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Temporal Variability of Soil Temperature in the North-West Arctic Zone of Russia. Part I: Interannual Linear Trends Based on Thermometer Measurements and Reanalysis Data

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Abstract: In this article we investigate near-surface air temperature (NSAT) and soil temperature variability at four depths in the region of the White Sea, Murmansk and Arkhangelsk Regions, and Republic of Karelia. For the analysis we used NOAA-CIRES-DOE 20th Century Reanalysis (Version 3) reanalysis data for the 1980–2015 time period and data of bent-stem thermometers at 5, 10, 15, 20 cm depths and extraction thermometers at 20, 60, 80, 120, 240 and 320 cm depths for 1985-2021 time period. Average variability of NSAT is estimated using linear trend as +0.028 °C/year. For soil temperature a linear trend is of +0.0137 °C/year on surface (0 cm), +0.0136 °C/year at 10 cm depth, +0.0142 °C/year at 40 cm depth and +0.0133 °C/year at 100 cm depth.

Keywords: Air temperature, soil temperature, bent-stem thermometer, extraction thermometer, NOAA-CIRES-DOE 20th Century Reanalysis V3, climate change, North-West Arctic Zone of Russia.

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1. Introduction

Most climate change scenarios are based on studies of air temperature fluctuations. However, for many theoretical and applied problems, the response of the earth's surface to these changes is important. For the territory of Russia, more than half of which is occupied by the most sensitive shell to climate change – permafrost, this is of paramount importance, determining sudden changes in natural conditions and, as a consequence, infrastructure risks. As a result of climate warming, the depth of thawing in soils increases, but unevenly in different regions of the permafrost zone, including due to the action of processes with negative and positive feedbacks.

When solving many problems in the construction of buildings and technical structures, in the operation of roads and railways and underground communications, data on soil temperature (ST) at depths are used. The most important characteristic is the minimum annual temperature, which is necessary to determine the depth of seasonal soil freezing, and the interannual variability of ST at different horizons for scientifically based forecasts.

2. Research area

According to observational data since the mid-1970s, average temperatures in the subarctic zone of Russia are growing 2.5 times faster than on the planet as a whole [*Intergovernmental Panel on Climate Change (IPCC)*, 2023; *IPCC*, 2007, 2013; *Roshydromet*, 2008, 2014, 2022]. This region of Russia is particularly vulnerable to climate change because hundreds of billions of dollars worth of infrastructure is located in the permafrost zone. If thawing of frozen strata occurs, then due to the significant ice content in them, the average soil settlement can be 10 meters or more.

Railway infrastructure in subarctic regions is operated in extremely difficult engineering-geological and landscape-climatic conditions, subject to continuous exposure to various external influences leading to deformations of the track and artificial structures [*Kostianaia and Kostianoy*, 2023; *Kostianaia et al.*, 2021]. Examples include coastal abrasion, mudflows, floods, erosion, landslides and drifts, karst failures, suffusion subsidence, ice dams, thermokarst, thermal erosion and solifluction, rupture deformations, snow avalanches, etc.

The Arctic zone of northwestern Russia (Murmansk, Arkhangelsk regions, Republic of Karelia) is characterized by the presence of island permafrost zones. The infrastructure of Russian Railways in this region is especially vulnerable to the negative factors of regional climate change, since the main problem of the Volkhovstroy - Murmansk section is the fact that out of 1.320 kilometers of its length, more than 340 kilometers are single-track sections, which limits its capacity and makes it vulnerable. In addition, on April 30, 2020, the Russian Government set the goal of increasing transportation from 28 to 44 million tons per year on the Murmansk branch of the Oktyabrskaya Railway by 2023, and not by 2035, as previously planned.

In this regard, studies of climate changes in the region under consideration (61°–70° N, 28°–45° E) are extremely important for Russian Railways. This study is a continuation of work begun in [*Gvishiani et al.*, 2023; *Serykh et al.*, 2022].

3. Data and Methods

To analyze the interannual variability of the state of the atmosphere and soil in the Arctic zone of northwestern Russia, the following data were selected: soil temperature (ST) observation data at 13 meteorological stations (Figure 1) of the Roshydromet network [*Bykhovets et al.*, 2007]. The data array contains daily ST values measured with bent-stem thermometers at 4 depths (5, 10, 15, 20 cm) under areas bare (cultivated) of vegetation, as well as daily ST values measured with extraction thermometers at 6 depths up to 320 cm (20, 60, 80, 120, 240, 320 cm). Typically, measurements with bent-stem thermometers are carried out from late spring to early autumn (May–October).

