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Climate Change and Its Impact on Agriculture

Yu. P. Perevedentsev[a]* **and A. A. Vasil'ev**[b]

[a]*Kazan (Volga Region) Federal University, ul. Kremlevskaya 18, Kazan, 420008 Russia*
[b]*Hydrometeorological Research Center of the Russian Federation, Bolshoi Predtechenskii per. 11–13, Moscow, 123242 Russia*
**e-mail: ypereved@kpfu.ru*

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Abstract—The overview of papers dealing with the analysis of current and future climate change on the territory of Russia and their impact on the crop productivity is presented. Using the reanalysis data for 1950–2020, trends in air temperature and precipitation are estimated for different regions of Russia. A correlation was found between changes in temperature and atmospheric circulation indices.

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The problem of current and expected regional climate change is relevant for the world community due to the occurrence of climate threats and the need for adaptation to the ongoing climate change. A risk of damage to the agricultural production from severe weather and climate events is increasing across the globe [7]

Russia is one of the major producers and exporters of agricultural products and plays a leading role in the world market of grain. The grain industry is a base for sustainable development of most areas of the agricultural industry and agrarian export, therefore, the evaluation of the grain and legume resources of Russia is a strategic goal of the state economy [5]. However, the dependence on weather conditions makes the agricultural production unstable. Currently, there is increasing aridity in most of the agricultural regions of Russia, which has a negative effect on the gross yield of grain crops [13].

Due to the sharp continentality of climate, droughts have the most significant effect on the crop yield among all severe weather events in most of the Russian Federation [20].

According to the National Association of Agriculture Insurance, the main risks in Russia that led to insurance payments in 2012–2018 were soil droughts (22.2% of payments), atmospheric droughts (21.7%), dry winds (19.5%), and waterlogged soil (16.6%) [1].

According to [12], when producing crops, the assessment of climate risks is of particular importance, since the dependence of the production results on random (primarily meteorological) factors is especially significant. In view of this, there is a need for reliable quantitative estimates of the weather and climate impacts on the grain crop productivity that would allow assessing climate risks and vulnerability of a territory. Climate risks of major crop failures (R) are proposed to be determined as the product of the frequency of adverse hydrometeorological conditions and the vulnerability of agricultural production on a specific territory:

$$R \quad pV \qquad (1)$$

where p is frequency of a severe weather event (%); V is vulnerability of agricultural production (dimensionless parameter).

Fig. 1. The mean summer and winter values of surface air temperature (°C) and linear trend slope coefficient (C/10 years) over the period of 1950–2020 in quasihomogeneous climatic regions of Russia.

Agriculture vulnerability factors in Russian regions located in different natural and climate zones differ considerably. For northern and wet regions, the potential vulnerability factors are freezes, ice crust formation, overmoistening. In southern and dry regions, these are heat waves, droughts, dry winds, and dust storms. An adverse effect of global warming is growing climate aridity in a significant part of Russia. The increasing frequency of droughts is observed not only in regions with an expected precipitation reduction, but also in areas where the amount of precipitation is increasing due to climate change.

As follows from the Third Roshydromet Assessment Report, the warming on the territory of Russia in the recent decades has been almost twice faster than in the Northern Hemisphere: by 0.51 C per decade, and every decade since 1981–1990 has been warmer than the previous one [19].

In view of this, the spatiotemporal features of the temperature regime in the lower atmospheric layer, which is directly affected by the Earth surface, atmospheric circulation, and radiation regime, were considered using the ERA5 reanalysis data for 1950–2020. For this purpose, the averaging of monthly, annual, summer, and winter means of air temperature was carried out for the entire continental territory of Russia, as well as for nine quasihomogeneous climatic regions of the country (I is the north of the European part of Russia (EPR) and Western Siberia, II is the northern part of Eastern Siberia and Yakutia, III is Chukotka and northern Kamchatka, IV is the central EPR, V is central and southern Western Siberia, VI is central and southern Eastern Siberia, VII is the Far East, VIII is the Altai and Sayan region, IX is the southern EPR). For the mentioned regions and time intervals, the main statistical characteristics (multiyear mean, standard deviation (SD), linear trend slope coefficient, linear trend determination coefficient, etc.) were computed, and the time series were smoothed by lowpass filtering with the cutoff point of 20 years. Figure 1 presents the distribution of the winter and summer mean values of temperature and the linear trend slope coefficient for the nine Russian regions.

The analysis of the low-frequency change characteristics in the winter (December–February) surface air temperature revealed that during 1950–2020, these temperature values were increasing in the linear approximation at a rate of about 0.38 C/10 year on average all over the territory of the Russian Federation. The highest rate of the winter temperature rise (0.5 C/10 years) was observed in the region IV including the central EPR. As a result, there was a temperature rise by 3.5°C here over the analyzed period, if defined this from the linear trend, and by 2.6 C, if estimated from the low-pass component with a period of more than 20 years. The greatest contribution to the total variance (22%) was made by the linear temperature rise in the region VII (the Far East), where the lowest variability of winter temperatures has been observed (SD = 1.46 C). The linear trend in winter temperatures was almost absent in the regions III (Chukotka and northern Kamchatka) and VIII (the Atlai and Sayan region). This is associated with the fact that the active

Fig. 2. The values of the linear trend slope coefficient (1950–2020) for surface air temperature (C/10 years) in (a) January and (b) July according to the ERA5 data.

temperature rise in the region III has started only in the recent 20 years, while the winter temperature rise in the region VIII in the late 1990s even changed into a slight temperature drop.

