Study of the Impact of Climatic Changes in 1980–2021 on Railway Infrastructure in the Central and Western Russian Arctic Based on Advanced Electronic Atlas of Hydrometeorological Parameters (Version 2, 2023)

A. D. Gvishiani[1,2], **I. N. Rozenberg**[3], **A. A. Soloviev**[1,2], **R. I. Krasnoperov**[1], **O. O. Shevaldysheva**[*,1,4], **A. G. Kostianoy**[1,5,6], **S. A. Lebedev**[1], **I. A. Dubchak**[3], **N. V. Sazonov**[7], **I. M. Nikitina**[1], **S. A. Gvozdik**[1], **V. N. Sergeev**[1], **G. A. Gvozdik**[1,4]

[1]Geophysical Center of the Russian Academy of Sciences, Moscow, Russia
[2]Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, Moscow, Russia
[3]Russian University of Transport, Moscow, Russia
[4]Lomonosov Moscow State University, Moscow, Russia
[5]Shirshov Institute of Oceanology of the Russian Academy of Sciences, Moscow, Russia
[6]Witte Moscow University, Moscow, Russia
[7]Research and Design Institute of Informatization, Automation and Communications in Railway Transport, Moscow, Russia
* **Correspondence to:** Olga Shevaldysheva, o.shevaldysheva@gcras.ru

Abstract: Arctic zone of the Russian Federation (AZRF) is the region of intensive economic development. In this regard, it is critical to give an adequate assessment of natural factors that may have a negative impact on the growing technological infrastructure. Rapid climate change effects show a significant influence on this activity, including the railway network development. Hence, the decision-making community requires relevant information on climatic variations that can put at hazard the construction and operation of railway facilities. This paper presents the analysis of climatic changes within the region of Central and Western Russian Arctic in 1980–2021. It was performed using the new electronic Atlas of climatic variations in main hydrometeorological parameters, created for the Russian Railways in 2023. This geoinformatic product includes about 400 digital maps reflecting the variability of seven climatic parameters over more than four decades within the studied region. These parameters are air temperature, total precipitation, wind speed, soil temperature, soil moisture content, air humidity, and snow cover thickness. The analysis of climatic maps and their comparison between selected periods showed spatial and temporal heterogeneity of climatic variations in this region. This justifies the feasibility of further research using additional analytical instruments, such as Hovmöller diagrams, time series graphs, etc. The implementation of advanced geoinformatic products in the practice of the Russian Railways will facilitate sustainable development of its infrastructure in rapidly altering climatic conditions.

Research Article

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1. Introduction

The Arctic Zone of the Russian Federation (AZRF) has taken incentives for development in recent years. As one of the richest regions in terms of valuable natural resources

[*Krivovichev*, 2019], it has received substantial support from the government to conduct economic activities within its territory. For instance, a reduced rate of mineral extraction tax (MET) has been established for new deposits of solid minerals, and there is no tax on the extraction of natural gas used for the production of liquefied gas or further petrochemical products, as well as other tax incentives [*Decree of the President of the Russian Federation*, 2014].

It is well known that the cost of transporting valuable minerals from remote deposits can significantly impact the overall cost of the final product. Therefore, exporting valuable minerals primarily by water transport becomes the only opportunity to make costly Arctic developments profitable [*Makarova et al.*, 2021].

Based on this, one of the most significant projects for the development of the region is the Northern Sea Route (NSR). This shipping route runs along the northern coasts of Russia in the Arctic Ocean, connecting European and Far Eastern ports. Estuaries of navigable Siberian rivers are also included into a unified transportation system. According to official statistical data, the cargo volume transported along the NSR in 2022 amounted to 34 million tons [*Department of Communications of the State Corporation "Rosatom"*, 2023]. It is planned to increase this volume to 150 million tons by 2030 and 220 million tons by 2035 [*Decree of the Government of the Russian Federation*, 2022]. The development of the NSR includes the construction of additional ice-class vessels, including icebreakers, and the expansion of port infrastructure in different regions of the AZRF.

The development of transportation infrastructure to increase cargo traffic along the NSR is connected to the delivery of goods to ports. The transportation infrastructure of AZRF encompasses all major modes of transportation: railways, roadways, waterways, and aviation. From an economic perspective, the combination of railway and water transport is often the most cost-effective option. For instance, when developing coal deposits and reaching full production capacity, it may be economically unfeasible to deliver the products to the port using railway transport only. The same applies to any other bulk cargo.

The only five out of the eight Arctic regions obtain railways. These are the Republic of Karelia, Murmansk and Arkhangelsk Oblasts, the Republic of Komi, and the Yamalo-Nenets Autonomous Okrug. Among private railways, it's well known the Norilsk Railway in Krasnoyarsk Krai, which runs from Dudinka to Talnakh, and a planned line from the Syradasai coal deposit to the Yenisei seaport. In the Republic of Sakha (Yakutia) and Khabarovsk Krai, the construction of the longest private railway, the Pacific Railway, is underway, connecting the Elginskoye coal deposit to the port of Elga on the Sea of Okhotsk. The total length of these railway tracks will exceed 500 kilometers.

The development of the state railway is planned for four Arctic regions: Arkhangelsk Oblast, Nenets Autonomous Okrug, Yamalo-Nenets Autonomous Okrug, and the Republic of Komi, as indicated in Table 1. This development primarily focuses on the western parts of the AZRF. This choice of the region for the present research is based on these development plans and priorities.

The area selected for the research in the limits of 55–80° N, 30–100° E is shown in Figure 1. This map provides an overview of the key ports and railway infrastructure in the western and central parts of the AZRF that are under the jurisdiction of the Russian Railways.

The AZRF is characterized by a range of characteristics that necessitate special approaches to its socio-economic development. Climate change, in particular, introduces risks to economic activities. Therefore, expansion of the railway infrastructure in the region requires understanding the trends in the regional climate change.

According to [*AMAP*, 2021], the average annual increase in surface air temperature in the Arctic has been 3.1 °C since 1971. Moreover, the reduction in climate severity is creating conditions conducive to more comfortable environments in the eastern part of the AZRF. Conversely, in the western part, such warming is accompanied by adverse consequences. For instance, the projected frequent transitions of air temperatures through 0 °C within the 21st century are expected to result in accelerated material aging and, ultimately, a reduction

Table 1. Fundamentals of the State Policy of the Russian Federation in the Arctic for the period up to 2035 [*Decree of the Government of the Russian Federation*, 2022]

Subject of the Russian Federation	Railway mainline	Development plan
The Republic of Komi	Sosnogorsk–Indiga	Construction
Nenets Autonomous Okrug	Sosnogorsk–Indiga	The development of a construction project
	Konosha–Kotlas–Chum–Labytnangi	Reconstruction
	Mikun–Vendinga	Justification of the feasibility of building a section
	Vendinga–Karpogory	Site construction
Yamalo-Nenets Autonomous Okrug	Obskaya–Salekhard–Nadym–Pangody–Novy Urengoy–Korotchaevo	Construction and development of railway mainlines
	Obskaya–Bovanenkovo–Sabetta	Construction and development of railway mainlines
Arkhangelsk Oblast	Karpogory–Vendinga	Justification of the feasibility of building a railway section
	Mikun–Solikamsk	Justification of the feasibility of building a railway section

Figure 1. Study area with a scheme of the main railways.

in their service life [*Kattsov*, 2022]. The increased period of warmth, together with changes in most climate parameters, is directly linked to the degradation of permafrost [*Kostianaia et al.*, 2021; *Serykh et al.*, 2022]. This, in turn, leads to changes in the landscape and the balance of water bodies in the region [*Vasiliev et al.*, 2020].

The changing climate conditions must be considered when operating existing railways and planning the new ones. This task becomes particularly crucial in the context of accelerated economic development in the region, where the burden on transportation infrastructure is expected to increase significantly over the next several decades. In 2022, *Gvishiani et al.* [2023a] have elaborated an "Electronic Atlas of Climatic Changes in the Western Russian Arctic in 1950–2021 as Geoinformatic Support of Railway Development" (Atlas-2022), and have analyzed the ongoing regional climate change based on a set of meteorological parameters derived from the MERRA-2 atmospheric reanalysis.

This article is dedicated to the investigation of interannual variability of key meteorological parameters in the western and central parts of the AZRF and its impact on railway infrastructure based on the second version of this Atlas. In Atlas-2023, the study area was expanded by 5 degrees to the South and to the North, and by 15 degrees to the East in comparison with the Atlas-2022. Thus, we investigated the western and central part of the Russian Arctic within the geographical boundaries 55–80° N, 30–100° E and time period from 1980 to 2022. To build the Atlas-2023 we used the same MERRA-2 atmospheric reanalysis and the same set of the main hydrometeorological parameters characterizing climate change in the region: air temperature, total precipitation, wind speed, soil temperature, soil moisture content, air humidity, and snow cover thickness. The choice of these meteorological parameters is determined by their influence on the infrastructure and reliable functioning of railways in the study area.