ST time intervals observation data at meteorological stations of Roshydromet network are presented in Table 1.

Observations contain gaps in data at individual depths or at all depths simultaneously. Sometimes these omissions coincide with various historical events and transitional moments in the development of the country. To assess the spatial variability of climate trends, the study area was divided into three subregions: (1) – Northern subregion (NSR): 65.5°–70° N, 28°–45° E; (2) – Central subregion (CSR): 63.5°–65.5° N, 28°–45° E; (3) – Southern subregion (SSR): 61°–62.5° N, 28°–45° E.

The density of these stations in the study region (Figure 1), unfortunately, does not allow us to assess climate variability for the entire region as a whole. For this reason, data from the NOAA-CIRES-DOE 20th Century Reanalysis (Version 3) [*Slivinski et al.*, 2019] for the period 1980–2015 were additionally used. with a spatial resolution of 1° in longitude and latitude at four horizons (0, 10, 40 and 100 cm). Calculations of the linear trend were carried out using average monthly near surface air temperature (NSAT) and ST data.

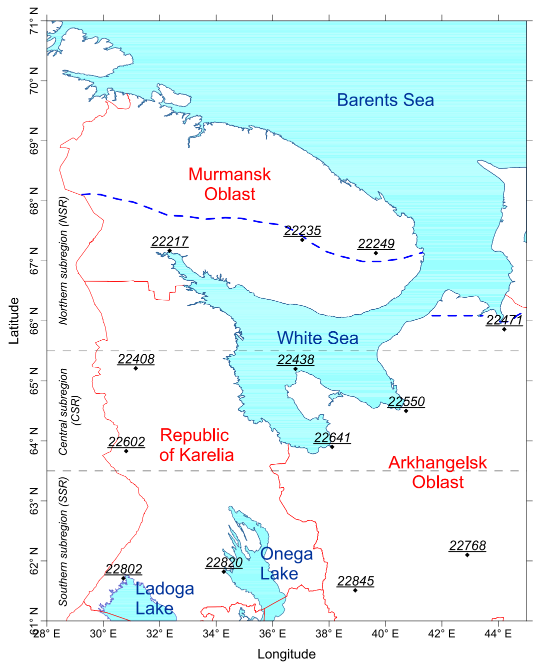


Figure 1. The location of weather stations in Arctic zone of northwest Russia, where ST observations are carried out at different depths. Blue dashed line is permafrost boundary. Gray dashed line is boundaries of subregions.

4. Results and their discussion

4.1. Results according to weather stations

Based on bent-stem thermometer ST measurements at weather stations, linear trends (°C/year) were calculated for the time interval 1985–2012. for each month when measurements were taken, at 4 depths. The maximum average positive climatic trends in ST changes across subregions according to bent-stem thermometer measurements for the period 1985–2012 are observed at all depths in July. The minimum trend in NSR is 0.085 °C/year and the maximum in SSR is 0.115 °C/year at a depth of 10 cm. In CSR this value in July is 0.081 °C/year. Below 10 cm depth, climate trends decrease with increasing depth in all subregions. Thus, we can say that the maximum contribution to the climate trend of ST changes is made in the summer months.

The average seasonal changes in TP climate trends across subregions at all depths exceeds 0.05 °C/year (Table 2). The maximum values are observed in CSR, the minimum – in NSR.

Since there are no ST measurements from the bent-stem thermometer in other months except for the period June–October, the contribution of other months can only be judged from the measurement data of extraction thermometers. Results of calculations of seasonal variability of climate trends at different depths for these measurements for the time interval 1985–2021. are presented in Figures 2–3 and Table 3.

In the seasonal course of depth-averaged linear trends in ST changes for all subregions, two maxima are observed: in spring-summer (May–June) and in autumn (September–October), and two minima – in spring (April) and in summer (July–August) (Figure 4).

