** Studies of the present-day Arctic climate are becoming increasingly relevant and in high demand in the light of the observed global warming and the expansion of long-term programs for the development of the Arctic regions. A quantitative assessment of changes and variability in surface air temperature (SAT) is presented for the climate norm period of 1991–2020, based on data from 31 meteorological stations (MSs), which reflect the diversity of climatic conditions in the area studied. Average monthly SAT values were taken as indicators of changes in the thermal regime, and the standard deviations (SD) of average monthly SAT were used as indicators of the thermal regime variability. The annual course of SAT (one maximum and one minimum) mainly reflects the radiation factor. The annual course of SD (in the northern part of the area — one maximum and one minimum, in the southern part — two maxima and two minima) reflects the patterns of the atmospheric and ocean circulation and the type of the underlying surface. The assessment of the changes and variability in the thermal regime of the surface atmosphere was based on a comprehensive analysis of the annual cycle of indicators on the SAT-SD plane using closed SAT-SD curves characterizing annual and seasonal cycles. 31 SAT-SD curves were classified, and the corresponding regions of the Barents and Kara Seas were identified. A typical SAT-SD curve was obtained for each region. The boundaries of natural climatic seasons (NCS) were determined based on a comparative analysis of the seasonal cycle of SAT-SD indicators and the absolute SAT-SD values characteristic of different seasons within each region. Zoning and determining the duration of the NCS refine the general understanding of the climate of the Western sector of the Arctic.

**Keywords:** Barents Sea, Kara Sea, climate change, climate variability, natural climatic seasons, seasonal zoning

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## **Introduction**

The development prospects of the Russian Arctic zone largely depend on the current and expected climatic conditions. Increasing the accuracy of assessing changes and variability of the Arctic climate by taking into account natural climatic seasons (NCS) is necessary for the development of strategic programs for the Arctic regions.

The basic principles for determining the internal structure of the year, the selection of criteria for dividing a year into natural climatic seasons (NCSs) (unlike calendar seasons), as well as the definition of the very concept of NCS were formulated back in the middle of the last century. For example, NCS was understood as a period characterized by a uniform course of meteorological processes and a certain thermal regime [1]. Air temperature in itself should be considered as a synthetic indicator reflecting the impact of all the components of climate formation: solar radiation, atmospheric circulation, and the type of the underlying surface [2].

Previously, the annual course of air temperature, cloudiness, and atmospheric pressure was analyzed to identify climatic seasons in the Arctic seas. The summer season was limited to the dates of the transition of the average monthly minimum temperature through 0 °C, the beginning of winter was determined by the time of a sharp decrease in lower cloudiness (the physical basis for this was associated with a change in atmospheric circulation), the beginning of spring — by the change of a trough of low pressure to an area of high pressure [3]. However, as has been noted, the criterion of transition through 0 °C is not suitable for the Arctic because in most of the Arctic, negative air temperatures are observed even in summer [4]. The main criterion for establishing climatic seasons and their boundaries was the annual course of the average monthly air temperature, while the annual course of atmospheric pressure and cloudiness were secondary criteria [4]. Using the example of the Murmansk region, it was shown that the identification of climatic seasons depends on the choice of a meteorological criterion that would take into account temperature contrasts between land and sea, temperature fluctuations associated with fluctuations in the radiation regime, and with features of atmospheric circulation [5]. The best criterion is assessment of the variability of the average daily air temperature [5].

In the work of Z.M. Prik [6], the climatic zoning of the Arctic was determined by the features of the circulation of the atmosphere and the ocean, and the type of the underlying surface. It was indicated that the influence of these factors varied in different seasons. The author identified seven large climatic regions and provided their climatic characteristics. Prik's zoning was entrenched in the fundamental Atlas of the Arctic [7] and is actively used by modern researchers [8]. It is also worth noting the zoning of individual Arctic seas based on the characteristics of ice conditions. For example, this was done for the Greenland and Barents Seas [9] and for the Kara Sea [10]. In general, a limited number of studies are devoted to the climatic zoning of the Arctic [6–8]. At the same time, the zoning was carried out based on physical and geographical conditions without identifying the NCS.

According to Terziev et al., the most valid criteria for dividing a year into NCSs were the characteristics of atmospheric circulation [11].

Modern studies of the Arctic climate, including its thermal regime, are mainly based on estimates obtained for calendar seasons and average annual temperatures [12–17]. At the same time, a number of studies use the concept of “winter season”. For example, in one study, “winter” was the period from December to March inclusive [18], and in another one, the year was divided into two equal periods: winter (November–April) and summer (May–October) [19].

Previously, the authors of this work, in a joint analysis of the indicators of change and variability of the thermal regime of the surface atmosphere, determined the duration of the NCS for the conditions of Franz Josef Land [20]. Further, the NCSs were identified for the Barents Sea region, based on the data of 4 MSs (Barentsburg, Teriberka, Malye Karmakuly, and the E.T. Krenkel Observatory) for the period of the present-day climate norm of 1991–2020 [21]. The NCSs identified corresponded to the physical and geographical conditions of the location of the MSs used.

The aim of this study is to identify the NCS in a large Arctic region using the Barents and Kara Seas as an example. The 1991–2020 climate norm period was chosen as a significant time interval, reflecting the current climate characteristics of the study region [22]. Based on the aim, the following objectives were set:

- assessing changes and variability in air temperature in the Barents and Kara Seas for the period 1991–2020;
- zoning the region through a comprehensive analysis of the annual cycle of average monthly temperature and its variability;
- identifying the NCS.

### Materials and methods

The materials for the study were observation data from 31 MSs, located in the region of the Barents and Kara Seas (see Fig. 1), and the database (DB)<sup>1</sup>.

To assess changes in SAT, monthly average SAT values were used as quantitative indicators. Standard deviations (SD) from the mean are typically used as a measure of variability (dispersion). For non-stationary processes, it is assumed that the total variability is divided into the variability explained by the trend of the mean and the residual variability associated with deviations from the trend. Residual variability is estimated as a SD from the trend [23].

