

Climate Change on the Territory of Russia in the Late 20th–Early 21st Centuries

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Abstract—The spatiotemporal variability of surface air temperature and precipitation in Russia is considered using the data from 1251 stations for two periods: 1976–2019 and 2001–2019. Main attention is paid to the analysis of trends in the above characteristics, which made it possible to estimate the scale of climate warming in recent decades. The connection between the atmospheric circulation indices (NAO, AO, EAWR, SCAND) and temperature fluctuations in the European part of Russia is revealed.

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INTRODUCTION

Meteorological and climatic observations and studies at Kazan Federal University have a long history since the Meteorological Observatory was founded there in January 1812 by Professor F.K. Bronner [12]. In 1815, F.K. Bronner published the first scientific article “Consequences of Meteorological Observations in Kazan in 1814.” The results of observations from 1828 to 1831 were published by Professor A.Ya. Kupfer from Kazan Federal University in his book “Voyage dans L'Oural” (“Journey to the Urals”). Observation data from the Meteorological Observatory of Kazan Federal University were later used in the fundamental works of outstanding Russian climatologists of the 19th century, including K.S. Veselovskii (“On the Climate of Russia,” 1857); H.I. Wild (“On Air Temperature in the Russian Empire,” 1881); A.I. Voeykov (“Climates of the Globe, Especially Russia,” 1884). For many years, climatologists of Kazan Federal University have focused on studying the regional climate, namely, the climate of Kazan and the Republic of Tatarstan, the Middle Volga region, the Volga Federal District [9, 11, 13, 14, 17, 19]. Due to this, an objective pattern of climate change in the region from 1828 till now was obtained.

The most noticeable regional climate events include the following:

—a revealed increase in average annual air temperature in Kazan by about 4 °C during 1828–2019; the contribution of global processes to the temperature variability was 37% in winter and 23% in summer;

—average annual air temperature averaged over the territory of the Volga Federal District dramatically increased by 1.2 °C at the beginning of the 21st century, while the value of interannual temperature variability decreased twice, and the minimum value of average annual temperature sharply increased from 0.55 °C (1969) to 3.58 °C (2018);

—from 1850 till now, the Volga Federal District, as well as the whole Northern Hemisphere is characterized by a trend toward an air temperature rise; until the mid-1970s, these changes were oscillatory, sometimes in the opposite phase, and only since the 1970s, there has been an intensive increase in air temperature throughout the Northern Hemisphere and, in particular, the Volga Federal District;

—according to the data of long-series stations, it was revealed that the intensive phase of modern warming in the western part of the district started 5–6 years earlier than in the east;

—there was a decrease in the variance of daily temperature deviations from the annual course in the Volga Federal District during 1966–2019.

An open access to meteorological data, the development of modern information and computing technologies allow investigating both global climate processes [2, 6, 18, 20] and the processes taking place in certain large regions of the globe, including Russia. A number of papers deal with studying the climate of Russia [2–5, 8, 10, 16]. For example, in [2], changes in surface air temperature over the land of the globe (1901–2019), as well as in temperature and precipitation on the territory of the Russian Federation (1936–2019) are considered. In particular, it was revealed [2] that annual air temperature averaged over Russia for the period 1976–2019 is rising with a rate of 0.47 °C/decade, while the warming in the European part of Russia is faster than in its Asian part; the warming rate in the Arctic zone reaches 0.69 °C/decade. An exceptionally rapid warming in Russia in winter occurred from the mid-1970s to the mid-1990s, which was apparently associated with an increase in the North Atlantic Oscillation index (NAO), that was followed by the cooling, which lasted until 2010.

In addition, the authors of [8] consider the problem of adaptation to the ongoing climatic changes.

It is known that most of the time in 1950–1987, 1988–1997, and 1998–2004, average annual global surface air temperature remained almost unvariable, and all warming occurred during short events through the jumps in 1987 and 1997. It is supposed that a similar jump occurred in 2015–2016, i.e., a “ladder” of warming has been detected since the middle of the 20th century [3].

The objective of the present study is to consider spatiotemporal changes in the main climatic indicators on the territory of Russia during two periods: 1976–2019 and 2001–2019.

INITIAL DATA AND METHODS

The calculations were performed using data from 1251 weather stations in Russia from the dataset of All-Russian Research Institute of Hydrometeorological Information–World Data Center (ARIHMI–WDC) for 1976–2019. Monthly data series were used only for the stations for which not more than two gaps were observed during 1976–2019. There were about 9% of such gaps. With the existing density of stations, extremely rare inaccuracies in trends were smoothed on the maps thanks to surrounding stations.