2. Data and Methods

2.1. Data

2.1.1. MERRA-2 reanalysis

The MERRA-2 reanalysis (Modern-Era Retrospective Analysis for Research and Applications, Second Edition) serves as an essential tool in climatology and meteorology, designed for the analysis and reconstruction of meteorological data within a historical context. This mission was initiated by the Global Modeling and Assimilation Office (GMAO), under the guidance of the National Aeronautics and Space Administration (NASA) [*Gelaro et al.*, 2017]. The primary objectives of MERRA-2 are to obtain and analyze historical meteorological and climatological data, including information on parameters such as temperature, pressure, humidity, wind, and various others, spanning several decades. These data are utilized for the analysis of climate changes, the development of climate models, and a deeper understanding of past climatic events. Additionally, MERRA-2 provides the capability to monitor climate changes based on long-term data, aiding scientists in gaining insights into climate trends and their implications.

The original MERRA project was created to synthesize the measurement results obtained from satellites into a unified climate catalog. Its primary goal was to analyze and describe the general hydrological cycle, encompassing processes from the upper atmospheric layers to the planet's surface. Starting in 1979, the MERRA project collected data and performed this task. However, by 2016, it was discontinued due to several shortcomings, such as errors in measurement systems, discrepancies in atmospheric and hydrological data, limited representation of the upper stratosphere, and challenges in integrating new data sources [*Gelaro et al.*, 2017]. The main objective of reprocessing and improving the MERRA project was to ensure continuous climate monitoring in near real-time mode, with data publication having only a small delay of a few weeks.

From a technical perspective, the MERRA-2 observation system, compared to the initial MERRA version, employed additional equipment to measure parameters such as atmospheric motion vectors (using the Advanced Very High Resolution Radiometer or AVHRR instrument), near-surface wind speed (using the Special Sensor Microwave Imager/Sounder or SSMIS), temperature profiles and ozone characteristics (utilizing instruments from the Earth Observing System and Aura MLS – Microwave Limb Sounder), among others [*McCarty et al.*, 2016]. Additionally, during the MERRA-2 reanalysis, the sensors for measuring near-surface wind speeds and ozone content were enhanced and replaced with more modern models throughout the mission's development.

Some advantages of the MERRA-2 reanalysis over other missions and data sets include its extensive temporal coverage, providing continuous data from 1980 to the present day, allowing access to long-term time series, and high spatial resolution. It is important to emphasize the integrated methodology employed in MERRA-2, which involves the combination of data originating from diverse observational systems and atmospheric models. This combination serves to augment the precision and dependability of the data. Furthermore, MERRA-2 consistently refines its techniques related to methodology and signal processing, incorporating up-to-date data and innovative approaches to ensure the currency and trustworthiness of its outcomes.

In general, the compilation of MERRA-2 catalogs is based on a complex and multi-component process, involving the following fundamental principles: data collection, data assimilation, interpolation and extrapolation, numerical modeling, validation, and verification. Data collection involves acquisition of information from various channels, including observations from meteorological satellites, weather stations, buoys, probes, and other meteorological data sources. Subsequently, the data is fed into numerical atmospheric models to account for the non-uniformity and incompleteness of the initial data. Atmospheric models are utilized to create continuous temporal and spatial reconstructions of climate parameters. To construct a more comprehensive and consistent climate reconstruction, data is interpolated and extrapolated in time and space, thereby filling gaps in data and providing higher spatial and temporal resolution. Following this, the data is assimilated into various numerical atmospheric models, representing complex physical and chemical processes occurring in the atmosphere. These models enable the prediction of parameters that may be absent from observations. The results of assimilation and modeling are compared with real observations to evaluate the accuracy and quality of MERRA-2 data. This is an essential stage ensuring the reliability and completeness of the reconstructions. After completing all the stages, the data is compiled into catalogs, serving as a unified source of climate data accessible for scientific research and practical use.

Several scientific research have underscored the advantages of the reanalysis, particularly when compared to other climate data compilations, including the initial MERRA iteration. To illustrate, *Bosilovich et al.* [2016] exemplified the high-fidelity portrayal of atmospheric precipitation and temperature patterns across North America, utilizing data from MERRA-2. *Tilinina et al.* [2013] conducted an analysis demonstrating that MERRA excels in capturing the dynamics of atmospheric cyclones in the Atlantic-Eurasian sector of the Northern Hemisphere. *Bentamy et al.* [2017] showcased how MERRA aligns effectively with the statistical features of turbulent exchanges between the atmosphere and ocean over marine regions. The research by *Luo et al.* [2020] signified that MERRA-2 consistently replicates sea surface temperature, atmospheric temperature, and humidity values over the Atlantic Ocean. *Schubert et al.* [2022] presented research outcomes corroborating the high precision of MERRA-2 in representing extreme temperature anomalies in the Northern Hemisphere.

The MERRA-2 reanalysis data employed in this study were acquired on a standardized grid with spatial intervals of 0.5° latitude by 0.625° longitude. The considered climatic parameters include air temperature, total precipitation, wind speed, soil temperature, soil moisture content, air humidity, and snow cover thickness. In the case of air temperature, MERRA-2 leverages observations from meteorological satellites and weather stations, in combination with outputs from numerical models. Wind speed data within MERRA-2 is deduced from observations made by meteorological satellites and probes, as well as from numerical models describing atmospheric dynamics. Precipitation estimates are derived from satellite, buoy, and ground station datasets. In a general sense, all these parameters represent outcomes of measurements subjected to subsequent processing and numerical modeling.

In the MERRA-2 reanalysis, air temperature and humidity are measured using advanced instruments for vertical profiling these parameters. These instruments include the Cross-Track Infrared Sounder (CrIS) and the Advanced Technology Microwave Sounder (ATMS) [*Luo et al.*, 2020].

Total precipitation in the MERRA-2 reanalysis initially relies on precipitation data based on ground measurements from observatories and stations, which are later archived and parameterized into calculations based on satellite observations [*Chen et al.*, 2002; *Reichle et al.*, 2011].

Wind speed measurements using satellites involve decomposing wind speed into two orthogonal components: eastward and northward. The measurement methodology is largely analogous to the principles of a scatterometer, relying on the analysis of signals reflected from the sea surface [*Gelaro et al.*, 2017]. It is important to note that wind speed is significant not only as a climatic parameter but also as a factor for correcting other types of climatic data. Therefore, the MERRA-2 reanalysis utilizes data from both ground meteorological stations (e.g., University Corporation for Atmospheric Research – UCAR and National Centers for Environmental Prediction – NCEP) and various satellite systems [*Poli et al.*, 2013].

Regarding soil temperature measurements, specialized instruments and remote sensing methods are employed. These instruments emit signals, which are subsequently measured by sensors after interaction with the surface. In MERRA-2, soil temperature is remotely measured hourly, allowing tracking of short-term variations [*Ma et al.*, 2021].

For accurate soil moisture measurements, a radar and a radiometer are required, which are implemented in the SMAP (Soil Moisture Active Passive Observatory) system. It includes radiometric and radar instruments measuring surface soil parameters, enabling the assessment of soil moisture [*Reichle et al.*, 2011].

In MERRA-2, the reanalysis for air humidity employs normalized pseudo-relative humidity [*Holm*, 2003], which is calculated by normalizing it to the standard deviation of background error. MERRA-2 conducts a temporal series of total atmospheric water content and water transport from the ocean to the land.

When measuring the snow cover thickness, the reanalysis considers not only the moment of snowfall but also changes in the snow layer after compaction, accounting for possible melting. For this, a methodology estimating the thickness of already compacted snow is used, providing high-precision values.

2.1.2. GIS-instruments and data application

The main geoinformatics instruments for the creation of the Atlas-2023 were Golden Software Surfer (version 17.1) [*Golden Software*, 2023] and ESRI ArcGIS (ArcMap) (version 10.8) [*ESRI ArcMAP*, 2023]. These software packages have a user-friendly interface and a wide range of functions for primary data processing, including interpolation capabilities. The resulting data were prepared for publication as a map service using a geoportal approach and exported as formatted maps.

The first step of Atlas-2023 creation was the preparation of initial data. For each parameter and each month within the considered period a catalogue was created. Then, calculations of mean-value data for certain periods were performed. The next stage was to create raster files with an interval similar to the one in the reanalysis (0.50° × 0.65°). Golden Software Surfer was selected as a tool for creating the grid (`.grd`) files.