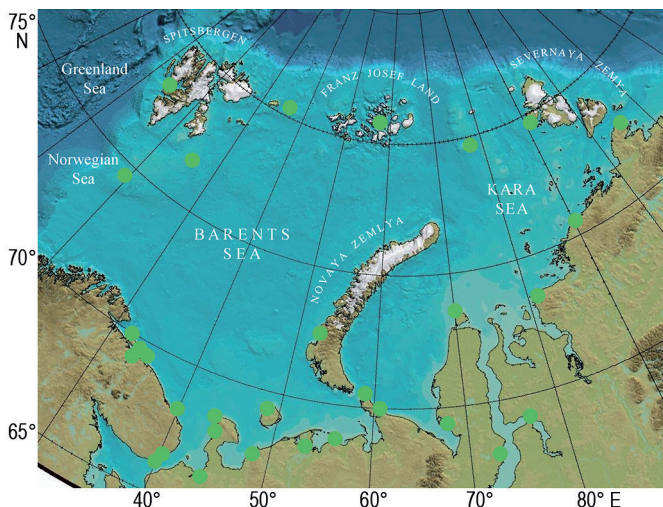


Fig. 1. Location of the 31 MSs in the Barents and Kara Seas region

Рис. 1. Местоположение 31 метеостанции в регионе Баренцева и Карского морей

<sup>1</sup> Ivanov B., Karandasheva T., Demin V., Ilyushchenkova I., Revina A. Database: Characteristics of current trends in surface air temperature in the Western sector of the Russian Arctic (CLIMATE), 2024. Patent No. 2024622557.

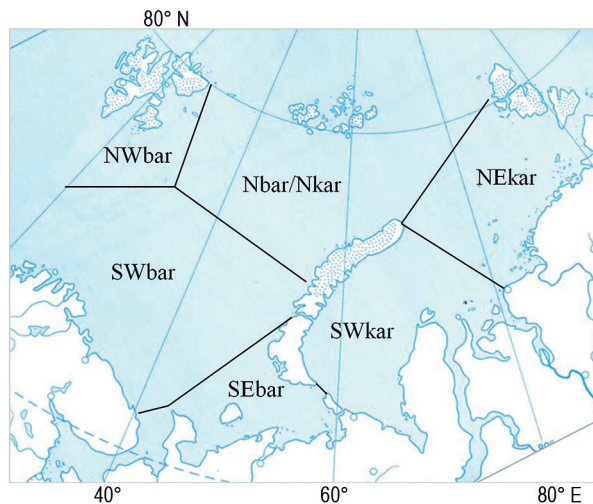


Fig. 2. Zoning of study region.

Nbar/Nkar — the north of the Barents and Kara Seas; NWbar — the northwest of the Barents Sea; SWbar — the southwest of the Barents Sea; SEbar — the southeast of the Barents Sea; NEkar — the northeast of the Kara Sea; SWkar — the southwest of the Kara Sea

Рис. 2. Районирование исследуемого региона.

Nbar/Nkar — север Баренцева и Карского морей; NWbar — северо-запад Баренцева моря; SWbar — юго-запад Баренцева моря; SEbar — юго-восток Баренцева моря; NEkar — северо-восток Карского моря; SWkar — юго-запад Карского моря

The characteristics of the linear trends of monthly average SAT value series for the MSs used were presented previously [24]. In this study, the SD was calculated in two ways: as the SD from the mean and as the SD from the trend. Preliminary analysis showed that, for a statistically significant trend of  $p > 0.20$ , the SD calculated from the SAT trend differs from the SD calculated from the mean SAT value by no more than 3 %. Therefore, for time series with statistically significant trends ( $p \leq 0.20$ ), the SD from the trend was calculated, and for other series, the SD from the mean SAT value was calculated.

*At the first stage*, a 30-year time series of monthly average SAT values and characteristics of linear SAT trends for 31 MSs for the period 1991–2020, obtained by the authors earlier [24], were used. For each MS, average SAT values were calculated for each calendar month and, depending on the statistical significance of the linear SAT trend, the corresponding SD of the SAT trend or SD of the average SAT values was obtained. Further, for each MS, a closed curve of the annual SAT-SD indicators was constructed on the SAT-SD plane. The resulting curves differed in shape, timing of maxima/minima, maximum/minimum values, and amplitude of the SAT and SD indicators.

*At the second stage*, an expert method was used to analyze the shapes of the curves obtained, the number and time of occurrence of the maxima and minima of the SAT and SD, and the amplitudes of the annual variation of these indicators. Taking into account the identified differences in the curve shapes and the features of the annual and seasonal cycles, 6 characteristic groups were identified. Each selected group of curves naturally corresponded to the geographic location of the MSs, according to the data from which they were constructed. As shown in Fig. 1, the MSs for which the SAT and SD

indicators were calculated are located mainly on the coast of the Barents and Kara Seas. In the open part of the sea waters, the boundaries of the areas were drawn taking into account the features of the thermal regime of the surface atmosphere and the surface layer of the sea, the wind and ice regime of the seas in modern climatic conditions [25]. The straight lines dividing the selected areas and drawn through open water (see Fig. 2) largely correspond to the boundaries of the ice regions of the Barents and Kara Seas, validated by E.U. Mironov [9] and V.P. Karklin et al. [10].

Then, for each identified area, average SAT values were calculated for the year and calendar months (as the arithmetic mean of the corresponding SAT values based on the MSs data for each area). For each area, linear trends in average monthly and average annual SAT values were calculated, estimates of the SD from the trend and from the average SAT value were obtained, and typical SAT-SD curves were constructed. Thus, we have zoned the sea areas using SAT-SD curves.