Long-term series of initial data were subjected to statistical processing: the average values, standard deviations, anomalies of air temperature and precipitation, linear trends in temperature and precipitation in Russia were found for the periods of 1976–2019 and 2001–2019.

The period of 2001–2019 was chosen because major climatic events took place during it: in 2010, the so called hiatus in climate warming stopped and, starting from 2015, global warming resumed after El Niño. The final five years of this period were the warmest in the series of global meteorological observations.

RESULTS

The maps of air temperature trends for the central months of seasons and the annual values for the entire territory of Russia were constructed using data from 1251 stations for two periods: 1976–2019 and 2001–2019. Figures 1a and 2a present the spatial distribution of temperature trends over the whole 44-year study period (1976–2019).

In January (Fig. 1a), the highest rate of warming is observed in Central Siberia, on the Arctic coast with a maximum on the Taimyr Peninsula and on the Arctic islands from Novaya Zemlya to the New Siberian Islands, where the linear trend slope coefficient (LTSC) reaches 1.2 °C/decade. A significant increase in air temperature (LTSC = 0.80–0.99 °C/decade) is observed in the Khabarovsk krai and in the northwest of the European part of Russia (EPR) in the area of Arkhangelsk. In the rest of the EPR, warming is also observed, but is less intensive (LTSC varies within 0.20–0.59 °C/decade). The cores of cooling were formed in the south of Western Siberia, where LTSC < 0 and varies from –0.40 to –0.79 °C/decade, and in the Far East (the Magadan oblast).

In April, the pattern is more uniform (figures for April are not presented). The entire EPR, except for the North Caucasus, is covered by moderate warming with a maximum on the Arctic coast, where the LTSC value reaches 0.80–0.99 °C/decade. The vast territory of Western, Central, and Eastern Siberia, the entire Arctic coast from the Yamal Peninsula to Chukotka, the Arctic islands are occupied by the intense warming (LTSC in the Taimyr region reaches 1.2 °C/decade). Climate warming is observed almost over the entire territory of Russia.