To improve the quality of the climate parameter mapping, the raw data, which were presented on an irregular 0.50° × 0.65°-grid, were interpolated using a Kriging tool to achieve the resolution of 0.05°. The Kriging tool allows to preserve the data detail without adding artifacts when transforming point data of a regular grid, as well as smoothing transitions between values the interpolated data were converted into raster (`.flt`) format for future analysis. The process of this conversion was performed in the Surfer program. Although such a tool is also available in other software packages, Surfer was chosen because of its good interpolation quality and its ability to export data with minimal time loss.

The next stage of data processing involves the removal of data located outside the terrestrial boundaries. Such an operation was performed for the following climatic parameters: snow cover thickness, soil temperature, and soil moisture content. For this purpose, a software module was developed in Python 2.7 using Python ArcPy tools and Python.os library. The main processing tool is the Clip tool, which is the part of the ArcGIS raster data processing toolbox.

The module has a graphical interface and is integrated into the ArcMap package. The input parameters are as follows: the name of the catalogue with processed raster data (in `.tif` or `.flt` format), the name of a vector file with contour mask in the shapefile (`.shp`) format for data clipping, and the name of a catalogue for saving the results. The software module processes each raster file in the catalogue separately using the Python.os library. Each layer is cropped using the Clip tool along the contour mask in the specified area along the coastline. The obtained results are saved in the specified catalogue. The resulting raster data cover the area from 55° to 80° N and from 30° to 100° E.

The georeferencing of the data during the Atlas-2023 preparation was determined by the choice of the map projection. WGS-84 (World Geodetic System 1984) geographic coordinate system was used for the initial raster data. The final maps of the atlas were compiled using the equidistant conic projection (ESRI:102026) with the central meridian of 103°. This map projection was chosen because of the geographical peculiarities of the study area located in high latitudes. The most commonly used map projections, such as the Web Mercator projection (EPSG:3857), distort spatial information as latitude increases.

The next stage in the construction of the atlas was the creation of a color palette for the data groups, as well as the selection of a color scale to make their display more visual. A single color palette was used for one characteristic of each climatic parameter. At this stage, the raster file and its isolines represent a ready tool for comparative analysis of the obtained data both within and between data groups.

The last stage of the Atlas-2023 creation was the merging of the prepared data into finished maps and their incorporation into the atlas layout. A coordinate grid and general information including legend, color scale, and numerical and linear scales were added. For each dataset, a GIS project was created in the MXD (Map Exchange Document) format, which contains all the necessary cartographic material for quick access and editing. The resulting maps were exported as TIFF images to compile a single atlas document.

3. Results

The elements of the created Atlas-2023 are blocks of electronic maps reflecting seven climatic parameters: air temperature, total precipitation, wind speed, soil temperature, soil moisture content, air humidity, and snow cover thickness. The division into blocks was carried out according to climatic parameters, and time periods: characterization of changes in mean values on an annual scale, and analysis of parameters for each month separately. For each block of parameters for different time periods, the mean values for the selected period were calculated and mapped, as well as the values of parameter changes between periods 2010–2021 and 1980–1989, and the linear trend of the parameter change for the period 1980–2021.

Thus, 8 characteristics of interannual variability were calculated and plotted on maps for each parameter:

1. Mean values of the parameter for the period 1980–2021.
2. Mean values of the parameter for the year 2022.
3. Mean values of the parameter for the period 1980–1989.
4. Mean values of the parameter for the period 1990–1999.
5. Mean values of the parameter for the period 2000–2009.
6. Mean values of the parameter for the period 2010–2021.
7. Changes in the parameter between the periods 2010–2021 and 1980–1989 (difference in mean values between these periods).

8. Mean rate of change of monthly mean values of the parameter for the period 1980–2021.

Also, for each parameter, the characteristics for each month (from January to December) were calculated and plotted on maps:

1. Mean values of the parameter for the period 1980–2021 for each month.
2. Mean values of the parameter for each month of 2022.
3. Changes in the parameter between the periods 2010–2021 and 1980–1989 (the difference in mean values between these periods) for each month.
4. Mean rate of change in the monthly mean values of the parameter between 1980–2021 for each month.

Air temperature and air humidity in the Atlas-2023 are given at the height of 2 m above the surface, soil temperature and soil moisture content refer to the first 10 cm of the ground. Wind speed is given for the height of 10 m above the surface.

The new Atlas-2023 (Version 2, 2023) of climatic parameters has a number of distinctive features in comparison with the previous Atlas-2022 [*Gvishiani et al.*, 2023a,b]:

- In Atlas-2023, for all considered hydrometeorological parameters, the rates of change were calculated using absolute values of the parameter instead of anomalies of the parameter relative to seasonal variability as it was done for Atlas-2022;
- Soil temperature and humidity were given for the upper 10 cm of soil instead of the average value for the upper 10 m;
- Wind speed near the surface was given at the height of 10 m, instead of 50 m;
- The 42-year study period in Atlas-2023 is divided into 4 decades – from 1980 to 1989, from 1990 to 1999, from 2000 to 2009, and from 2010 to 2021. In Atlas-2022 it was divided into two 20-year periods;
- Calculation of interdecadal changes in hydrometeorological characteristics in Atlas-2023 is made between the last (2010–2021) and the first (1980–1989) decade to emphasize the significance of the changes. In Atlas-2022, these changes were fairly smoothed out, since the difference was calculated between two 20-year periods.

3.1. Air temperature

The air temperature near the surface is the most important climatic characteristic that significantly affects the operation of railways, especially in the Far North (Figure 2). Figure 3 presents a map of changes in the average monthly air temperature between the periods 2010–2021 and 1980–1989. In the central part of the study area there were no significant changes in air temperature over the past four decades, however, in the western, eastern and northern parts, the air temperature has increased from 0.5 to 1.5 °C, both in the northern areas (e.g., Igarka, Dudinka) and in the southern areas (e.g., Krasnoyarsk, St. Petersburg). Figure 3 clearly shows at which sections of the railway network the largest changes in air temperature have occurred. However, regional climate warming occurs significantly unevenly by space and by seasons. For instance, in January, along the conventional line Moscow–Syktyvkar–Pechora–Novy Urengoy, there were practically no temperature changes, while to the north-west of it, around St. Petersburg, the warming was up to 1.5 °C, and in the Barents Sea – up to 4 °C, and the south and east of this line, on the contrary, there is a decrease in temperature in some areas by 2.5 °C. In February, almost the entire study area warmed by 3.0 °C, with the exception of the Ob Bay, where a decrease in temperature by 1 °C was observed [*Geophysical Center of the RAS*, 2023]. Figure 4 shows the changes in monthly mean air temperature between the periods 2010–2021 and 1980–1989 (the difference in mean values between these periods) for March. In March, the warming to the northeast of the conventional line Naryan-Mar–Pechora–Khanty-Mansiysk–Tomsk was quite high – up to 7.5 °C in the Dudinka area, while in the southern part of the central region (Perm–Khanty-Mansiysk–Tyumen) the air temperature became lower by 1 °C.

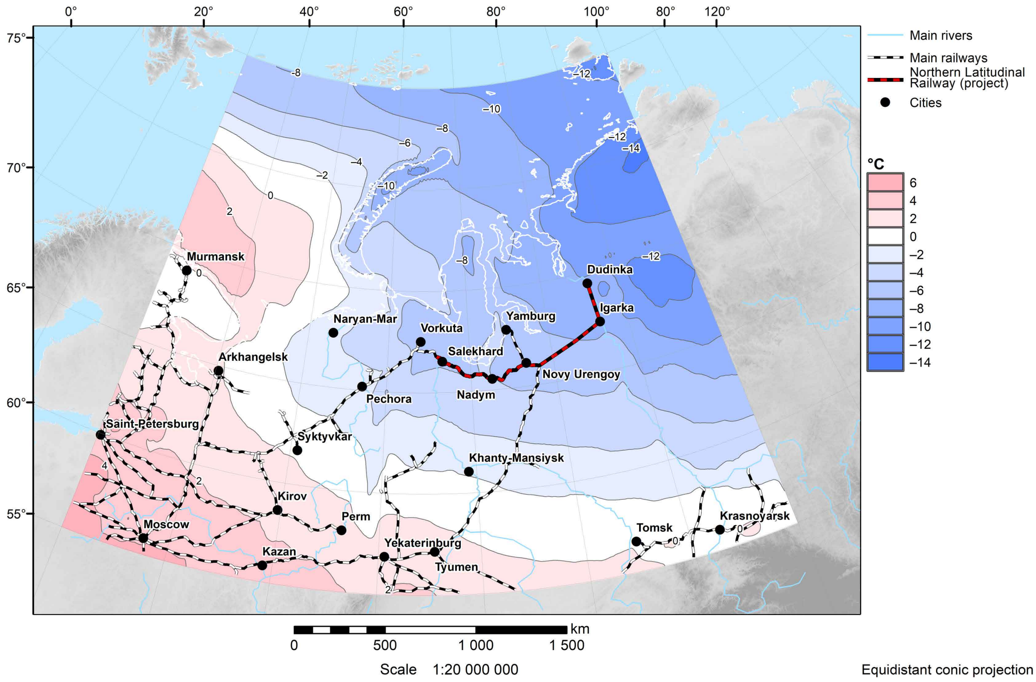

Figure 2. Mean annual monthly average air temperature for 1980–2021.