*At the third stage*, a comparative analysis was carried out of the SAT and SD values and the rates of their increase/decrease were carried out, which allowed us to identify and determine the duration of the NCS for each region. The winter and summer seasons were characterized by low and high values of the average monthly SAT, respectively, with relatively small changes in the average monthly SAT. At the same time, the winter season was characterized by high SD values, and the summer season was characterized by low SD values. In the transitional seasons (spring and autumn), relatively rapid changes in the values of the average monthly SAT and SD were observed.

The magnitude of the velocity of a point with coordinates ( $t$ ;  $\sigma$ ) on the plane of the SAT-SD was adopted as a complex indicator of the rates of change of the SAT and SD:

$$V_i = \sqrt{(t_i - t_{i-1})^2 + (\sigma_i - \sigma_{i-1})^2},$$

where  $V_i$  is the velocity of the point in the  $i$  — the calendar month,  $t_i$  and  $\sigma_i$  are the values of the SAT and its SD in the current calendar month,  $t_{i-1}$  and  $\sigma_{i-1}$  are the SAT and SD values in the previous calendar month.

Thus, for each area studied, the rates of change of the SAT-SD-indicator from month to month during the year, the ranges of SAT and SD values characteristic of winter/spring/summer/autumn, and the duration of the NCS were estimated.

## Results

A comparative analysis of the closed SAT-SD curves characterizing the annual and seasonal SAT cycles obtained for all MSs revealed 4 characteristic shapes of these curves, typical of the region studied. Examples of such curves are shown in Fig. 3 (*a, b, e, f*). The shape of the figure formed by the closed SAT-SD curve is determined by the annual variation of the SAT and SD indices (see Fig. 3: *c, d, g, h*).

Certain patterns are observed in the annual variations of the SAT and SD indices. In the annual SAT variations, one maximum and one minimum were observed at all MSs. In the annual SD variations, two minima and two maxima were observed at most of the MSs (see Fig. 3*c, b, h*), while the remaining MSs exhibit one minimum and one maximum (see Fig. 3*g*). Accordingly, based on the shape of the SAT-SD curves and the number and timing of SAT and SD minima/maxima, the set of SAT-SD curves was divided into four groups.

Geographically, it looks as follows: the northwest of the Barents Sea (3 MSs), the north of the Barents and Kara Seas (3 MSs), the northeast of the Kara Sea (4 MSs), and the southern part of the Barents and Kara Seas (21 MSs). In the last group, there were

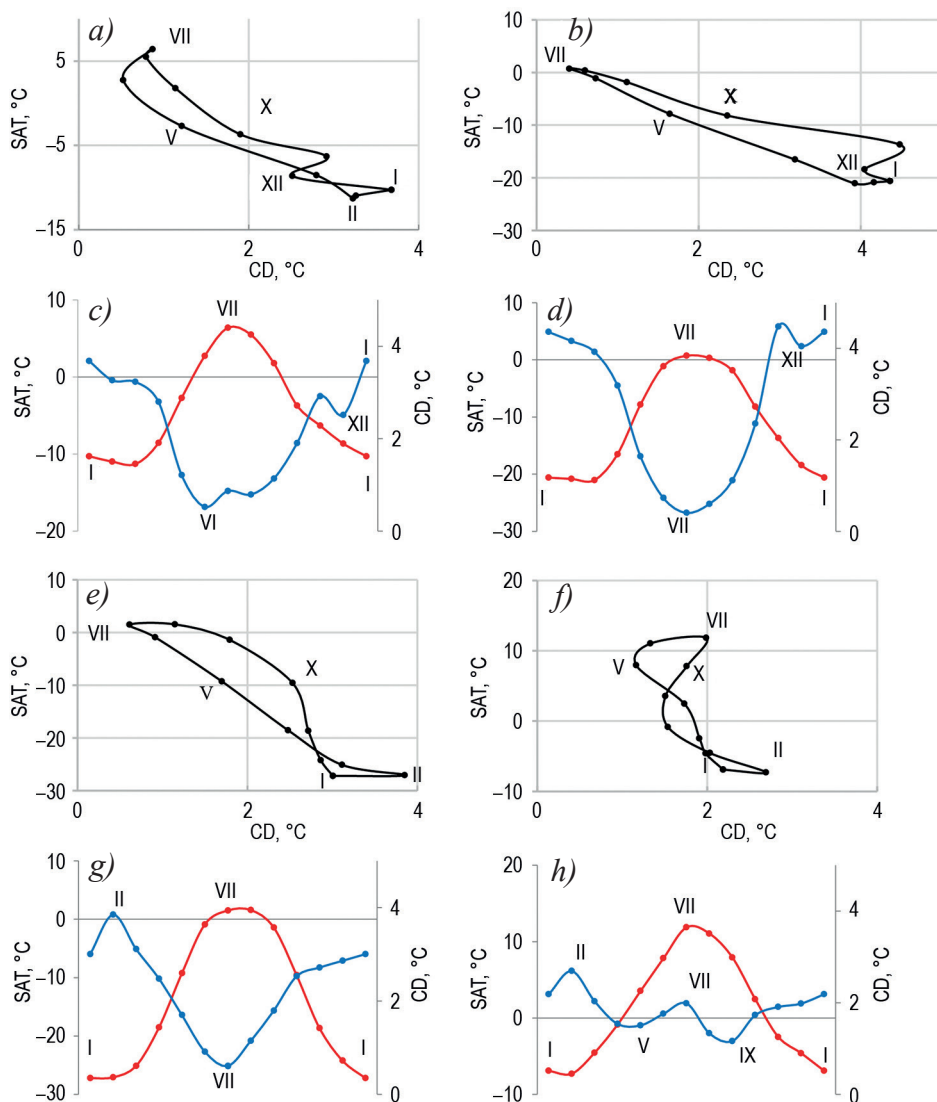


Fig. 3. Four characteristic shapes of the SAT-SD curves (*a, b, e, f*) and the annual cycle of SAT and SD (from January to January inclusive) (*c, d, g, h*).