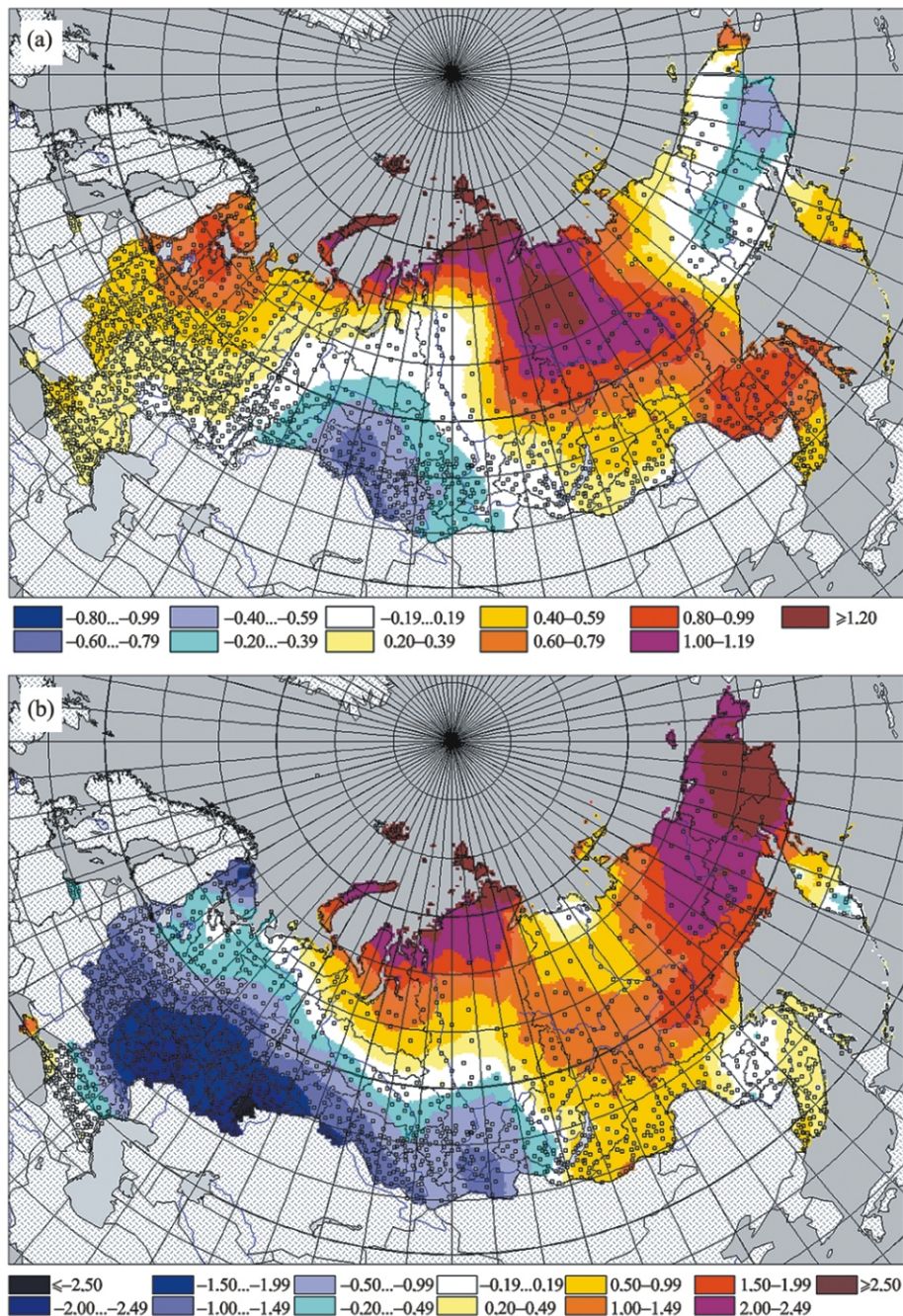


Fig. 1. The temperature trend (C/decade) in January for the periods of (a) 1976–2019 and (b) 2001–2019.

In July (Fig. 2a), the west and southwest of the EPR are occupied by an area of rather intense warming (LTSC varies from 0.60 to 0.99 C/decade); in the rest of Russia, except for the central zone of Western Siberia, where warming is almost absent, a weak increase in air temperature prevails with a rate of 0.20 to 0.59 C/decade.

In October, there is a more active warming in entire Russia from its western to eastern borders (except for Kamchatka) (figures for October are not given). The most intense temperature rise is observed in the northern regions of Siberia, on the Arctic coast and Chukotka, where LTSC exceeds 1.2 C/decade.

The trends in average annual temperature indicate moderate climate warming in almost entire Russia. It occurs most intensively on the Arctic coast of the Asian part of Russia and adjacent islands. For example, in the area of the Taimyr Peninsula, LTSC reaches a value of 1.2 C/decade. At the same time, warming is more pronounced in the central and northern parts of Siberia than in the EPR, where Karelia and the southwest of the Central Federal District stand out (LTSC = 0.60–0.79 C/decade).