For NSR and CSR, the values of the June maxima are almost the same and amount to 0.055 and 0.056 °C/year, respectively, and for SSR this value is 0.044 °C/year (Figure 4). This can be explained by the fact that in NSR in June at depths up to 140 cm there is an area of high ST trends of more than 0.06 °C/year with a local maximum of 0.083 °C/year at a depth of 120 cm (Figure 5a). In June, in the CSR at depths of 65–175 cm, an area of high ST trends of more than 0.06 °C/year is observed (Figure 5b). In May in SSR, the area of increased ST trends of more than 0.08 °C/year is localized at depths up to 55 cm. With increasing depth, the trend sharply decreases to 0.025 °C/year (at 320 cm). The large trend

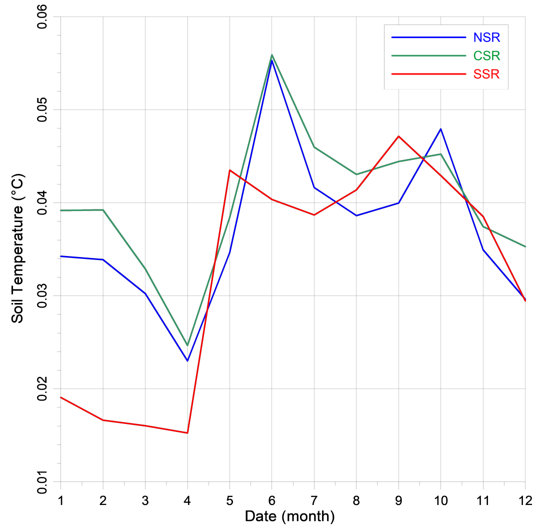
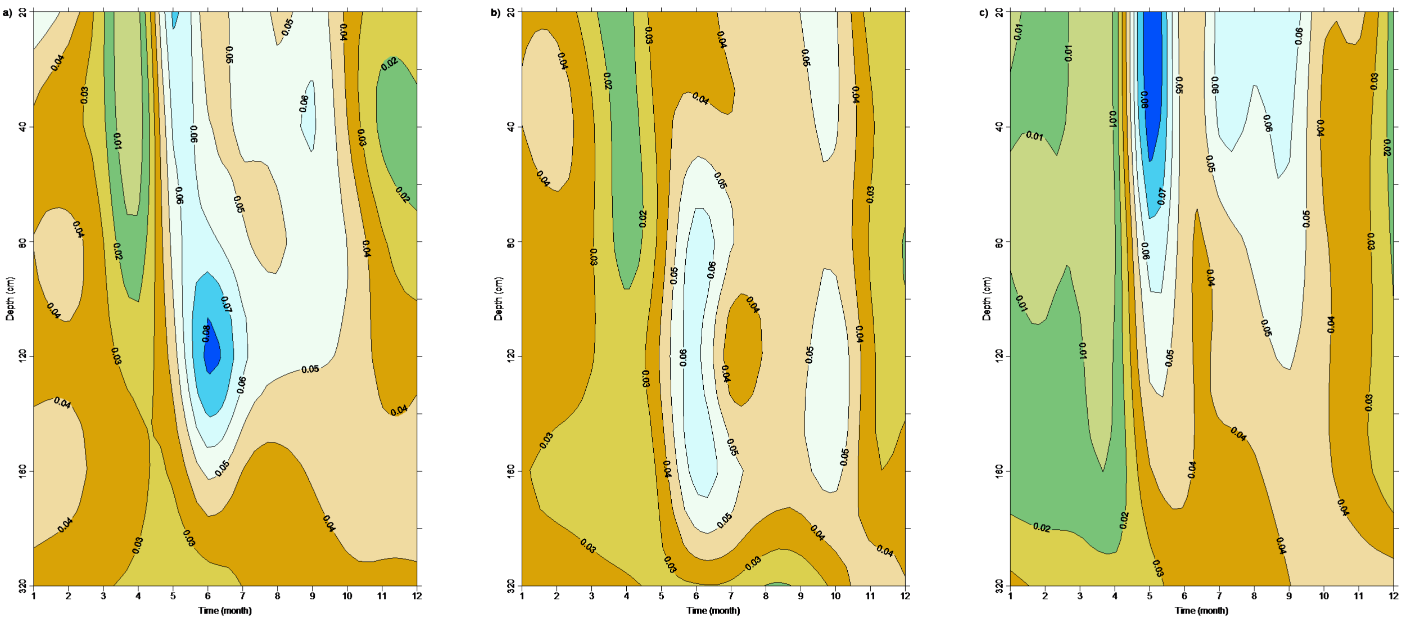


Figure 2. Seasonal variability of depth-averaged linear trends (°C/year) in subregions according to ST observations at meteorological stations of the Roshydromet network for extraction thermometer for the time interval (1985–2021).

gradient reduces the depth-average value to 0.044 °C/year (Figure 5c). A similar monthly shift between SSR and CSR/NSR is also observed in autumn maxima, the values of which lie in the range of 0.045–0.048 °C/year. This is explained by slower changes in the ST trend with depth (Figure 5).