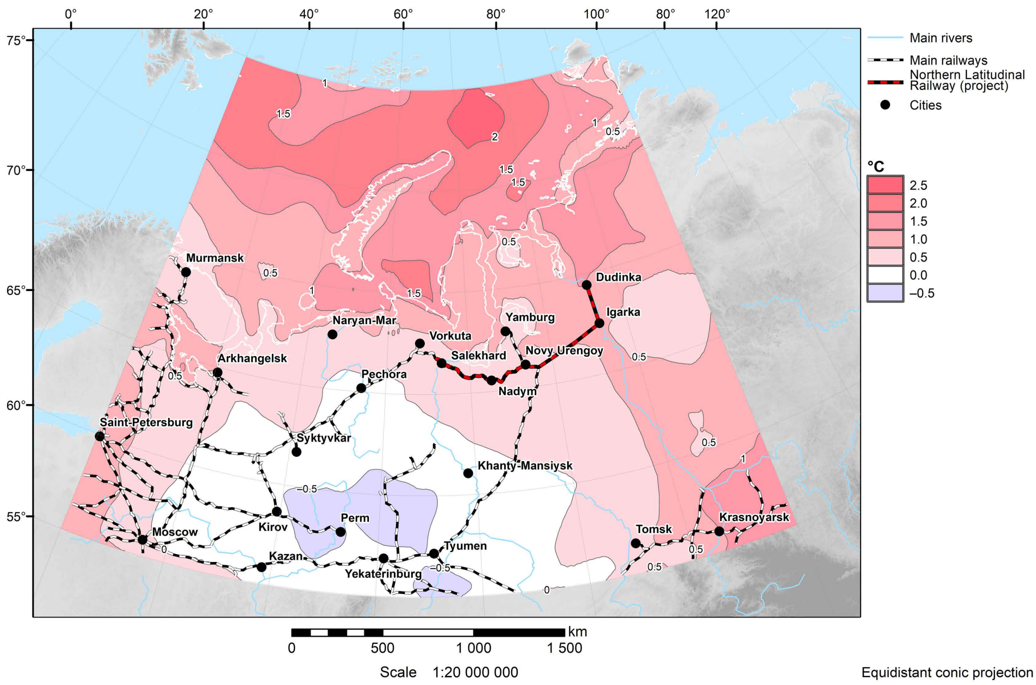

Figure 3. Changes in mean monthly average air temperature between the periods 2010–2021 and 1980–1989.

3.2. Soil temperature

Soil temperature is an important parameter for assessments of the reliability of railway operations, especially in areas with permafrost soils [*Kostianaia and Kostianoy*, 2023; *Kostianaia et al.*, 2021]. The permafrost soils contain ice, so when the soil temperature rises above 0 °C, the frozen soil thaws and its strength decreases sharply. Thawing of permafrost soils and a significant increase in average temperatures also leads to a change in the water balance of numerous rivers and lakes, to an intensification of snow-water flows, mudflow

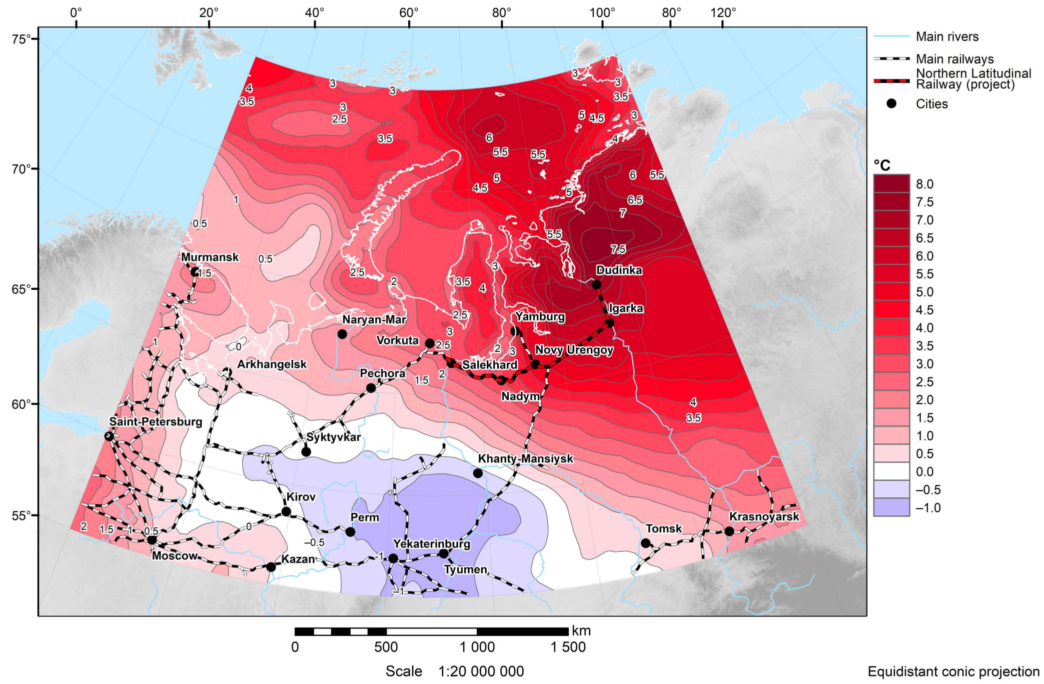

Figure 4. Changes in mean monthly average air temperature in March between the periods 2010–2021 and 1980–1989.

and landslides [*Romanenko and Shilovtseva*, 2016] and can have a negative impact on transport infrastructure [*Yakubovich and Yakubovich*, 2019]. This process can significantly affect the infrastructure and performance of the Russian Railways in the region under study. *Lebedev et al.* [2023] have showed for the North-West Arctic Zone of Russia that reanalysis describes well spatial and temporal variability of soil temperature which was proved by a comparison with *in situ* measurements made by bent-stem and extraction thermometers at 13 meteorological stations.

Figure 5 shows the average soil temperature field for 1980–2021. It shows that permafrost remained only in the northeastern part of the study area north of Vorkuta and Yamburg and north and east of Igarka. Figure 6 shows the changes in the average values of soil temperature between the periods 2010–2021 and 1980–1989. Soil temperature in the study area has increased over the four decades from 0.25 to 1 °C. The largest temperature increase (>0.75 °C) is observed in Karelia, Murmansk, Leningrad, and Moscow Oblasts, on the Pechora–Vorkuta–Salekhard railway section, between Novy Urengoy and Igarka, and in the Krasnoyarsk area. The greatest warming from 1 to 2 °C is registered in Taimyr, but there is no railway infrastructure there even in the plans for the development of northern regions.

3.3. Total precipitation

Large amounts of precipitation can lead to waterlogging or scouring of railway tracks, river overbanking, and destruction of railway tracks and even bridges, which require repair work. The highest amount of average monthly precipitation 60 mm/month is observed in the western part of the study region, from Moscow to Murmansk and from St. Petersburg to the Urals. In the eastern part of the region, this applies to the central part of the section from Tyumen to Novy Urengoy. Regarding the changes over the last four decades (Figure 7), precipitation has increased by about 10% north of Moscow, in Karelia, near Perm, from Novy Urengoy to Dudinka, near Khanty-Mansiysk, and has decreased significantly near Krasnoyarsk. There is still a significant spatial heterogeneity of these changes for each month separately. So, for example, in May, in the Arkhangelsk Region, precipitation