(*a, c*) — Barentsburg MS (northwest of the Barents Sea); (*b, d*) — E.T. Krenkel GMO (north of the Barents and Kara Seas); (*e, g*) — E.K. Fedorov OGMS (northeast of the Kara Sea); (*e, g*) — Teriberka MS (south of the Barents Sea). The Roman numerals indicate months. The point on SAT-SD curve corresponds to the 15th day of the month

Рис. 3. Четыре характерные формы ПТВ-СКО-кривых (*a, b, e, f*) и годовой ход (с января по январь включительно) (*c, d, g, h*) ПТВ и СКО.

(*a, c*) — МС Баренцбург (северо-запад Баренцева моря); (*b, d*) — ГМО им. Э.Т. Кренкеля (север Баренцева и Карского морей); (*e, g*) — ОГМС им. Е.К. Федорова (северо-восток Карского моря); (*e, g*) — МС Терiberка (юг Баренцева моря). Римскими цифрами обозначены месяцы. Точка на ПТВ-СКО-кривой соответствует 15 числу месяца

significant differences in the amplitude of the annual cycle of the SAT (from 15 °C to 35 °C) and SD indicators (from 1 °C to 4.5 °C). Therefore, this group, based on the location of the MSs, was divided into three subgroups (6, 9 and 6 MSs in each) with different amplitudes of the SAT and SD indicators, respectively: 1) from 15 to 23 °C and from 1 to 2.5 °C; 2) from 20 to 30 °C and from 2.5 to 4.0 °C; 3) from 25 to 35 °C and from 3.5 to 4.5 °C.

Thus, we classified the SAT-SD curves for all MSs and identified the regions of the Barents and Kara Seas corresponding to this classification. In the northern part of the study region (see Fig. 2), three characteristic SAT-SD curve shapes were observed (the NWbar, Nbar/Nkar, and NEkar regions), while in the southern part, one shape was observed (the SWbar, SEbar, and SWkar regions).

For each area, the average SAT values and linear trend indicators were calculated for the year and calendar months. All linear trends calculated for the average annual SAT values were statistically significant at the  $p < 0.01$  level. The statistical significance of the linear SAT trends for calendar months varies within a fairly wide range (see Table 1). The majority (89 %) of the linear trends were statistically significant at the  $p < 0.20$  level, and for these cases, the SD from the trend was calculated to exclude the influence of the trend. Statistically insignificant trends ( $p > 0.20$ ) were observed mainly in the southern Barents Sea (the SWBar and SEBar areas) in January–March and June. For cases of statistically insignificant trends, the SD from the mean was calculated.

Quantitative estimates of the SAT and SD, reflecting seasonal changes and variability of air temperature for 6 regions, are presented in Table 2.

*Table 1*

**Surface air temperature linear trend indicators**

*Таблица 1*

**Показатели линейных трендов поверхностной температуры воздуха**

Area	NWbar		Nbar/Nkar		NEkar		SWbar		SEbar		SWkar	
	<i>a</i>	<i>p</i> <	<i>a</i>	<i>p</i> <	<i>a</i>	<i>p</i> <	<i>a</i>	<i>p</i> <	<i>a</i>	<i>p</i> <	<i>a</i>	<i>p</i> <
I	0.228	0.01	0.367	0.01	0.246	0.01	-0.042	0.45	0.060	0.50	0.140	0.15
II	0.221	0.01	0.403	0.01	0.262	0.01	0.046	0.50	0.126	0.20	0.200	0.10
III	0.023	0.75	0.138	0.10	0.143	0.10	0.041	0.40	0.064	0.45	0.098	0.35
IV	0.083	0.20	0.181	0.01	0.238	0.01	0.081	0.05	0.116	0.05	0.159	0.10
V	0.093	0.01	0.089	0.01	0.087	0.10	0.088	0.01	0.083	0.05	0.063	0.15
VI	0.045	0.01	0.028	0.01	0.074	0.01	0.045	0.20	0.028	0.45	0.083	0.05
VII	0.045	0.01	0.015	0.10	0.046	0.05	0.082	0.05	0.095	0.05	0.122	0.01
VIII	0.022	0.20	0.047	0.01	0.086	0.01	0.046	0.10	0.064	0.05	0.062	0.10
IX	0.074	0.01	0.125	0.01	0.161	0.01	0.088	0.01	0.087	0.01	0.093	0.05
X	0.157	0.01	0.441	0.01	0.324	0.01	0.067	0.10	0.087	0.10	0.136	0.05
XI	0.155	0.01	0.344	0.01	0.219	0.01	0.113	0.01	0.166	0.01	0.137	0.10
XII	0.199	0.01	0.349	0.01	0.224	0.01	0.064	0.15	0.136	0.05	0.172	0.10
Год	0.112	0.01	0.211	0.01	0.176	0.01	0.060	0.01	0.093	0.01	0.122	0.01

*Note.* *a* — slope of the linear trend, °C/year; *p* — level of statistical significance.

*Примечание.* *a* — угловой коэффициент линейного тренда, °C/год; *p* — уровень статистической значимости.

*Table 2*

**Average annual and seasonal characteristics of changes (surface air temperature) and variability (standard deviation) of air temperature for 6 regions**

*Таблица 2*

**Среднегодовые и сезонные характеристики изменений (поверхностная температура воздуха) и изменчивости (среднеквадратическое отклонение) температуры воздуха для 6 районов**

Areas	SAT			SD		
	$t_{cp}, ^\circ\text{C}$	$A_p, ^\circ\text{C}$	min/max	$\sigma_{year}, ^\circ\text{C}$	$A_\sigma, ^\circ\text{C}$	max/min
NWbar	-2.6	14	II-III / VII-VIII	0.9	2.9	I / VI-VIII; XII
Nbar/Nkar	-10.5	21	II-III / VII-VIII	1.3	4.0	I / VI-VIII; XII
NEkar	-12.2	29	I-II / VII-VIII	1.1	2.9	II / VI-VII
SWbar	1.3	19	I-II / VII-VIII	0.7	1.7	II, VII / IV-VI; VIII-IX
SEbar	-1.4	24	I-II / VII-VIII	1.1	2.9	II, VII / VI; VIII-IX
SWkar	-6.9	30	I-II / VII-VIII	1.5	3.8	II, VII / VI; VIII

*Note.*  $t_{cp}, ^\circ\text{C}$  — average annual SAT value;  $A_p, ^\circ\text{C}$  — amplitude of annual SAT variation; min/max — coldest/warmest months;  $\sigma_{year}, ^\circ\text{C}$  — SD of average annual SAT values;  $A_\sigma, ^\circ\text{C}$  — amplitude of annual SD variation; max/min — months with maximum and minimum SD values (or months with maximum/minimum SAT variability).