(a) **(b)** **(c)**

Figure 3. Seasonal and deep linear trends variability (°C/year) for NSR (a), CSR (b) and SSR (c) according to ST observations at meteorological stations of Roshydromet network for extraction thermometer for time interval (1985–2021).

The April minimum of the depth-averaged TP climate trend according to extraction thermometer data for NSR and CSR are also close to each other: 0.023 and 0.025 °C/year, respectively, and for SSR this value is 0.015 °C/year (Figure 2). As well as for the June maximum of ST trends, changes in depth are observed to include a vast area of less than 0.02 °C/year, which extends from the surface to 100 cm in the NSR and CSR (Figure 3a, 3b). In SSR, this area is observed down to a depth of 240 cm (Figure 3c).

Table 1. Time intervals of ST data observation data observation at meteorological stations of Roshydromet network for various thermometers types.

# WMO	Name of station	Bent-stem thermometers	Extraction thermometers
NSR: 28°–45°E – 65.5°–70°N			
22217	Kandalaksha	1985–2012	1963–2022
22235	Krasnoshchelye	1985–2012	1977–2022
22249	Kanevka	1984–2012	1977–2022
22471	Mezen	1984–2012	1977–2022
CSR: 28°–45°E – 63.5°–65.5°N			
22408	Kalevala	1984–2012	1977–2022
22438	Zhizhgin Island	–	1977–2022
22550	Arkhangelsk	–	1965–2022
22602	Reboly	1984–2012	1963–2022
22641	Onega	1984–2012	1963–2022
SSR: 28°–45°E – 61°–63.5°N			
22768	Shenkursk	1984–2012	1977–2022
22802	Sortavala	1984–2012	1963–2022
22820	Petrozavodsk	1984–2012	1963–2022
22845	Kargopol	1984–2012	1963–2022

As in local maxima, a monthly shift between SSR and CSR/NSR is also observed in summer minima, the values of which lie in the range of 0.040–0.046 °C/year. This is explained by the presence of a large area of less than 0.05 °C/year in August to depths of 170 cm (NSR) and 240 cm (CSR) (Figures 3a, 3b). In the SSR, this area is located at depths of 120–320 cm (Figure 3c)

The average seasonal changes in TP climate trends across subregions at all depths exceeds 0.03 °C/year (Table 3). The maximum value of 0.0459 °C/year is observed in CSR at a depth of 120 cm, and minimum value is of 0.0296 °C/year is observed at depth of 160 cm in SSR.

5. Results according to reanalysis data

In the study region, according to [*Serykh et al.*, 2022], according to the NCEP/NCAR reanalysis data, in the last 2 decades (1999–2020), NSAT increased from 0.9 to 1.5 °C compared to previous years (1977–1998), and the increase in NST was 0.04–0.1 °C. This led to a shift of the +2 °C isotherm by 550 km to the north up to the southern part of the White Sea and to the complete disappearance of average negative temperatures. According to the NOAA-CIRES-DOE 20th Century Reanalysis (Version 3) for the period 1980–2015, a linear trend for NSAT at a height of 2 m for the region as a whole was 0.024 °C/year. The maximum trend was observed in NSR – 0.031 °C/year, and the minimum in CSR – 0.023 °C/year. In SSR, the climate trend was 0.024 °C/year, which is slightly higher than in CSR (Table 4).

Analysis of the spatial distribution of interannual trends (Figure 4) shows. that the linear NSAT trend begins to increase from +0.005 °C/year from north to south till the Onega Bay of the White Sea. Further, the growth of the interannual trend increases in the northeast direction.

The climatic increase in ST for the entire region was: 0.0095 °C/year at the surface (0 cm), 0.0096 °C/year at a depth of 10 cm, 0.0102 °C/year at a depth of 40 cm and 0.0097 °C/year at a depth of 100 cm (Table 4). In NSR, the maximum climate trend was

Table 2. Average linear trends in the sub-regions (°C/year) according to ST observations at meteorological stations of Roshydromet network for bent-stem thermometer over a time interval 1985–2012.