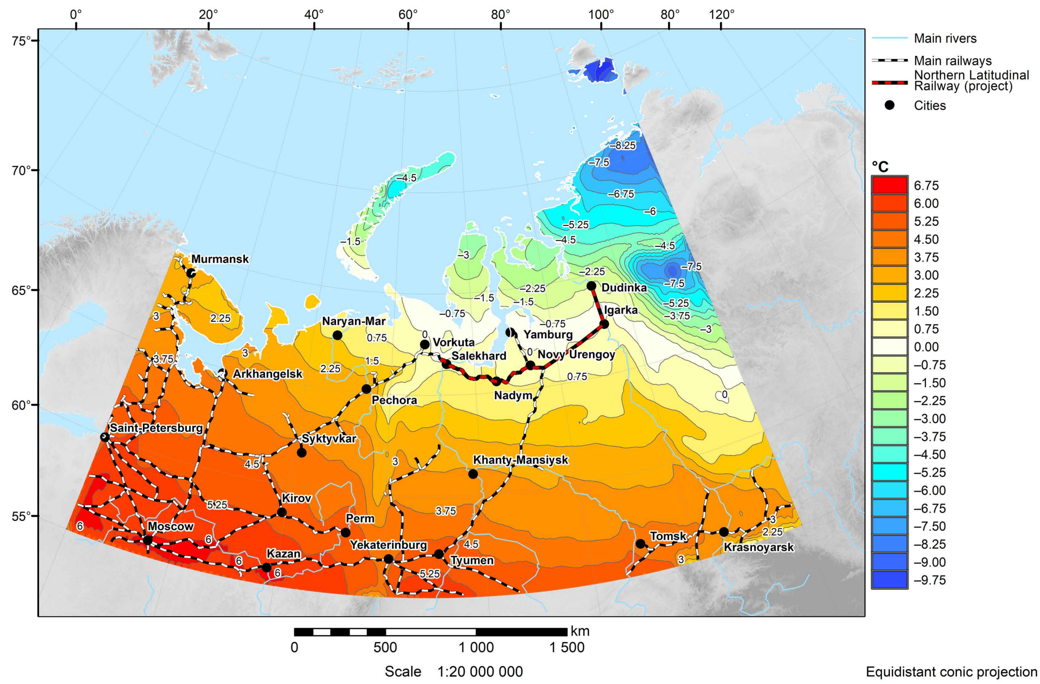

Figure 5. Mean annual monthly average soil temperature for 1980–2021.

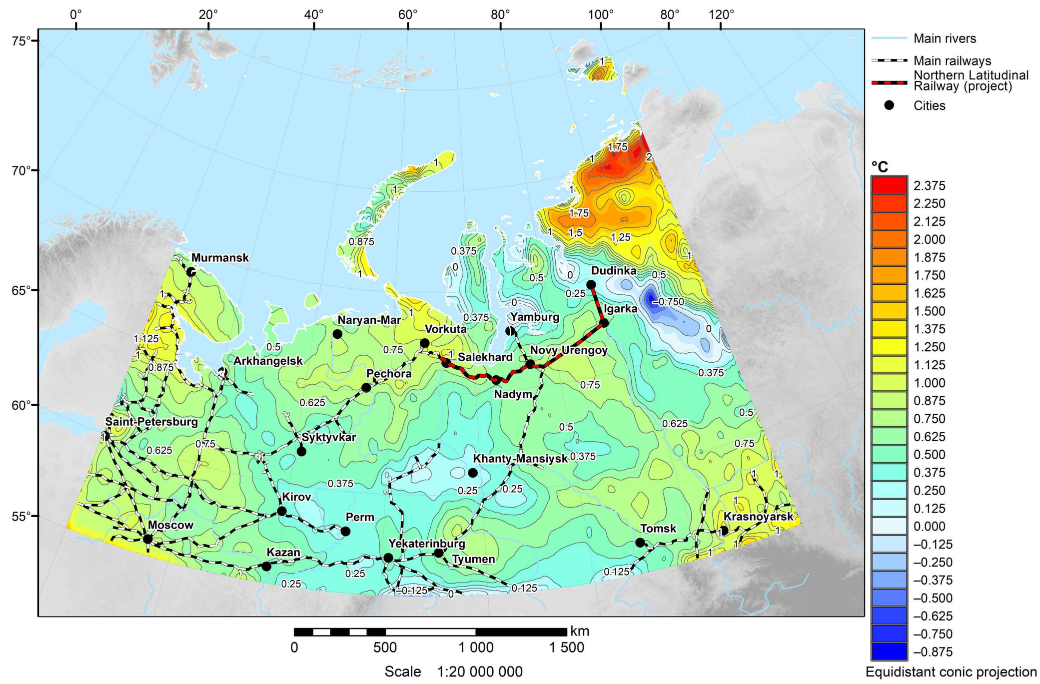

Figure 6. Changes in mean monthly average soil temperature between the periods 2010–2021 and 1980–1989.

decreased by 25 mm, in the Yekaterinburg region – by 35 mm, and from Novy Urengoy to Igarka, precipitation increased by 40 mm [*Geophysical Center of the RAS*, 2023].

3.4. Wind speed

High winds can cause loss of contact between the current collector and the contact wire, increasing the risk of derailment or train overturning [*Kostianaia et al.*, 2021]. Strong winds can also lead to accidents and disruption of the rail network due to trains colliding with fallen trees, branches, or debris on the tracks [*Baker et al.*, 2009]. The zone of strongest

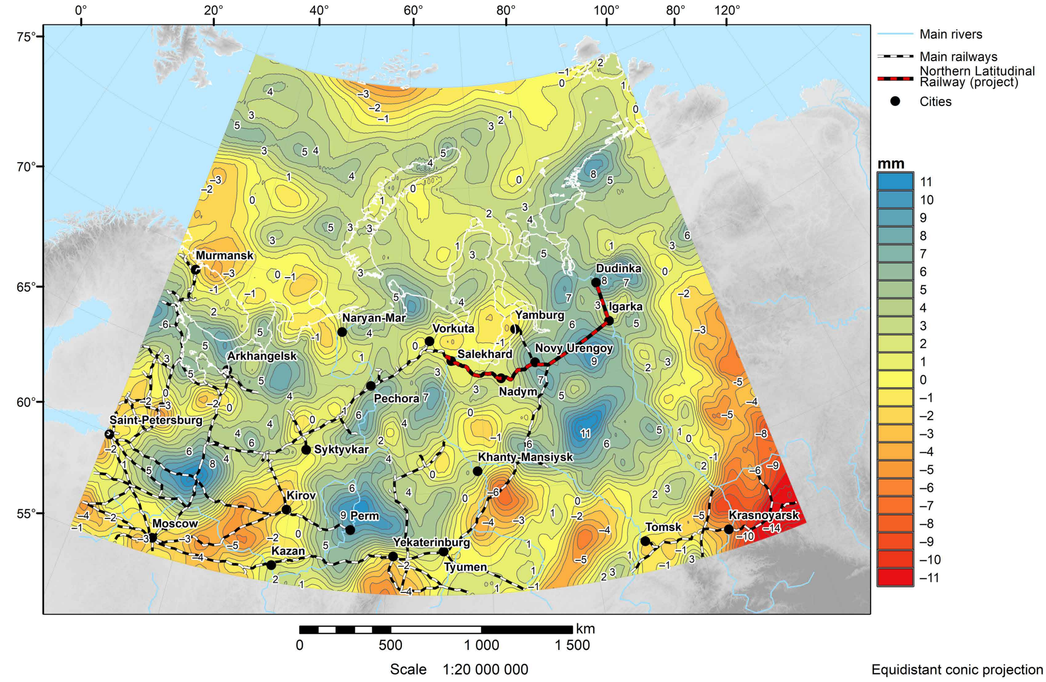

Figure 7. Changes in mean monthly average precipitation (mm) between the periods 2010–2021 and 1980–1989.

winds is located in the northern part of the study area and over the waters of the Barents and Kara Seas. This zone completely covers the area of construction of the Northern Latitudinal Railway. A similar zone of relatively strong winds runs along the southern edge of the study area along the conventional line Moscow–Kazan–Yekaterinburg–Tyumen–Tomsk–Krasnoyarsk. Between these zones lies a wide zone of relatively weak winds, where a fairly extensive railway network is located. As for the changes that have occurred over the last four decades (Figure 8), the wind speed has increased by about 10% over the water area of the Barents Sea, as well as on the sections of railways from Kazan to Krasnoyarsk along the southern edge of the study area. Over the rest of the territory the average wind speed remained practically unchanged.

However, there is a significant spatial heterogeneity in these changes for each month separately. For example, in March, wind speed has increased significantly throughout the eastern part of the study region, especially in its northern and southern parts. In the extreme western part of the region, and especially over the White Sea, wind speed, on the contrary, has decreased quite significantly [*Geophysical Center of the RAS*, 2023].

3.5. Soil moisture content

Soil moisture content is the percentage of water in the soil compared to the dry one. The general pattern of spatial distribution of soil moisture content is such that lower values are observed in the southern part of the study region and higher values are observed in the north. On some sections of the railway network, for example, south of Arkhangelsk, southwest of Syktyvkar, and between Pechora and Vorkuta, soil moisture exceeds 35%. As for the changes that have occurred over the last four decades (Figure 9), the pattern of changes is quite heterogeneous spatially. For example, in the southwestern part of the study region soil moisture has decreased by about 1–3% of soil moisture, in the area of the Yekaterinburg–Tyumen–Khanty-Mansiysk line by 1–2.5%, and in the area of Krasnoyarsk by 1–4%, which is about 10% of the average absolute value of soil moisture in these areas. In contrast, in the districts of Arkhangelsk, Perm, and Tomsk, soil moisture has increased by 1–4%.