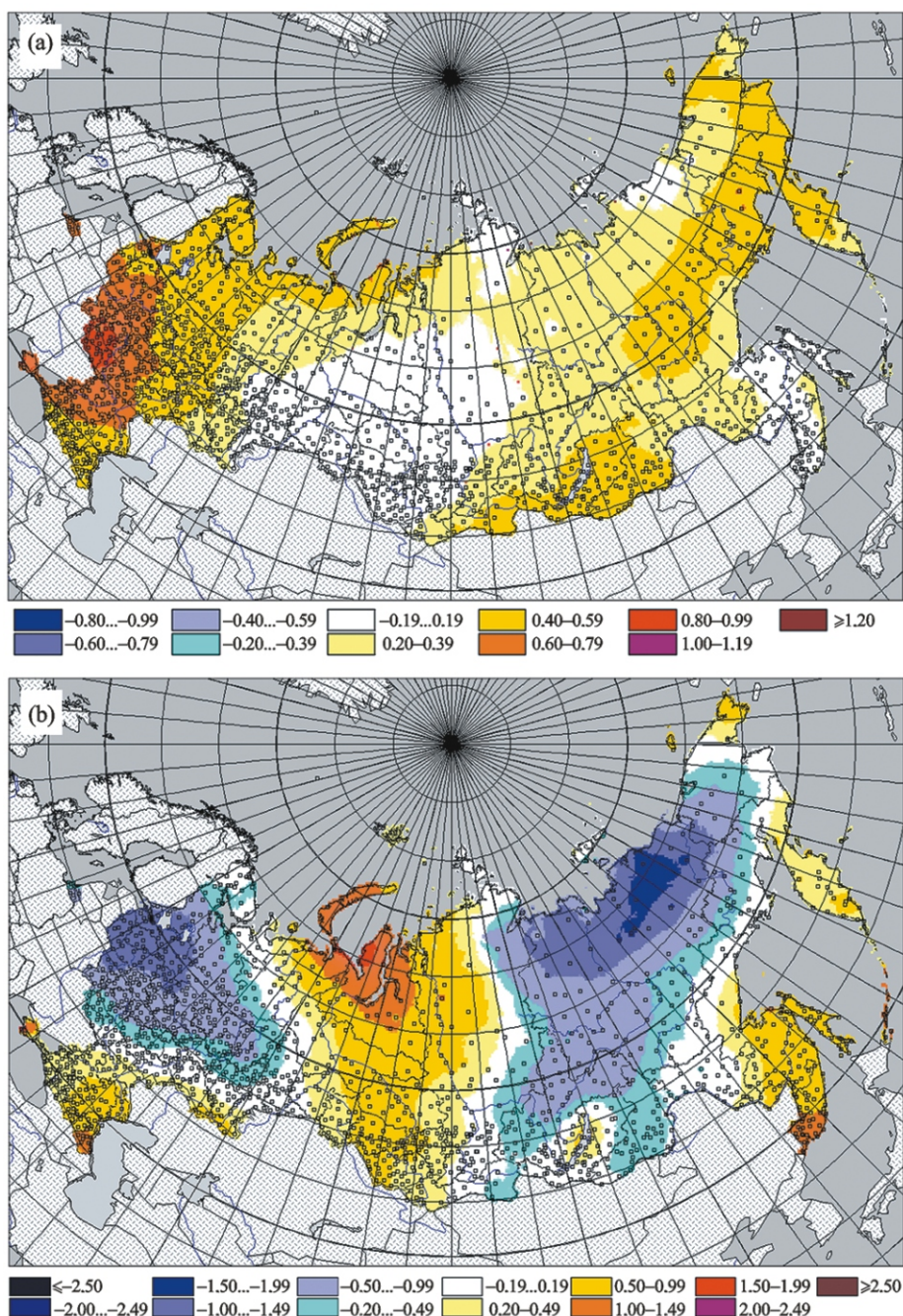


Fig. 2. The temperature trend (°C/decade) in July for the periods of (a) 1976–2019 and (b) 2001–2019.

These results for the territory of Russia are consistent with the data from [2], that presents the results of the global monitoring of the temperature regime over the land using data from 3288 weather stations. According to average annual data [2], the trend during 1976–2019 reaches 0.8°C/decade or more along the entire Arctic coast of Russia, 1.5°C/decade on the islands of the Barents and Kara seas, about 1.2°C/decade on the Taimyr Peninsula and Kamchatka, and 0.7°C/decade in the EPR.

The trend in climatic processes in Russia at the beginning of the 21st century is of interest. In January (Fig. 2a), the highest rate of warming is observed in Eastern Siberia and the Far East (in the Magadan oblast, LTSC exceeds 2.5°C/decade), as well as on the Arctic coast from Novaya Zemlya to Severnaya Zemlya, where LTSC varies from 2.0 to 2.49°C/decade, and on the Taimyr Peninsula and Severnaya Zemlya, where it reaches 2.5°C/decade. In general, the Asian part of Russia, except for the southern regions of Western and Central Siberia, is in the zone of warming with a varying degree of intensity. At the same time,

almost the entire territory of the EPR, the Southern Urals, the south of Western and Central Siberia are in the cooling zone: for example, in the Lower Volga region, in the south of the Urals and Western Siberia, LTSC is $-2.00 \dots -2.49$ C/decade. The distribution of air temperature trends over the territory of Russia in January during 2001–2019 differs significantly from the distribution of trends for the period of 1976–2019.

In April, the whole Asian part of Russia, except for the southern extremity of Primorye, is covered by a warming of considerable intensity. At the same time, the highest rate of air temperature growth is observed on the vast territory of Western and Eastern Siberia, including the Arctic, where LTSC exceeds 2.5 C/decade; in the EPR, there is a weaker warming with a rate of 0.50–0.99 C/decade, except for the cooling zone in its western and central parts, where LTSC varies from -1.00 to -1.49 C/decade.

In July (Fig. 2b), unlike January and April, the processes of temperature variation are less intense. A significant part of the EPR (the west and center), Eastern Siberia are in the cooling zone (LTSC varies from -0.50 to -1.49 C/decade); in the northwest of Western Siberia, there is a small zone of warming (1.00–1.49 C/decade). Most of the territory of Western Siberia, Kamchatka, and Primorye is occupied by the warming zone of insignificant intensity (LTSC ~ 0.20 – 0.49 C/decade).

In October, the cooling occurs in the North Caucasus, the south of the Urals, Western and Eastern Siberia, in Primorye (LTSC is $-0.20 \dots -0.49$ C/decade), and the warming takes place in the center of the EPR and in the north of the Asian part of Russia, that is especially intense on the Arctic coast and Arctic islands, where LTSC > 2.50 C/decade.