*Примечание.*  $t_{cp}, ^\circ\text{C}$  — среднегодовое значение ПТВ;  $A_p, ^\circ\text{C}$  — амплитуда годового хода ПТВ; мин/макс — самый холодный/самый теплый месяцы;  $\sigma_{year}, ^\circ\text{C}$  — СКО среднегодовых значений ПТВ;  $A_\sigma, ^\circ\text{C}$  — амплитуда годового хода СКО; макс/мин — месяцы с максимальным и минимальным значением СКО (или месяцы с максимальной/минимальной изменчивостью ПТВ).

Typical SAT-SD curves, constructed using average monthly SAT values and corresponding SD values, are shown in Fig. 4.

In the region studied, the average annual SAT value decreased significantly from southwest to northeast: from 1.3 °C (SWbar) to -12.2 °C (NEkar). The amplitude of the annual SAT cycle increased from west to east, from 14 °C (NWbar) and 19 °C (SWbar) to 30 °C (NEkar, SWkar) (see Table 2 and Fig. 4a, d and c, f).

The SAT minimum a were shifted to the time of the Sun's appearance above the horizon after the polar night: in the southern regions, the minima were observed in January–February, while in the northern regions they were observed later — in February–March (see Table 2 and Fig. 4). The shift of the SAT minimum to March in the northern regions was also due to the fact that anticyclonic circulation begins to predominate over the Arctic, and heat transfer from the ice-covered sea significantly decreases [11]. The maxima were observed after the summer solstice — in July–August (see Table 2 and Fig. 4).

SD values in the northern regions were within a relatively narrow range: 0.9–1.3 °C. In the southern regions, SD values increased significantly (almost doubling) from west to east: from 0.7 °C (SWbar) to 1.5 °C (SWkar) (see Table 2 and Fig. 4).

The smallest annual amplitude of the SD (1.7 °C) was observed in the southwest of the region (SWbar) (see Table 2 and Fig. 4d). In this area, frequent changes in air masses (temperate and arctic) should have led to significant variability in air temperature, but this was prevented by the relatively rapid transformation of air masses over the non-freezing water surface. In other regions, the annual amplitude of the SD was significantly

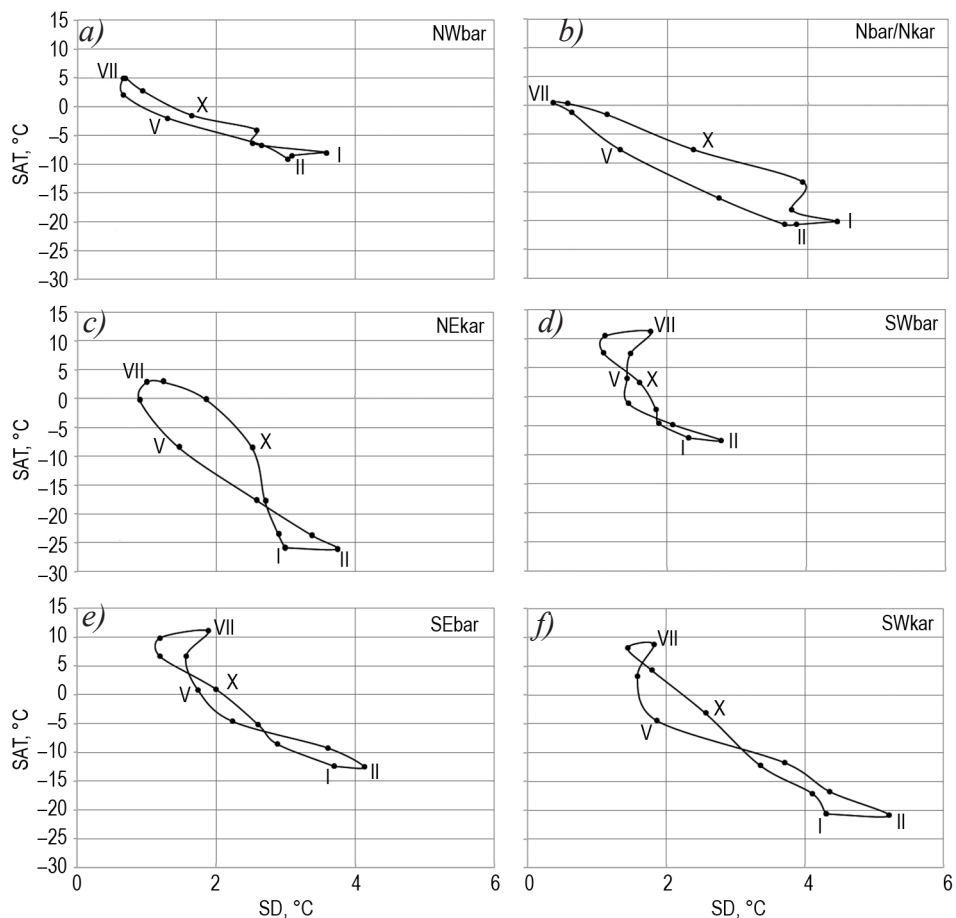


Fig. 4. Annual cycle of SAT-SD indicators for 6 regions of the Barents and Kara Seas.

The point on SAT-SD curve corresponds to the 15th day of the month

Рис. 4. Годовой цикл ПТВ-СКО-показателей для 6-ти районов Баренцева и Карского морей.