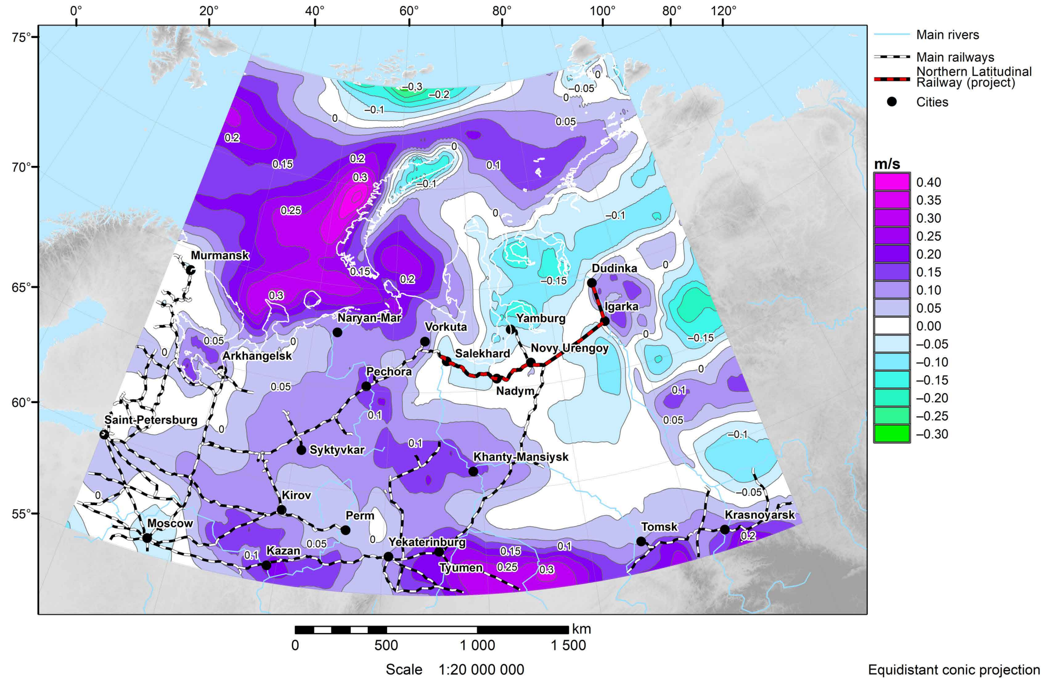

Figure 8. Changes in mean monthly average wind speed (m/s) between the periods 2010–2021 and 1980–1989.

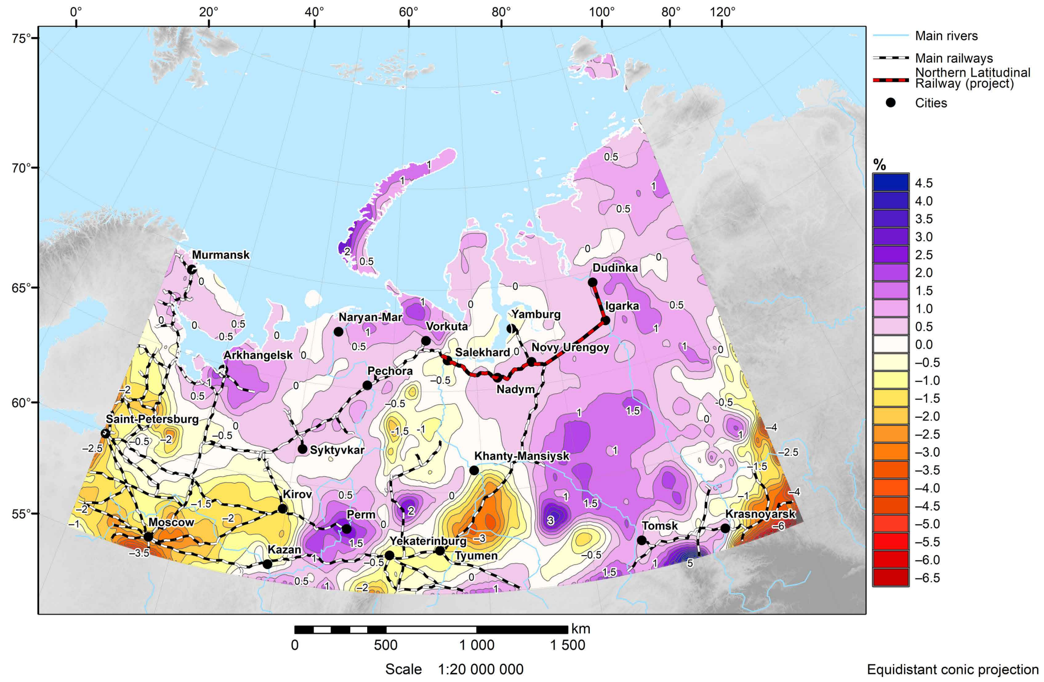

Figure 9. Changes in mean monthly average soil moisture content (%) between the periods 2010–2021 and 1980–1989.

There is significant spatial heterogeneity in these changes for each month separately. For example, in April, soil moisture increased significantly throughout almost the entire study area, with the greatest increase in humidity occurring in the Perm–Ekaterinburg–Tyumen region, where it increased by 7–14% of soil moisture [*Geophysical Center of the RAS*, 2023].

3.6. Air humidity

Air humidity characterizes the water vapor content in the atmosphere. The general picture of the spatial distribution of air humidity is such that it decreases from southwest to northeast, which is associated with a general decrease in air temperature in the same direction since absolute air humidity depends on its temperature.

Regarding the changes that have occurred over the last four decades (Figure 10), the pattern of changes is very heterogeneous spatially. For example, air humidity has increased by about 5% in the far western part of the study region, over the waters of the Barents and Kara Seas, as well as in the northeastern part of the region, which is explained by the air temperature increase by 1–2 °C in the same regions over the same period of time (Figure 3).

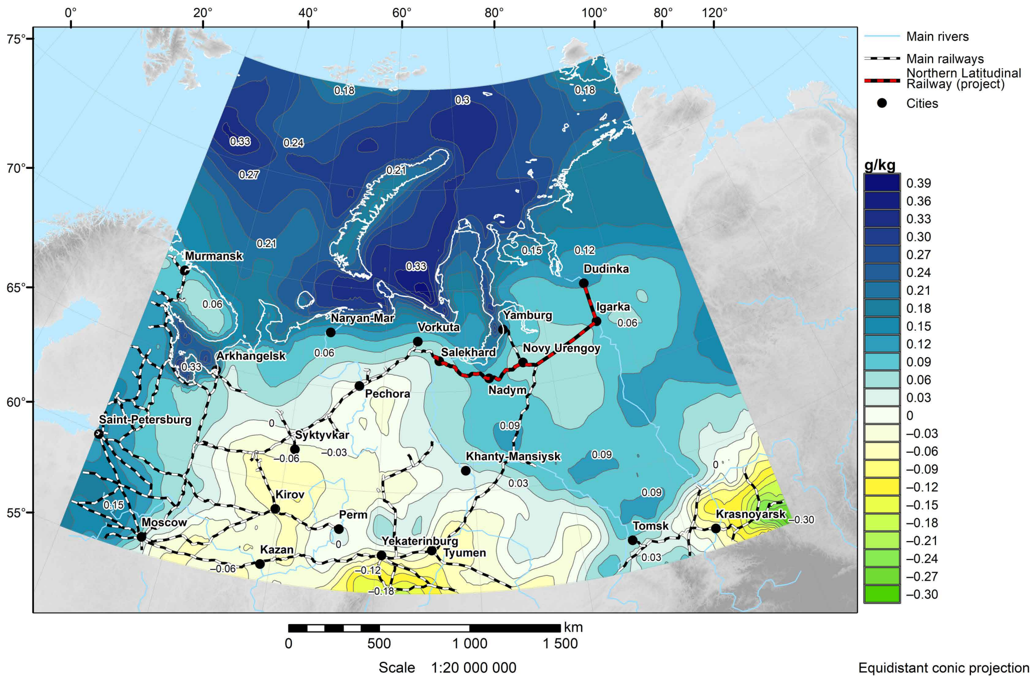

Figure 10. Changes in mean monthly average air humidity (g/kg) between the periods 2010–2021 and 1980–1989.

3.7. Snow cover thickness

The thickness of the snow cover is commonly referred to as the thickness of the layer of snow covering the surface of the ground. The general pattern of spatial distribution is determined mainly by the latitude of the location – the more northerly, the more snow. For example, in the area between Moscow and St. Petersburg, Yekaterinburg, and Tyumen, and near Krasnoyarsk, snow thickness is about 15 cm. In the northern regions snow thickness reaches 30 cm, and in the area of the Ural Mountains and east of Igarka–Dudinka it already exceeds 50 cm and in some places reaches 95 cm [*Geophysical Center of the RAS*, 2023].