The temperature trends based on the average annual values of 1251 stations for 2001–2019 do not reveal significant territorial contrasts in temperature changes (figures are not presented). Almost the entire territory of Russia (except for a rather narrow zone in the south of Western Siberia, where LTSC is about $-0.20 \dots -0.49$ C/decade) is occupied by the warming zone, that is more intense in the north of the EPR, Western Siberia, on the Arctic coast, and in Chukotka, where the warming rate can reach 1.49 C/decade.

Thus, the distribution of the trends in average annual air temperature during 2001–2019, unlike the entire period of 1976–2019, reveals a noticeable cooling in the south of Western Siberia.

Let us consider regional features of changes in the precipitation regime during 1976–2019 on the territory of Russia (Figs. 3 and 4). The spatial pattern of the distribution of precipitation trends is very heterogeneous. For example, in January (Fig. 3a) there is an increase in precipitation with a rate of 1.0–1.9 mm/decade in the EPR, with a maximum in the northwest, where LTSC = 2.0–2.9 mm/decade. In the center and south of Western Siberia, in Altai, and in the northern regions of the Far East, including Chukotka, there is a decrease in precipitation (LTSC reaches $-2.0 \dots -2.9$ mm/decade). At the same time, the northern region of Western and Central Siberia from the Taimyr Peninsula to the New Siberian Islands stands out, where precipitation increases with a rate reaching 2.0–2.9 mm/decade.

In April, the main zone of precipitation growth moves from the EPR in the eastern direction to the Western Urals, Western and Central Siberia, where LTSC reaches 3.0–3.9 mm/decade. The main zones of precipitation decrease are formed in the North Caucasus, the Magadan oblast, the Amur region and Primorye, where LTSC is ~ -4.0 mm/decade in some places.

In July (Fig. 4a), almost the entire EPR (except for the northwest), the western part of Western Siberia, the Arctic coast from the Taimyr Peninsula to Chukotka, the Magadan oblast and Kamchatka, the Cis-Baikal region and Transbaikalia are in the zone of precipitation reduction; for example, LTSC < -4 mm/decade in the EPR and Kamchatka, while the south of Eastern Siberia, the Amur region, and Primorye are located in the zone of precipitation growth (LTSC > 4 mm/decade).

In October, an increase in the amount of precipitation is observed in most of Russia (with a maximum in Chukotka, where LTSC > 4 mm/decade). The distribution of the zones with the precipitation reduction is spotty, they are scattered throughout Russia and less intense: Karelia, the south of Western Siberia, and the Far Eastern regions stand out, where LTSC on Sakhalin Island is about $-3.0 \dots -3.9$ mm/decade.

The trends based on annual total precipitation for the period of 1976–2019 indicate a precipitation increase in most of Russia. For example, on the coast of the Sea of Okhotsk, LTSC > 25 mm/decade. A decrease in total precipitation is observed in the center and south of the EPR, in the North Caucasus, where LTSC $\sim -10 \dots -14$ mm/decade. Small zones with a decrease in precipitation are registered on Novaya Zemlya, in the south of Central Siberia and the northeast of Chukotka.

The Report on Climate Features on the Territory of the Russian Federation in 2020 [7] indicates that a trend towards an increase in annual total precipitation with a trend making up 2.2% of the normal/decade prevails in Russia during 1976–2019, which is consistent with the conclusions made by the authors of the present paper.

A more contrast pattern of the distribution of precipitation trends in Russia is observed in the period of 2001–2019. For example, in January (Fig. 3b), in most of the EPR, especially in the Black Sea region, in the northeast of Eastern Siberia, and in the Far East, except for Chukotka, the zones with an intense precipita-