Точка на ПТВ-СКО-кривой соответствует 15 числу месяца

larger, (about 3–4 °C)(see Table 2 and Fig. 4). This could be explained, firstly, by frequent winter temperature inversions and a sharp increase in SAT as a result of the destruction of the inversion layer (increased wind strength, cloud formation, advection of air masses). Secondly, by the influence of cold air masses of continental origin formed in the Siberian anticyclone (SEbar) and warm air masses transported by cyclones (eastern trough of the Icelandic low) (SWkar). Third, by ocean circulation: a complex system of alternating warm and cold currents (NW and SE currents), and the influx of warm Barents Sea waters through the Kara Strait and Yugorsky Strait (SWkar). This leads to thermal heterogeneity of the underlying surface (open water, ice of varying concentrations).

The main winter maximum of the SD occurred during the period of the most intense atmospheric circulation and was also formed under the influence of the radiation regime during the polar night: in the northern regions (NWbar, Nbar/Nkar) — in January, in NEkar

and in the southern regions — in February (see Table 2, Fig. 4). In the southern regions, in July, against the background of the summer decrease in the SD, a small secondary summer maximum of the SD was observed, associated with the alternation of cold Arctic and warm continental air masses in the region of the Arctic front [11].

The spring-summer minimum of the SD was caused by the seasonal decrease in atmospheric circulation intensity and the melting of sea ice and snow on the coast and islands. Melting processes prevent a rapid increase in air temperature during the influx of warm air masses and a sharp decrease in temperature during the influx of cold air masses (due to the latent heat released during refreezing) [11]. The earliest spring-summer minimum of the SD was observed in April-June in the southwest of the study region (SWbar), the latest in June-August in the northern regions (NWbar and Nbar/Nkar), and in other regions in June-July (see Table 2 and Fig. 4).

In the southern regions (SWbar, SEbar, SWkar), the summer-autumn minimum in SD was still observed in August-September (see Table 2 and Fig. 4d-f). The main reason for the low air temperature variability in autumn is the intense heat transfer from the sea surface, as water heat content of sea reaches its maximum value at this time.

In the north of the study region (NWBar, Nbar/Nkar), a slight minimum in SD was observed in December. The physical origin of the decrease in air temperature variability in December is still unclear, but under current warming conditions (for the period 1985–2015), a similar decrease in other meteorological parameters (mean monthly wind speed, average monthly precipitation) was recorded at the beginning of winter (November) in the Barents and Kara Seas [25].

To identify the NCS, we propose considering both the change in air temperature (SAT), whose annual cycle in polar regions is determined by the radiation factor, and its variability (SD), whose annual cycle, as shown above, reflects the characteristics of atmospheric/oceanic circulation and the type of the underlying surface. By winter and summer seasons, we mean periods of time during which SAT and SD values change relatively slowly and within narrow ranges, while during transitional seasons (spring, autumn), these values change relatively rapidly and within wide ranges. Quantitative estimates of the rates of change in SAT and SD for various seasons are presented in Table 3.

*Table 3*

**Ranges of the module of the complex indicator of the velocity of change  
of surface air temperature and standard deviation ( $V_p$ , °C/month)  
for the natural climatic seasons**

*Таблица 3*

**Диапазоны модуля комплексного показателя скоростей изменения  
приземной температуры воздуха и среднеквадратического отклонения ( $V_p$ , °C/мес)  
для естественных климатических сезонов**

Areas	Winter	Spring	Summer	Autumn
NWbar	1–2	4–5	0–3	3–4
Nbar/Nkar	0–5	6–9	0–2	6
NEkar	1–6	8–9	0–3	8–9
SWbar	1–3	4	1–4	5
SEbar	0–4	5–6	1–4	6
SWkar	1–5	8	1–6	7–9

Table 4

**Ranges of values of surface air temperature and standard deviation (°C)  
 for natural climatic seasons**

Таблица 4

**Диапазоны значений поверхностной температуры воздуха  
 и среднеквадратического отклонения (°C)  
 для естественных климатических сезонов**

Areas	Winter		Spring		Summer		Autumn	
	SAT	SD	SAT	SD	SAT	SD	SAT	SD
NWbar	-9...-4	3...4	-7...-2	1...3	2...5	1	-4...3	1...3
Nbar/Nkar	-21...-13	3...4	-16...-1	1...3	-1...1	0...1	-13...-1	1...4
NEkar	-26...-18	3...4	-18...0	1...3	0...3	1...2	-18...0	2...3
SWbar	-7...-2	2...3	-3...5	1...2	5...11	1...2	-2...5	1...2
SEbar	-13...-7	3...4	-7...4	2...3	4...11	1...2	-7...4	2...3
SWkar	-21...-12	3...5	-12...3	2...4	3...9	1...2	-12...4	2...3

Table 5

**Duration of NCS for the study region**

Таблица 5

**Продолжительность ЕКС для региона исследований**

Regions	Months												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
NWbar	Winter			Spring			Summer			Autumn			
Nbar/Nkar													
NEkar	Winter			Spring			Summer			Autumn			
SWbar													
SEbar	Winter			Spring			Summer			Autumn			
SWkar													

In the north and northeast of the study region (Nbar/Nkar and NEkar), in summer, lower  $V_i$  values than in winter were observed; in other areas, summer and winter  $V_i$  values were comparable. During the transitional seasons,  $V_i$  values were significantly higher: in spring compared to winter and in autumn compared to summer, 1.5 to 2 times. The highest  $V_i$  values were observed in the Kara Sea regions.

The observed relatively low/high SAT values and relatively high/low SD values for the winter/summer seasons, as well as the intermediate SAT and SD values for the transitional seasons, are presented in Table 4.