As for the changes that have occurred over the last four decades (Figure 11), the pattern of changes is quite heterogeneous spatially. For example, in the far western and eastern parts of the study region, the snow thickness has decreased by 1–8 cm as a result of regional climate warming, while in the wide zone from Arkhangelsk to Perm and further to Kazan, as well as in the zone from Vorkuta to Yekaterinburg the snow cover thickness even has increased by 1–4 cm.

There is a significant spatial heterogeneity in these changes for each winter month separately. For example, in January, February, and March there was more snow throughout almost the entire study area, and in September and October, it became much less than four decades ago. This is an indirect sign of a shift in seasons, i.e. summer extends into autumn, and winter into spring [*Geophysical Center of the RAS*, 2023].

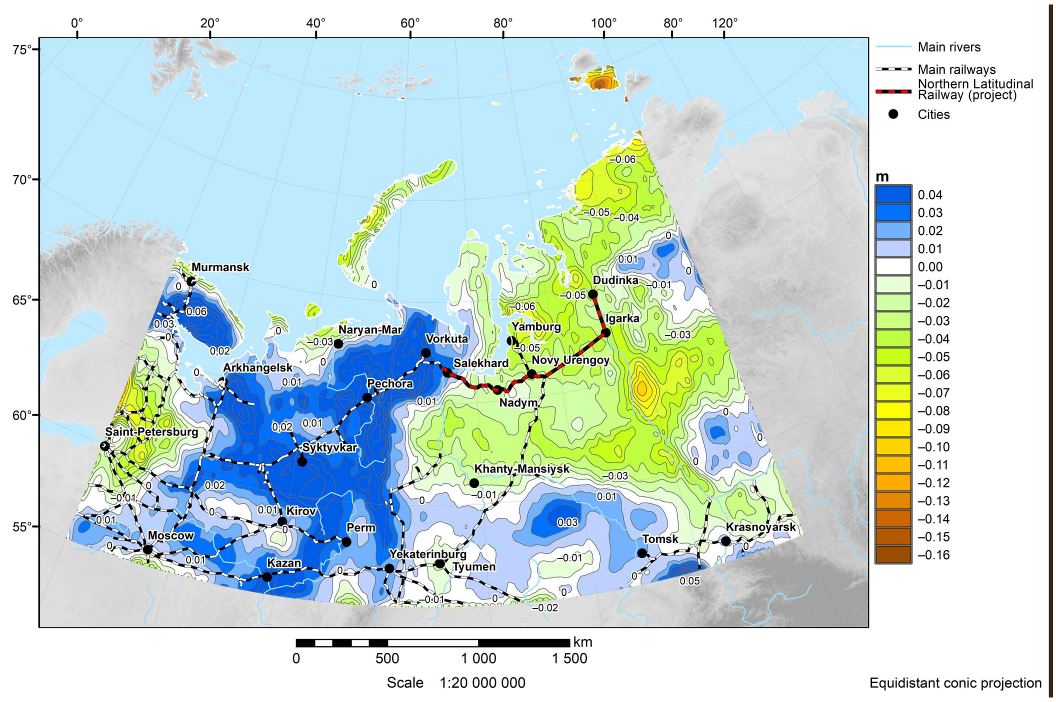

Figure 11. Changes in mean monthly average snow cover thickness (m) between the periods 2010–2021 and 1980–1989.

4. Discussion

This paper aimed to overview the content of the "Electronic Atlas of Climatic Changes of Hydrometeorological Parameters of the Western and Central Part of the Russian Arctic" (Atlas-2023). It is elaborated as a supporting tool for the Russian Railways development in this region, and to show the most interesting findings of the analysis of regional climate change, especially for railway operation. This is the second updated and upgraded version of the Atlas-2022, which was issued by the end of 2022 and transferred to the Russian Railways for practical use [*Gvishiani et al.*, 2023a]. In Atlas-2023, the study area was expanded by 5 degrees to the South and the North, and by 15 degrees to the East in comparison with Atlas-2022. Thus, we investigated the western and central part of the Russian Arctic within the geographical boundaries of 55–80° N, 30–100° E, and time period from 1980 to 2022.

To build this Atlas we used the same MERRA-2 atmospheric reanalysis and the same set of the main hydrometeorological parameters characterizing climate change in the region: air temperature, total precipitation, wind speed, soil temperature, soil moisture content, air humidity, and snow cover thickness. The choice of these meteorological parameters is determined by their influence on the infrastructure and reliable functioning of railways in the study area.

Air temperature at the earth's surface is the most important climatic characteristic. It significantly affects the functioning of railways, especially in the Far North. The ongoing warming of the regional climate leads to a thawing of permafrost soils, a change in the water balance of numerous rivers and lakes, and an intensification of such geomorphological processes as snow-water flows (a type of mudflow) and landslides. This may have a negative impact on the infrastructure of railways and roads, the oil and gas industry, and pipeline transport [*Kostianaia et al.*, 2021]. For example, previous study of changes in surface air temperature in the Murmansk and Arkhangelsk Oblasts and the Republic of Karelia showed *Serykh et al.* [2022], that in 1999–2020 there was a significant change in the regional climate. It was expressed in the warming of this region from +0.9 to +1.5 °C compared to previous years (1977–1998), in a sharp increase in air temperature growth (from +0.4 to +1.0 °C over 10 years), to a shift of the +2 °C isotherm by 550 km to the North up to the southern part of the White Sea and the complete disappearance of average negative temperatures. An important conclusion follows from the study: objects on pile foundations with a depth of less than 6 m are at increased risk even with warming up to +2 °C. Therefore, engineering protection of these objects should be carried out at a pace that is faster than the warming of the regional climate [*Yakubovich and Yakubovich*, 2019].

Soil temperature is the second important parameter for assessing the reliability of railway operation, especially in areas with permafrost [*Kostianaia and Kostianoy*, 2023; *Kostianaia et al.*, 2021; *Lebedev et al.*, 2023]. The specificity of permafrost soils is that they contain ice. When the temperature rises above 0 °C, the frozen soil thaws, its strength decreases sharply, and other properties also change qualitatively, especially in silty-clayey soils. Under buildings, supports and railway tracks, unique "bowls" of thawing are formed. *Yakubovich and Yakubovich* [2019] showed that for the territory of the Kola Peninsula, characterized by high-temperature permafrost of rare island nature, construction objects foundation of which is formed by piles with a depth of 5 m or less are subject to very high risks of reducing their functionality, down to zero level. For example, with relatively small warming of up to +1 °C, piles 5 m deep, as a rule, still provide functionality $U = 0.65–0.85$ ($U = 1$ corresponds to the maximum level of functionality for the base, constant climate), which is considered as an average level of climate risk in relation to a transport infrastructure facility. Warming up to +2 °C often leads to a decrease in functionality to $U < 0.5$ (in the presence of low-humidity soils), and warming to +3 °C for construction objects in this group can be considered catastrophic; functionality is reduced to the level $U = 0–0.35$, which corresponds to an unacceptably high level of climate risks.

Large amounts of precipitation can lead to flooding or erosion of railway tracks, overflowing of rivers, and destruction of railway tracks and even bridges, which requires repair work [*Kostianaia et al.*, 2021].

Strong winds can cause the pantograph to lose contact with the trolley wire, increasing the risk of derailment or train overturning [*Kostianaia et al.*, 2021]. This has been the subject of research for high-speed trains in many countries, such as the X2000 in Sweden [*Andersson et al.*, 2004], the ICE in Germany [*Diedrichs et al.*, 2007], and the Class 390 Pendolino in the UK [*Baker et al.*, 2004]. For example, a study in Austria found that winds of more than 120 km/h could, under certain conditions, overturn a train or cause serious damage. Wind speeds greater than 130 km/h may cause the trolley wire to vibrate, which may increase the risk of serious problems with the pantograph. In addition, strong winds can also move parked freight cars and shift machinery and cargo inside freight cars [*Rachoy and Spazierer*, 2008]. High winds can also lead to accidents and disruptions to the rail network due to trains colliding with fallen trees, branches, or construction debris on the rails [*Baker et al.*, 2009]. Such high wind speeds are now more common in Europe. For example, on 18 January 2007, a windstorm swept through Europe, reaching a maximum wind speed of 216 km/h, in Germany – 148 km/h, and in Austria – 140 km/h. On 18 January 2018, windstorm "David" crossed Northern Europe with the strongest winds (up to 203 km/h recorded in Brocken, Germany). Deutsche Bahn canceled all intercity services and hired additional 150 foresters due to damage to railways caused by fallen trees. The total damage was estimated between 1 and 2.6 billion Euro. From 23 September to 4 October 2019, windstorm "Lorenzo" affected the UK, Ireland, and France with its strongest wind gust of 163 km/h and damage estimated at 284–330 million Euro. On 7–16 February 2020, windstorm "Ciara" affected the UK, Ireland, Isle of Man, Northern Europe, Western Europe, Central Europe, and Eastern Europe with its strongest wind gust of 219 km/h and damage ranging from 1.6 to 1.9 billion Euro. On 13–19 February 2020, windstorm "Dennis" affected the UK, Ireland, Iceland, Norway, Sweden, and the Netherlands with its strongest wind gust of 230 km/h. On 18–20 August 2020, windstorm "Ellen" hit the British Isles with its strongest wind gust of 143 km/h [*List of European windstorms*, 2023]. In autumn 2023, severe wind storms have continued to hit Europe [*2023–2024 European windstorm season*, 2023]:

- Storm "Agnes", 25–29 September 2023, UK, Ireland, 135 km/h (max wind gust);

- Storm "Babet", 16–22 October 2023, Western and Northern Europe, 185 km/h;
- Storm "Aline", 18–27 October 2023, Western Europe, 146 km/h;
- Storm "Bernard", 21–26 October 2023, Western Europe;
- Storm "Celine", 28 October – 3 November 2023, Western Europe, 90 km/h;
- Storm "Ciarán", 29 October – 4 November 2023, Western Europe, 207 km/h;
- Storm "Domingos", 3–5 November 2023, Western Europe.

Determining the degree of soil moisture is necessary for making competent design decisions on the location of railway infrastructure facilities, choosing the type of foundation, and other engineering decisions. The bearing capacity of the rock and its resistance to future loads directly depend on this parameter. Thus, with increasing humidity, friction between soil particles decreases and their displacement for dispersed rocks occurs. Clay soils transform into a fluid and also flexible plastic state, which leads to deformations. With regard to rocky soils, their bearing capacity is practically independent of humidity. At the same time, humidity also affects other significant characteristics of rocks: density, subsidence and compressibility, strength, swelling, and frost heaving. During design, it is extremely important to take into account these parameters for clayey, silty, fine sandy, and rocky soils. The competence of design decisions, budget, safety of construction, and operation of railway infrastructure directly depends on this.

It is well known that excess air humidity negatively affects the properties of various materials [*Vishnevsky and Chepurin*, 2010]. The vast majority of inorganic and organic materials, substances, and components have some degree of hygroscopicity, i.e. have the property of absorbing water vapor from the air. For all porous materials, there is a certain relationship between the amount of moisture they absorb (the so-called hygroscopic humidity) and the relative humidity of the surrounding air. The maximum hygroscopic humidity of materials corresponds to a maximum of 100% air humidity [*Vishnevsky and Chepurin*, 2010].

Regarding railway infrastructure, an increase in the hygroscopic humidity of materials will lead to an increase in weight and (or) volume (change in density); changes in electrical conductivity; changes in heat transfer; the occurrence of chemical reactions; changes in liquid viscosity; change in tensile strength; changes in the elasticity and plasticity of materials [*Vishnevsky and Chepurin*, 2010]. The influence of excessively humid air is dangerous not only for hygroscopic materials. Materials with negligible hygroscopicity are also susceptible to the effects of water vapor from humid air, which initially manifests itself in the surface layers. It is worth highlighting certain, frequently occurring negative consequences of excessive increases in air humidity, which may be directly related to the railway infrastructure [*Vishnevsky and Chepurin*, 2010]:

1. At high air humidity, the quality of resistance of electrical insulating materials deteriorates, including air itself as an electrical insulator. This leads to uncontrolled failures, which can lead to major accidents and disasters, primarily due to short circuits.
2. Relative humidity above 70% creates favorable conditions for the rapid growth of mold, the spores of which are present everywhere. At lower humidity values, mold growth stops completely.
3. Metals that are practically non-hygroscopic are susceptible to corrosion in air, the intensity of which also depends on air humidity. Low humidity guarantees low corrosion intensity. Iron has virtually no corrosion at relative humidity up to 40–45%. Minor corrosion of iron begins when the relative humidity increases from 40–45% to 60–70% (the so-called "critical" humidity value). Above this value, the corrosion rate of iron increases sharply (according to a logarithmic dependence), and rapid destruction of the metal occurs.
4. Another manifestation of high air humidity is observed when air saturated with moisture is cooled. The air then becomes supersaturated with moisture, and it begins to be released from it in the form of fog or dew. Two specific causes of condensation are most often encountered. Firstly, these are cold surfaces of equipment, the low temperature of which is due to technological processes. For example, all kinds of

pipelines, containers, etc. Secondly, condensation is associated with daily changes in air temperatures, which are most pronounced in continental climates and northern regions with low temperatures. Massive metal parts of structures and equipment cool down at night and, due to their significant heat capacity, remain supercooled in the morning and, partially, during the day. Atmospheric air relatively quickly increases its heat and moisture content in the morning hours. Due to this, its dew point under certain conditions exceeds the temperature of metal surfaces, resulting in condensation of excess moisture. The moisture condensed on external surfaces evaporates more or less quickly under the influence of wind, for example. Much more dangerous is the condensation of moisture on the internal surfaces of equipment in various hidden channels and cavities, since due to the high thermal conductivity of metals, the temperature on the internal surfaces differs little from the external ones. At the same time, in stagnant internal cavities and channels, condensed moisture evaporates little and gradually accumulates [*Vishnevsky and Chepurin*, 2010].

Heavy snowfalls, blizzards, snow drifts, and debris are among the types of natural disasters that significantly affect the performance and capacity of railways [*Pashchenko and Potapenko*, 2016]. Snow thickness is one of the parameters that is calculated in models and measured at weather stations, the influence of which on the functioning of railways is being studied in northern countries, for example, in Canada, Sweden and Russia [*Kostianaia and Kostianoy*, 2023].

When snow falls on a railway track, it creates resistance to the movement of trains, causes additional energy and fuel consumption, reduces travel speeds, delays trains, complicates the operational work of the snowed section [*Pashchenko and Potapenko*, 2016]. Snow drifts are usually the result of snowstorms and snow transfers. A snowdrift can form in a fairly short period of time. At the same time, the thickness of the snow cover can be measured in several meters, and it can be formed in 1–2 hours. In winter, the operating conditions of railways become significantly more complicated, especially in the northern regions of Russia, so much attention is paid to the timely and high-quality preparation of track facilities and other services for work in the winter. The concept of "snow fighting" implies a system of complex measures, including snow retention from the field sides of the railway and removal of snow from the railway. It should be borne in mind that snow removal is a much more expensive operation, so it is necessary to ensure maximum snow retention. The railway can be protected from snow drifts by protective forest plantations, permanent fences, portable shields, as well as natural forests, among them protective forest plantations are of great importance [*Pashchenko and Potapenko*, 2016].

5. Conclusions

A discussion of the above-mentioned meteorological parameters showed their vital importance for infrastructure and stable operability of the Russian Railways in the northern regions of Russia in the changing climate. The Atlas-2022 and Atlas-2023 have been transferred to the Russian Railways for practical use. This experience can be transferred to other sections of the Russian Railways in other regions of Russia, especially in Siberia where there are several plans of railway development related to an increase of trade with China, Central Asia, and other countries. These climatic atlases can be used for the analysis of the sustainable operability of automobile roads as well because the same set of meteorological parameters is important for the assessment of the quality of the roads and transportation of goods.

One of the most important conclusions from this research is that the climate warming as well as change of other meteorological parameters in the study area is very irregular within a year (by months), spatially, and even along each section of the railway. It is necessary to study thoroughly the climatic parameters along each railway section separately with the help of Hovmöller diagrams, as the performed analysis has shown significant spatial and temporal heterogeneity of the considered parameters variability during the past 40 years. This was done in the framework of the Russian Science Foundation Project No. 21-

77-30010 (2021–2024) "System analysis of geophysical process dynamics in the Russian Arctic and their impact on the development and operation of the railway infrastructure".

Future development of Atlas-2023 is related to: (1) the creation of maps and diagrams of spatial and temporal variability of extreme weather phenomena in the form of observed anomalies, occurrence frequency, and duration based on daily data instead of monthly averaged data; and (2) creation of forecast maps and diagrams of spatial and temporal variability of basic hydrometeorological parameters up to the end of 21st century for the existing and planned railway infrastructure.

We hope that the detailed analysis of the Atlas-2023 maps and Hovmöller diagrams prepared for the Russian Railways, along with the future generation of atlases will contribute to sustainable development and adaptation of the railway infrastructure to climate change in the northwestern and central part of the Russian Arctic.

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