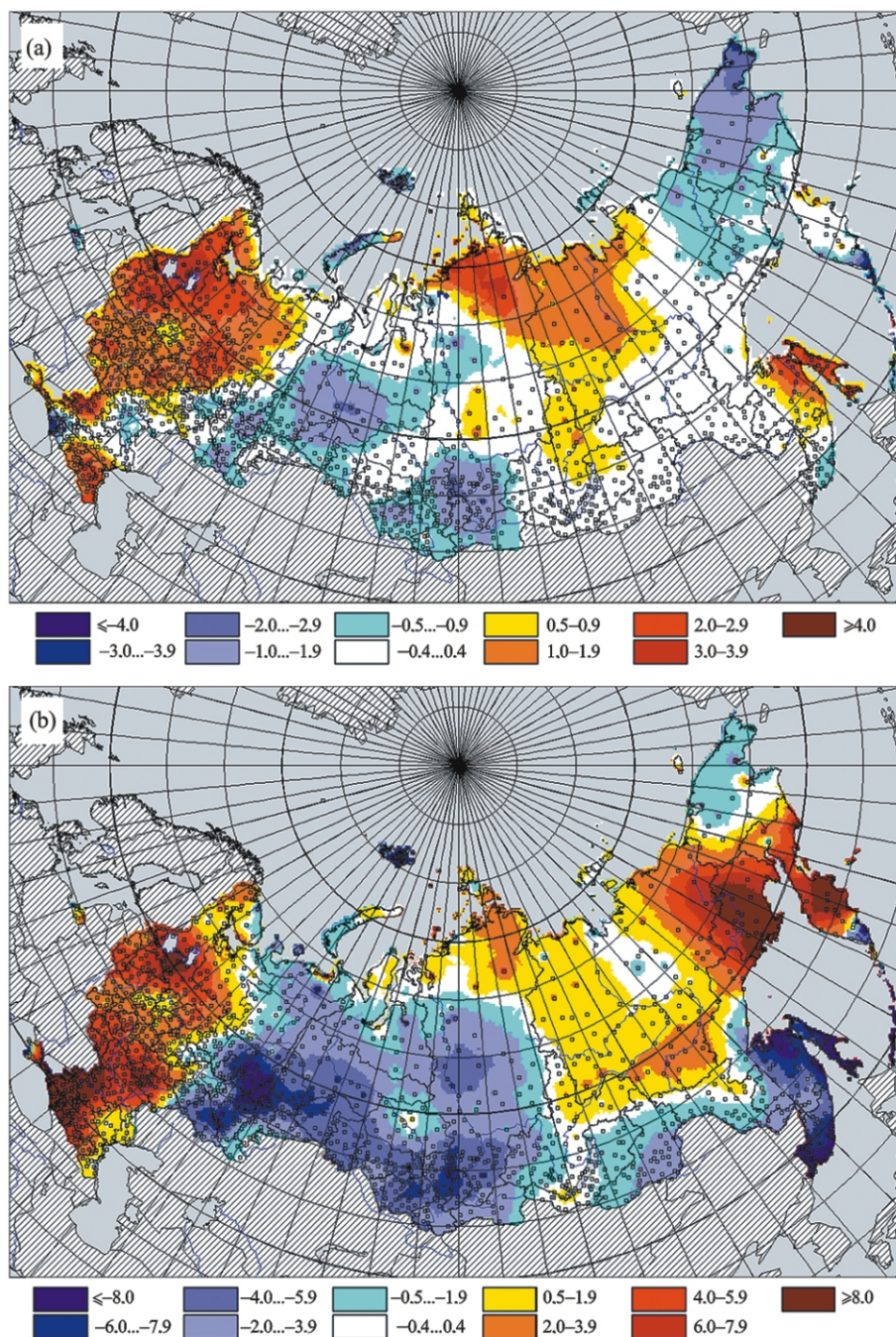


Fig. 3. The precipitation trend (mm/decade) in January for the periods of (a) 1976–2019 and (b) 2001–2019.

tion growth (LTSC > 8.0 mm/decade) stand out; at the same time, in the northeast of the EPR, in the Southern Urals, Western and Central Siberia, the extreme south of Eastern Siberia, in the Amur region and Primorye, there is a precipitation reduction (in some areas, LTSC < -8.0 mm/decade).

In April, an increase in total precipitation with a rate of 8 mm/decade is observed on the vast territory of the EPR, the Urals, and Western Siberia, and a precipitation decrease is registered in the southern regions of Central Siberia, in Chukotka and Primorye, where LTSC = $-4.0 \dots -5.9$ mm/decade.

In July (Fig. 4b), a significant increase in total precipitation occurs in the EPR, in the south of Western Siberia, and in the Amur River basin (LTSC = 25 mm/decade), and a decrease in precipitation is observed in the north of the EPR, in Western and Central Siberia, where LTSC is about $-10 \dots -14$ mm/decade.

In October, there is an alternation of the zones of changes in total precipitation from the west of Russia to the east. A decrease in total precipitation is observed in the western and southern regions of the EPR, in