Value	Depth			
	5 cm	10 cm	15 cm	20 cm
NSR: 28°–45°E – 65.5°–70°N				
Average value	0.0522	0.0558	0.0518	0.0510
Standard deviation	0.0156	0.0138	0.0070	0.0112
CSR: 28°–45°E – 63.5°–65.5°N				
Average value	0.0632	0.0652	0.0589	0.0561
Standard deviation	0.0220	0.0209	0.0189	0.0158
SSR: 28°–45°E – 61°–63.5°N				
Average value	0.0577	0.0564	0.0561	0.0552
Standard deviation	0.0391	0.0372	0.0334	0.0162

Table 3. Sub-regions average linear trends (°C/year) according to ST observations at meteorological stations of Roshydromet network for extraction thermometers for time interval 1985–2021.

Value	Soil depth					
	20 cm	40 cm	80 cm	120 cm	160 cm	320 cm
NSR: 28°–45°E – 65.5°–70°N						
Average value	0.0356	0.0375	0.0378	0.0388	0.0393	0.0321
Standard deviation	0.0095	0.0083	0.0110	0.0094	0.0116	0.0058
CSR: 28°–45°E – 63.5°–65.5°N						
Average value	0.0417	0.0373	0.0418	0.0459	0.0409	0.0320
Standard deviation	0.0148	0.0158	0.0119	0.0113	0.0047	0.0040
SSR: 28°–45°E – 61°–63.5°N						
Average value	0.0385	0.0363	0.0326	0.0311	0.0296	0.0350
Standard deviation	0.0233	0.0215	0.0183	0.0150	0.0117	0.0070

0.0166 °C/year at a depth of 40 cm, in CSR – 0.0072 °C/year and SSR – 0.0018 °C/year at the same depth (Table 4). In general, the same picture is observed as according to measurement data at weather stations only relative to a depth of 10 cm. This difference is apparently associated with the parameterization of heat and moisture exchange processes in the soil, which is used in the atmospheric circulation model when calculating reanalysis fields [*Arzhanov and Mokhov*, 2013; *Slivinski et al.*, 2019].

On the Kola Peninsula and the eastern coast of the White Sea (Zimny and Kaninsky coasts and Mezen Bay) value of ST linear trends exceeds +0.025 °C/year (Figure 5a). The linear trend of ST behaves the same at all depths. In the southern part of the region (south of latitude 61.5°) it has negative values. On the territory of the Republic of Karelia there is an area of negative values elongated in a northeast direction towards the Pechersk coast (Figures 5a–5d). For the Kola Peninsula, the interannual ST trend is more than +0.01 °C/year at all 4 depths. A similar picture is observed on the eastern coast of the White Sea north of the Northern Dvina Delta.

More informative is the ratio of the linear trend of ST at a depth of 100 cm to the linear trend of NSAT [*Pavlov*, 2008]. For the Kola Peninsula and the eastern coast of the White Sea north of the Northern Dvina Delta, its value is more than 0.4. At the same time, in the area of the Rybachy and Teriberka Peninsulas (northern coast of the Kola Peninsula) and

Table 4. Average linear trends for air and soil temperature in the sub-regions (°C/year) according to NOAA-CIRES-DOE 20th Century Reanalysis for time period 1980–2015.

Value	Air	Soil Depth			
		0 cm	10 cm	40 cm	100 cm
NSR: 28°–45°E – 65.5°–70°N					
Average value	0.0312	0.0154	0.0161	0.0166	0.0155
Standard deviation	0.0050	0.0033	0.0037	0.0036	0.0035
CSR: 28°–45°E – 63.5°–65.5°N					
Average value	0.0231	0.0068	0.0065	0.0072	0.0069
Standard deviation	0.0032	0.0053	0.0059	0.0059	0.0055
SSR: 28°–45°E – 61°–63.5°N					
Average value	0.0108	0.0013	0.0008	0.0018	0.0017
Standard deviation	0.0046	0.0019	0.0019	0.0019	0.0019
Total region: 28°–45°E – 61°–70°N					
Average value	0.0235	0.0095	0.0096	0.0102	0.0097
Standard deviation	0.0084	0.0070	0.0076	0.0075	0.0069