In summer (June–August), surface air temperatures on average over the territory of the Russian Federation increased much more slowly, and the linear trend slope coefficient was 0.20 C/10 years. The highest rate of the summer temperature rise in the linear approximation was observed in the region III (0.34 C/10 years), where the linear trend was insignificant in winter. The linear trend slope coefficient for summer air temperature was also quite high in the regions II and IX, where it was equal to about 0.26 C/10 years. The least pronounced summer temperature rise was registered in the region IV, where the winter temperature rise was, on the contrary, maximal. This was associated with the fact that the summer temperature in this region was noticeably decreased during the period until the late 1970s. It was then increasing until 2012 and has again been decreasing in the recent years.

Thus, in most Russian regions, the temperature rise was greater in winter than in summer. The exception was the region of the central EPR and the Altai and Sayan region, where in terms of the linear trend, the rate of increase in winter and summer temperatures was almost the same and, in terms of the curve of the lowpass component, the temperature rise was even slightly greater. The same statistical characteristics were calculated at the points of the grid with the 1 spacing in latitude and longitude for the territory of continental Russia. Based on the results presented in a cartographic form (Fig. 2), the features of the spatial distribution and temporal variability of air temperature were analyzed. The figure shows that the warming in winter was more intensive than in summer.

The correlation between the variations in air temperature and atmospheric circulation indices was estimated to assess the role of the circulation factor in the formation of the thermal regime on the territory of the Russian Federation.

The time series of the atmospheric circulation indices for the North Atlantic Oscillation (NAO), East Atlantic/Western Russia pattern (EAWR), Scandinavia pattern (Scand) characterize the oscillations of the major pressure centers in the Euro-Atlantic sector, which affect the changes in air temperature and precipitation in Russia. The Atlantic Multidecadal Oscillation (AMO) associated with the sea surface temperature anomalies and oceanic heat transfer in the North Atlantic forms climate anomalies in the European sector on decadal and interdecadal timescales. For assessing the impact of atmospheric circulation on the thermal regime of Russia, the coefficients of correlation r between the time series of the circulation indices (AO, NAO, EAWR, Scand) and air temperature at 26 stations distributed throughout Russia were calculated for all months during 1976–2019. The following features were revealed: the best correlation with the NAO index was found for the air temperature in the northwestern EPR during December–March (in March, the value of r for St. Petersburg reached 0.75), as well as in the central EPR. The Arctic Oscillation (AO) also had the greatest effect in the cold season, and the high correlation was found in the Siberian and Far Eastern regions (for Vladivostok in March, $r = 0.61$). Consequently, the NAO and AO favor the formation of positive air temperature anomalies during the cold season.

The EAWR had the strongest negative impact on the EPR and the Ural region during April–October (e.g., for Kazan in September, r reached the value of –0.78), thereby facilitating the air temperature drop in the warm season. The most active influence on the Volga region, the Cis-Ural region, and southern Western Siberia is exerted by the Scandinavia pattern ($r < 0$). For example, air temperature at the Siberian stations Yeniseisk, Novosibirsk, and Barnaul highly correlates with the Scand index all year round ($r = -0.73$ for Barnaul in December). This was manifested in negative temperature trends in southern Western Siberia and in the Altai region in winter during 1976–2019 and all year round in southern Western Siberia during 2001–2019. The territory with the negative air temperature trend in January in 2001–2019 occupies almost the entire EPR, the Ural region, and the south of Western and Central Siberia, which confirms the role of the Scandinavia pattern in the air temperature decrease in these regions.

The AOM favors the formation of long-period temperature anomalies within both the whole Northern Hemisphere and the EPR. There was an oscillatory regime of air temperature averaged over the Northern Hemisphere and the EPR until the mid-1970s, and then a subsequent prevalent role in climate warming was played by the greenhouse effect.

Synchronous correlations were calculated between the air temperature at 150 stations located throughout the Russian Federation and the AMO index for 1966–2020. The highest values of r were obtained for the calculations based on average annual data. A higher correlation was found for the central and southern EPR, the south of Western Siberia and Chukotka (the values of r up to 0.61). At the same time, the correlations were low in some regions (the northern EPR, the center of Central Siberia, etc.).

The results of the presented analysis of regional climate change in the recent decades and the role of the circulation factor are generally consistent with the basic conclusions made in the previous studies [24–27].