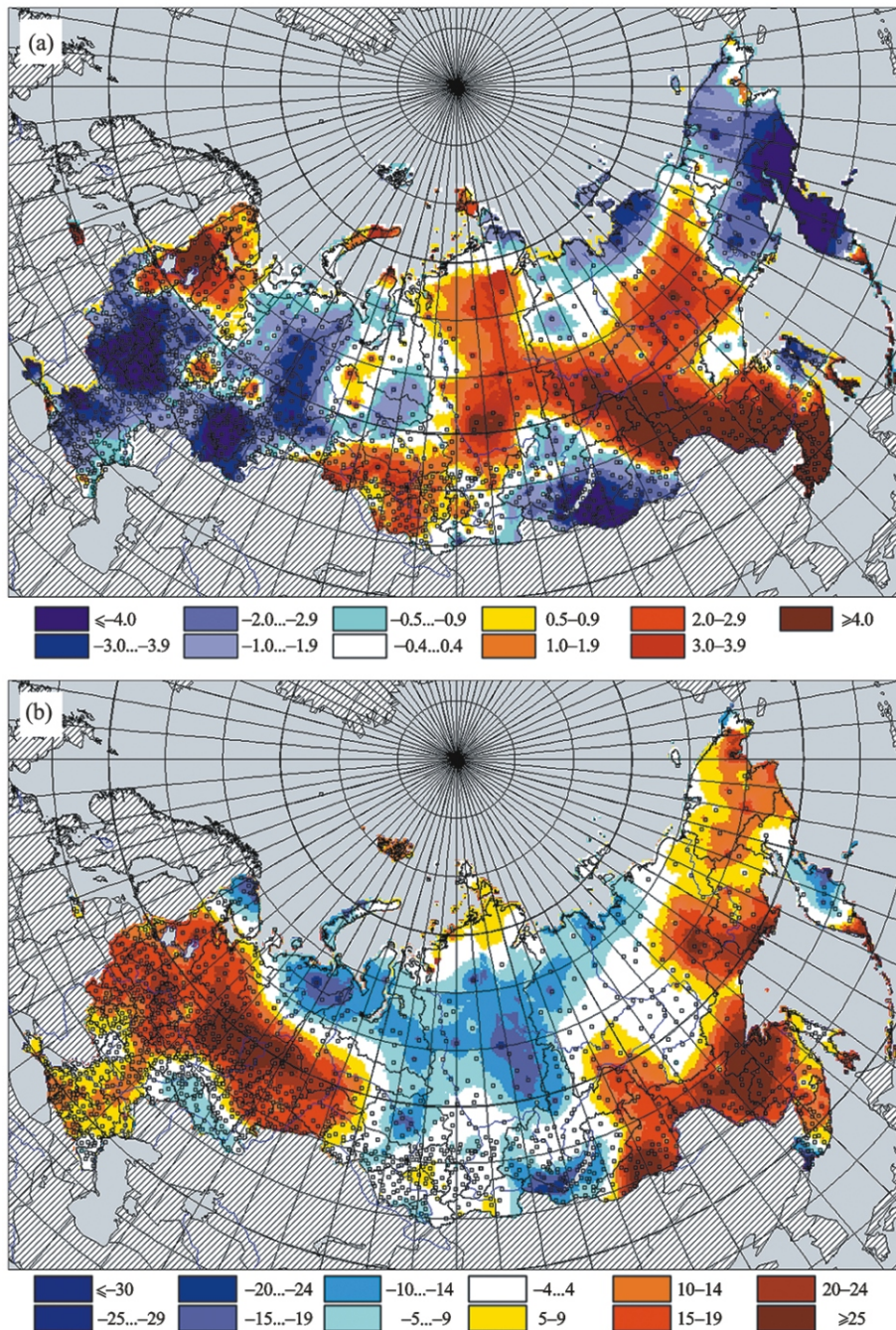


Fig. 4. The precipitation trend (mm/decade) in July for the periods of (a) 1976–2019 and (b) 2001–2019.

Central Siberia and Primorye (for example, in the southwest of the EPR, LTSC < -16 mm/decade), the zone with a positive precipitation trend covers Eastern Siberia, the Amur region, and Kamchatka. In addition, in the latitude zone of 50–60° N (the EPR, the Urals, Western Siberia), there is a precipitation growth in the Altai Mountains (LTSC = 12–15 mm/decade).

The spatial distribution of trends in annual total precipitation based on the data for 2001–2019 has a motley, contrasting pattern. The northwest of the EPR, the Middle Volga region, the Taimyr Peninsula, and the eastern regions of Russia are in the zone of precipitation growth with a rate of 40 mm/decade. The greatest increase in total precipitation occurs in the Amur region and Primorye, a decrease is registered in the south and northeast of the EPR, in the North Caucasus, Central Siberia and on the Arctic coast near the New Siberian Islands. For example, in the Black Sea region, LTSC reaches -50 mm/decade.