In winter, negative SAT values were observed in all regions, with the lowest values in Nbar/Nkar and NEkar, and the highest in SWbar. SD values in winter in most of the regions of the Barents and Kara Seas were within a narrow range of 3–4 °C. In spring, SAT values crossed 0 °C in all the regions, with the exception of Nbar/Nkar and NEkar, and SD values decreased. However, in the northern regions, the range of SD values increased, while in the southern regions, it remained the same. In summer, positive SAT values and the lowest SD values were observed in almost all the regions. In autumn, SAT values crossed 0 °C in most regions. SD values increased significantly, with the range of SD values increasing in the northern regions (with the exception of NEkar), while in the southern regions, it remained the same.

The time boundaries of the NCS are presented in Table 5.

“Spring” began earliest in the southern Barents Sea (SWbar, SEbar), and half a month later in the other areas of the study region. The duration of spring was the same in all the areas — two months. The longest summer (4 months) was observed in the southern Barents Sea (SWbar, SEbar), while in the other areas, summer was shorter and of equal duration (3 months). In most of the areas, autumn began in the second half of September; in the southern areas of the Barents Sea (SWbar, SEbar), it began in October. In the southwest of the region (SWbar), autumn was short (1.5 months), while in the other areas it was longer (2 months). Winter began in the second half of November, and in the SEbar in December. In the northern regions (NWbar, Nbar/Nkar, NEkar) and in the southwest of the Kara Sea (SWkar), “winter” lasted 5 months, in the south of the Barents Sea: 4.5 months (SWbar) and 4 months (SEbar).

The identified temporal boundaries of the NCS refine the description of seasonal ice processes in the Barents and Kara Seas [25, 26]. The temporal boundaries of the NCS correspond to the ice regime characteristics of the study region, with ice extent extremes occurring 1–2 months later than SAT extremes. Thus, minimum SAT values in the study region were observed in January–March (see Table 2), and maximum ice extent was observed in March–April. Maximum SAT values were observed in July–August, and minimum ice extent was observed in September. Moreover, the directions of both increasing SAT and decreasing ice extent, and decreasing SAT and increasing ice extent, coincided. Thus, during relatively warm periods (May–September), the seasonal process of decreasing ice coverage begins in the southwest of the study region and, gradually encompassing other areas, moves northeast. During relatively cold periods (October–February), the seasonal process of increasing ice coverage begins in the northeast of the study region and gradually moves southwest.

Thus, the NCSs determined using the principle of joint analysis of air temperature changes and variability in six regions of the Barents and Kara Seas correspond to the physical and geographical conditions of the study region.

## **Discussion**

The zoning of the Barents and Kara Seas and the determination of the duration of the NCS carried out in our work based on the characteristics of the SAT-SD curves are in good agreement with the climatic zoning of the Arctic carried out by other researchers.

For example, according to the zoning proposed by Prik, three regions were distinguished in the Barents and Kara Seas, as part of the Atlantic climatic region [6, 7]. The extreme northeastern Kara Sea was classified as part of the Siberian climatic region. In our study, the zoning was performed with a higher spatial resolution, and six distinct regions were identified.

In the previous study, the temporal boundaries of the NCS for the Barents Sea were established based on changes in atmospheric circulation patterns with an accuracy of one month: “winter” (November–April), “spring” (May–June), “summer” (July–August), and “autumn” (September–October) [11]. In our study, the Barents Sea was divided into four regions, and the NCS boundaries were determined with a higher temporal resolution and refined. For example, in the Barents Sea areas that we identified, “winter” began later and ended earlier, while “summer” began earlier and ended later. The duration of the transition seasons in these areas and in the Barents Sea as a whole was almost identical, lasting two months. It should be noted that the NCS time boundaries for the Barents Sea were established using data prior to 1990 (including MSs observations for the period

1936–1980), i.e., for the period that included the “cold 1960s”. Our study was conducted for the period 1991–2020, which reflects present-day sustained warming. This could explain the shorter “winter” and longer “summer” in our case compared to the previous study [11].

In the work of Korolkova, the temporary boundaries of the NCS and the zoning of the Arctic were determined primarily based on the analysis of the annual variability of SAT [4]. In our study, the MSs, whose data Korolkova used to identify the NCS in the western Barents Sea (2 MSs) and in the Kara Sea (1 MS), were assigned to the NWbar and SWkar regions. A comparison of the results shows that our estimates of the NCS temporal boundaries in these regions coincided with Korolkova’s estimates within the accuracy of determining the NCS boundaries (half a month). In addition to the annual variability of SAT, Korolkova also considered the annual variability of the frequency of overcast sky. In some cases, this indicator confirmed the temporary boundaries of the NCS identified based on SAT; in others, it did not, or data on the frequency of overcast sky were simply unavailable. Therefore, in working with SAT time series it seems appropriate to use not only the annual SAT cycle but also an additional characteristic—namely, the SD.

Among recent studies, the climatic regionalization performed by Johannessen and coauthors [12] is noteworthy. Using ERA-40 and Nansen SAT reanalyses, the authors identified six regions in the Northern Hemisphere from 40° to 90°N and analyzed changes in SAT for both the year and for calendar seasons.

Since transition from one type of climatic conditions to another occurs gradually, the boundaries of climatic regions and the duration of the NCS can be determined with a sufficient degree of approximation, based on explicit and implicit knowledge (expert methods). In climate zoning and defining NCS boundaries, various experts use both qualitative (strong/weak influence of cyclonic/anticyclonic circulation, the influence of warm/cold currents, ice cover/open water) and quantitative criteria (characteristics of the annual course of SAT and SD). In our study, zoning was conducted using qualitative (SAT-SD curve shapes) and quantitative (characteristics of the annual course of SAT and SD.) criteria. The NCSs for each region were identified through a comparative analysis of a complex indicator—the rate of change of SAT and SD values within each area and the absolute values of SAT and SD characteristic of different seasons within a given area.

Thus, the zoning of the Barents and Kara Seas that we carried out and the identified boundaries of the NCS not only do not contradict the results of previous studies, but also significantly complement and detail our understanding of the climate of the Western Arctic.