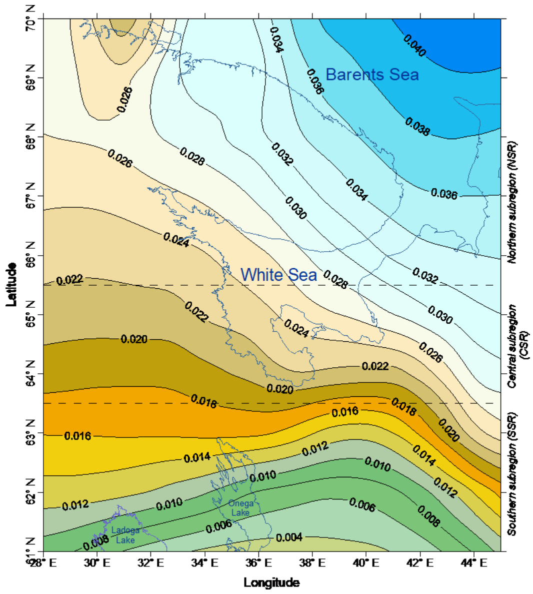


Figure 4. NSAT climatic trends (°C/year) changes according to NOAA-CIRES-DOE 20th Century Reanalysis data for time period 1980–2015.

north of the White Sea – Kuloi Plateau (eastern coast of the White Sea), areas of maximum values of this ratio of more than 0.6 are observed. It is in these areas that island permafrost zones are observed. which are at high risk of destruction (Figure 6).

6. Conclusions

Analysis of ST climatic variability according to bent-stem thermometer measurements at weather stations for time period 1985–2012 shows positive trend values at all 4 depths exceeding 0.05 °C/year. Maximum values of 0.0561–0.0652 °C/year are observed for CSR, the minimum 0.0510–0.0558 °C/year – for NSR. According to extraction thermometers for time interval 1985–2021, ST linear trends for all depths exceeds 0.03 °C/year. Maximum value is 0.0459 °C/year is observed in CSR at a depth of 120 cm, and minimum value is 0.0296 °C/year at a depth 160 cm in SSR.

According to NOAA-CIRES-DOE 20th Century Reanalysis for time period 1980–2015, ST climatic growth in whole region was 0.0095 °C/year at surface (0 cm), 0.0096 °C/year at a depth of 10 cm, 0.0102 °C/year at a depth of 40 cm and 0.0097 °C/year at a depth of 100 cm. In NSR, maximum climatic trend was 0.0166 °C/year at a depth of 40 cm, in CSR –0.0072 °C/year and SSR – 0.0018 °C/year at same depth.