To evaluate the influence of atmospheric circulation on the thermal regime of the EPR, correlation coefficients r between the time series of atmospheric circulation indices (AO, NAO, EAWR, SCAND) and

air temperature at individual stations were calculated during 1976–2019. In total, data from 95 stations were used. The maps of isocorrelates were constructed for January and July. Their analysis revealed the following features. In January, the connections with the Arctic Oscillation (AO) are closer in the west and center of the region (in the area of Pskov, $r = 0.6$) and weaken in the direction from the southwest to the northeast (in the Northwestern Urals, $r = 0.2$). In July, the connections are insignificant. The connections with the North Atlantic Oscillation (NAO) index in January are also closer in the western and central parts of the region ($r = 0.7$), there is a noticeable weakening of the NAO effect in the eastern direction; in the southeast of the EPR, r decreases to 0.2 and lower values (Orenburg). In July, the values of the correlation coefficients are insignificant (~ 0.2). Thus, the Arctic Oscillation and North Atlantic Oscillation have a noticeable effect on the thermal regime of the region in winter, primarily its western and central parts. This effect is positive, i.e., the atmospheric circulation contributes to the warming in the region in winter. The East Atlantic–Western Russia (EAWR) circulation pattern has the greatest influence in summer, mainly in the center and especially on the east of the region, where the value of $r = -0.7$, which indicates the cooling influence of the North Atlantic during that period. The connection between air temperature and the SCAND index in January is better pronounced in the southern half of the EPR and especially in the east of the territory (the Urals, the Orenburg region, the North Caucasus), where r takes a negative value ($r = -0.6$). Thus, the formation of the blocking Scandinavian anticyclone significantly affects the winter thermal regime in the east of the EPR and contributes to a decrease in air temperature. In July, the relationship between the components is higher in the northwest of the EPR ($r = 0.4$) and weakens toward the southeast.

The previous studies [1, 15] show an important role of large-scale atmospheric circulation in modern climate change. According to [15], temperature extremes occurred in July and June in 2010, 2012, and 2016 in the north of Eurasia during the period of weakening of the zonal circulation (the AO index had a stable downward trend). It is shown in [1] that winter air temperature in Russia in recent decades is characterized mainly by the trend that approximately by twice exceeds the global warming trend, and by a natural oscillation superimposed on it with a period of about 40 years and an amplitude of slightly less than a degree (this is associated with variations in the leading modes of large-scale atmospheric circulation in the Euro-Atlantic sector: NAO and SCAND).

In general, the results of assessing the influence of large-scale atmospheric circulation on the thermal regime of the EPR during 1976–2019 do not contradict the conclusions made in [1, 15].

CONCLUSIONS

The analysis of calculated trends for the central months of seasons and the annual values of surface air temperature and precipitation revealed the following main features of changes in the temperature and humidity regime in Russia during 1976–2019.

In 1976–2019, climate warming was observed almost over the entire territory of Russia, that is also registered in 2001–2019, except for the southern regions of Western and Central Siberia.

During 1976–2019, an increase in annual total precipitation is recorded in most of Russia, especially in its Asian part.

During 2001–2019, the contrast in the distribution of precipitation over the territory of Russia significantly increased. In some regions, a sign of the trend in total precipitation changed. For example, there was an increase in total precipitation in Western and Central Siberia in 1976–2019, while, on the contrary, its decrease was registered in 2001–2019. At the same time, annual total precipitation noticeably increased in the marginal eastern regions of Russia. The negative trend towards precipitation reduction and, consequently, towards an aridity increase in the southern half of the EPR should also be noted.

The trends in air temperature and precipitation obtained in the present study for the central months of seasons may be an addition to the results of the analysis of seasonal trends in these parameters presented in the report [7]. According to [1], the course of seasonal temperature, especially in winter, in recent decades has not been necessarily determined only by the contribution of the central month of a season.

The circulation factor plays an important role in the dynamics of the thermal regime of the EPR. There is a noticeable change in the nature of statistical relationships depending on the circulation index. The Arctic and North Atlantic oscillations more strongly affect the thermal regime of western regions in winter (the connections are positive), whereas the SCAND pattern in winter has a much greater effect on the east of the region (the connection is negative). The EAWR pattern also affects the east of the region more strongly, but already in summer and with a negative sign. The role of circulation factors on the territory under consideration is heterogeneous both in sign and intensity.

In further studies, it is planned to apply more advanced approaches developed in [1, 15] to evaluate the contribution of circulation patterns to the spatiotemporal temperature variations in the region. They are as

follows: the method of multiple stepwise regression, that allowed the author of [15] to explain temperature changes in the north of Eurasia since the middle of the 20th century by the anomalies of some circulation modes, the comprehensive approach of the authors of [1] to the estimation of the linear trend in temperature in the Northern Hemisphere mid-latitudes using circulation indices and to taking into account the effect of global warming, which turned out to be quite strong for the territory of Russia.

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