## **Conclusions**

For the period of the present-day climate norm 1991–2020, based on the data of 31 MSs (Russian and Norwegian) located in the Barents and Kara Seas, as a result of a comprehensive analysis of changes (annual course) in the average monthly values of SAT and its variability (SD), zoning of the study region has been performed, and the time boundaries of the NCS for the zones have been identified.

1. To assess the changes and variability, the monthly average values of SAT and its SD were used as quantitative indicators. A new approach was applied: 31 closed curves of the annual cycle of the SAT-SD indicators were constructed on the SAT-SD plane, characterizing the annual and seasonal cycles of the thermal regime of the surface atmosphere. Based on qualitative (curve shape) and quantitative (maximum/minimum values, number and time of occurrence of the maxima/minima, annual amplitude of SAT and SD) features, 6 groups of SAT-SD curves were distinguished. Each group of curves

corresponds to the location of certain MSs, and, thus, the boundaries of 6 large climatic regions were determined. In the Barents Sea, there were three of them: northwest (NWbar), southwest (SWbar), southeast (SEbar). In the Kara Sea, two: southwest (SWkar) and northeast (NEkar). The northern part of the study region comprises one common area: the northern Barents and Kara Seas (Sbar/Skar). For each area, a typical closed SAT-SD curve was constructed using combined and averaged data, and quantitative estimates of SAT changes and variability were provided.

2. The NCSs were identified based on a combined analysis of SAT changes, the annual cycle of which in Polar Regions is determined by the radiation factor, and SAT variability (SD), the annual cycle of which reflects the features of atmospheric/oceanic circulation and the type of the underlying surface. By winter and summer seasons, we mean time periods during which the SAT and SD values change relatively slowly and within narrow ranges, while in transitional seasons (spring, autumn), these values change relatively rapidly and within wide ranges. To identify the temporal boundaries of the NCS, the modulus of the SAT-SD indicator movement velocity from month to month on the SAT-SD plane and the SAT and SD values themselves were used as quantitative indicators. “Winter” in most of the study region lasted 5 months (the second half of November — the first half of April), in the southern Barents Sea, “winter” began later and ended earlier, and lasted 4–4.5 months. Summer lasted three months in most of the study region (from the second half of June to the first half of September). In the southern Barents Sea, summer began earlier and ended later, lasting four months. The transition periods (spring/fall) lasted two months throughout the study region.

3. The zoning carried out in this work and the temporal boundaries of the NCS correspond to the physical and geographical conditions of the Barents and Kara Seas.

4. The use of calendar seasons allows a rough comparison of climate change patterns across different territories. However, when they are applied to specific regions with varying climatic conditions, it is difficult to expect that these seasons will accurately reflect the changes. For a more detailed study of regional climate, it is advisable to identify the NCS. This is currently relevant not only to the further development of Earth sciences but also to supporting economic activities, and to other activities in the Arctic. The proposed accuracy of defining the NCS’s temporal boundaries, half a month, appears sufficient for long-term development planning for Russia’s Arctic regions.

**Competing interests.** The authors have no conflict of interest to declare.

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## **Районирование региона Баренцева и Карского морей по изменениям изменчивости температуры приземного воздуха. Естественные климатические сезоны**

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## Расширенный реферат

В связи с наблюдаемым устойчивым потеплением и разработкой перспективных программ развития арктических регионов крайне актуальными и востребованными являются исследования современного климата Арктики. Для периода современной климатической нормы 1991–2020 гг. по данным 31 метеорологической станции (МС), отражающим многообразие климатических условий региона Баренцева и Карского морей, дана количественная оценка изменений и изменчивости приземной температуры воздуха (ПТВ) как одного из главных индикаторов потепления климата. В качестве показателя изменений ПТВ используются ее среднемесячные значения, изменчивости — среднеквадратические отклонения (СКО) среднемесячных значений ПТВ. Годовой ход ПТВ (один максимум и минимум) обусловлен радиационным фактором. Годовой ход СКО (в северной части региона один максимум и минимум, в южной — два максимума и минимума) характеризует особенности циркуляции атмосферы/океана и состояния подстилающей поверхности. Применен новый подход: на плоскости ПТВ-СКО построена 31 замкнутая кривая годового хода ПТВ-СКО-показателей, характеризующая годовые и сезонные циклы термического режима приземной атмосферы. По качественным (форма кривой) и количественным (максимальные/минимальные значения ПТВ и СКО, количество и время наступления их максимумов/минимумов) признакам проведена типизация ПТВ-СКО-кривых и выделено 6 групп. Каждой группе соответствует местоположение определенных МС, таким образом, были установлены границы 6 климатических районов. Для каждого района по объединенным и осредненным данным построена типовая ПТВ-СКО-кривая и даны количественные оценки изменений и изменчивости ПТВ. Для каждого района при сравнительном анализе модуля скорости движения ПТВ-СКО-показателя и значениям ПТВ и СКО установлены временные границы естественных климатических сезонов (ЕКС). Под зимним и летним сезонами мы понимаем промежутки времени, в течение которых значения ПТВ и СКО изменяются относительно медленно и в узких диапазонах, а в переходные сезоны (весна, осень) указанные значения изменяются относительно быстро и в широких диапазонах. «Зима» на большей части исследуемого региона длится 5 месяцев (вторая половина ноября — первая половина апреля), на юге Баренцева моря она начинается позднее, заканчивается раньше и длится 4–4,5 месяца. «Лето» на большей части исследуемого региона длится 3 месяца (вторая половина июня — первая половина сентября), на юге Баренцева моря оно начинается раньше, заканчивается позднее и длится 4 месяца. Продолжительность переходных сезонов («весна»/«осень») во всем исследуемом регионе составляет 2 месяца. Районирование и определение продолжительности ЕКС уточняют общее представление о климате Западного сектора Арктики.

**Ключевые слова:** Баренцево море, Карское море, изменения и изменчивость температуры воздуха, естественные климатические сезоны, районирование

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