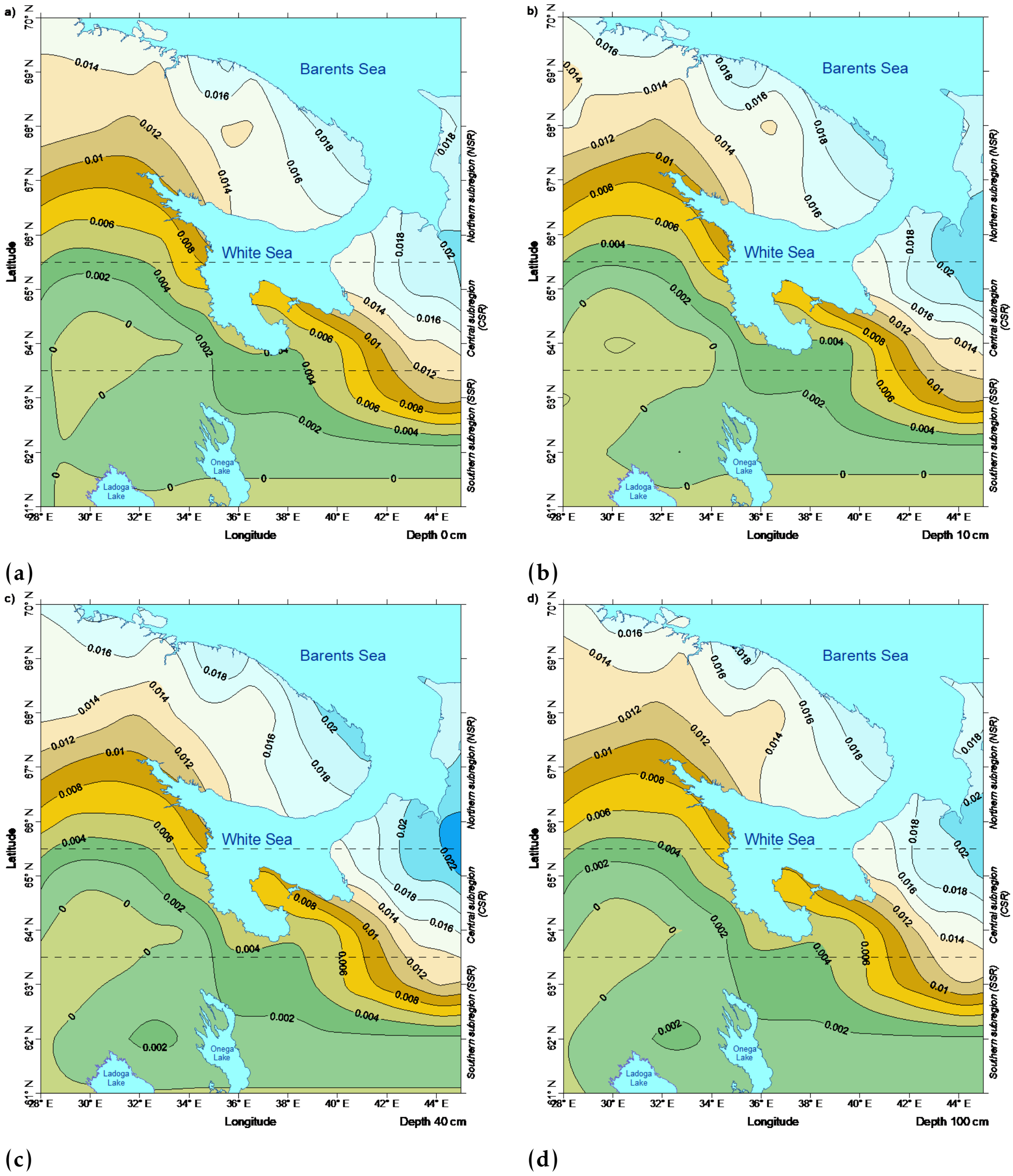


Figure 5. Climatic trends (°C/year) in ST changes at depths of 0 cm (a). 10 cm (b). 40 cm (c) and 100 cm (d) according to NOAA-CIRES-DOE 20th Century Reanalysis for the period 1980–2015.

These data are in a good agreement with values calculated according to the data for permafrost thermal monitoring for the past 25–35 years. According to work [*Pavlov*, 2008] linear trends of NSAT and ST for 1961–2003 in the north of the European part of Russia were +0.026 °C/year and +0.018 °C/year, respectively. Time interval for interannual trends in the Second Assessment Report of Roshydromet on climate change and its consequences on Russian Federation territory [*Roshydromet*, 2014] was expanded to 1961–2010. Linear trens presented in the Report become higher: +0.033 °C/year and +0.024 °C/year, respectively. The ratio of the linear trend of ST to the linear trend of NSAT was 0.69 in [*Pavlov*, 2008] and 0.73 in [*Roshydromet*, 2014]. According to our data, this ratio was

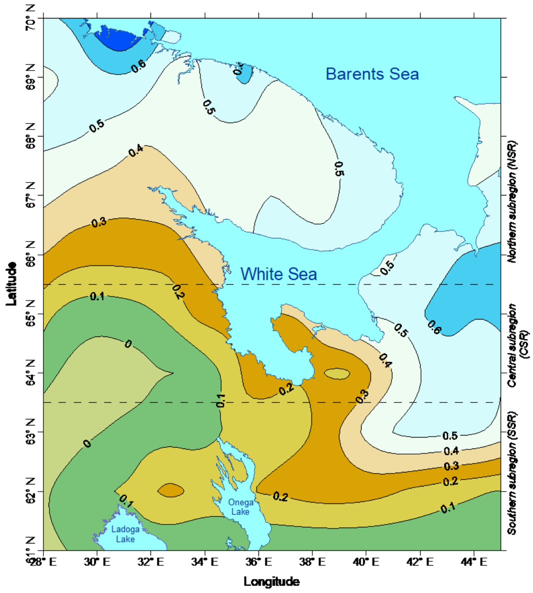


Figure 6. The ratio of the linear trend of ST at a depth of 100 cm to the linear trend of NSAT

0.49 ± 0.01. This difference is due to the fact, that a maximum depth for soil temperature in NOAA-CIRES-DOE 20th Century Reanalysis is of 1 m and in-situ thermal monitoring of permafrost involves measuring soil temperature at a depth of 10 m.

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