The regional features of changes in the precipitation regime during 1976–2019 on the territory of Russia were analyzed, in particular, in [15]. The analysis of the trends constructed based on annual total precipitation for 1976–2019 indicated an increase in the amount of precipitation in most of Russia. Decreasing total precipitation was observed in the central and southern EPR, in the North Caucasus, where the linear trend slope coefficient was –10…–14 mm/year. In 2001–2019, the contrasts in the distribution of precipitation over the territory of Russia increased. For example, in Western and Central Siberia, there was decreasing total precipitation, while the annual total precipitation increased in the eastern regions of Russia. There was a decreasing precipitation trend and, hence, an increasing aridity trend in the southern half of the EPR.

It should be noted that much attention was paid in the literature to the problem of the formation of atmospheric droughts and their negative effects on agriculture. For example, the authors of [21] analyzed the dynamics of severe atmospheric droughts in the southeastern EPR over the period of 1936–2010. It was noted that according to the climatic scenarios of global warming, the increasing trend in the frequency, duration, and area of severe atmospheric droughts in the south of the Russian Plain would be preserved until the end of the 21st century. The later study [23] has demonstrated that modern and projected climate change creates significant risks for the development of Russian agriculture. It is expected that the southern boundary of short-term droughts with a length of 5–10 days per month will move to the north. In the regions where the end of the 20th century was characterized by short-term droughts, their transition to the category of durable droughts (>20 days per month) and the increasing risks of crop damage are predicted.

It is noteworthy that the climate of grain-producing southern regions of Russia in the recent decades has been characterized by the increasing frequency and length of meteorological droughts.

The authors of [10] assessed the impact of projected climate change on the crop productivity on the territory of Russia during the 21st century based on new climatic scenarios. The general conclusion is the following: if global warming leads to a 3.9–11.1% growth in the bioclimatic potential of Russia's territory by the mid-21st century as compared to the current one, the level of the bioclimatic potential at the end of the century may be reduced by 7%, which may lead to the loss of grain crop productivity in the country by 16–18%.

Taking into account the need for the adaptation of humans and economy, including agricultural industry, to the current and future climate change, the problem of assessing future climate change on the vast territory of Russia becomes relevant [6, 22]. According to [22], the ensemble projections of future climate change obtained using the most advanced climate models show that at the turn of the 21st and 22nd centuries, climate aridity may pose a range of new threats to the development of many Russian regions. At the same time, the formation of the milder and wetter climate as compared to the recent decades is expected under the influence of global warming in most Russian regions throughout the 21st century.

It was noted in synoptic practice that with the beginning of the global warming period, the number of ultrapolar invasions started decreasing, and they have almost ceased by now. At present, cold anticyclones move not from the Kara Sea but from Greenland to Scandinavia, the central EPR and further to Kazakhstan, and only their edges affect the Northern Caucasus. Such trajectories were also registered before, but are starting to prevail just now. The air formed over Greenland in such anticyclones is less cold and more humid, so winters are getting warmer, and May becomes colder and wetter. Strong spring droughts have not been registered in the EPR at all in the recent decade. The last extremely cold ultrapolar invasion was observed at the end of December 1979 and led to the destruction of not only winter crops but also fruit trees. In view of this, the popular omen “if May is cold, a year will be corny” is almost always true. When May is cold, as a rule, precipitation is falling, which is so necessary for the successful growth of grain crops. It should be noted that this is valid only for the EPR. In Siberia, June is such a critical month for the yield, since spring crops are sown later there.

Climate change is reflected in the dynamics of the agroclimatic resources of Russian regions over the past decades. The authors of [1, 2, 4, 8, 9, 11, 16–18] evaluated the dynamics of the thermal and humidity regime parameters in several agricultural regions of Russia, as well as the weather and climate risks connected with cultivating agricultural crops.

It has been shown that the beginning of the growing season is shifted to the earlier dates, the sum of effective temperatures is increasing, and the amount of summer precipitation in grain-producing regions of Russia is decreasing now. There are calculated linear increasing trends in the aridity index developed by M.I. Budyko, as well as decreasing trends in the Selyaninov’s hydrothermal coefficient, which indicates growing climate aridity. For entire Russia, the warming trends have brought about a reduction of the climate-related spring wheat yield approximately by 12% from 1976 to 2015, i.e., by ~3% per decade [14].

Taking into account the importance of the food security problem in Russia under conditions of changing climate and the role of climatic factors in the formation of crop productivity, it became necessary to prepare the special issue of the Russian Meteorology and Hydrology journal called “Modern Climate Change and Its Consequences for Agricultural Sphere.”

This issue presents the series of papers dealing with the assessment of the current and future climate change on the territory of Russia and the dynamics of its agroclimatic resources. Special attention is paid to the natural conditions for the formation of summer droughts that have a negative impact on agricultural production, to the evaluation of agroclimatic conditions for wintering of winter grain crops, and some other factors that favor revealing an objective picture of the vulnerability of Russian regions to negative weather events and climate risks arising when cultivating agricultural crops.

The results of the studies contained in the present issue of the journal indicate an ambiguous impact of global climate change on the features of general circulation in different regions of Russia. At the same time, these features affect the development of atmospheric processes that are favorable or unfavorable for different kinds of economic activities, in particular, for agriculture. In view of this, the detailed investigation of regional climate change is required in order to develop methods for its prediction.

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