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Climate Change on the Territory of the Volga Federal District in the 20th–21st Centuries and Its Consequences for the Agrosphere

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Abstract—The spatial and temporal variability of the main climatic indicators on the territory of the Volga Federal District in the 20th–21st centuries is considered. A general increasing trend in air temperature is revealed, and a heterogeneous pattern of precipitation changes is shown. The temperature variations until the end of the 21st century are analyzed on the example of Kazan using 40 CMIP6 climate models for four anthropogenic scenarios. In the paper, there is an assessment of the dynamics of agroclimatic resources on the territory of the Volga Federal District: the duration of the growing season, the sum of positive temperatures, total precipitation, and photosynthetic radiation. A correlation has been found between the temperature fluctuations in the region and the atmospheric circulation indices (NAO, AO, SCAND, and EAWR). For the territory of Tatarstan, a degree of aridity and waterlogging is evaluated using the agroclimatic indices: the Budyko's dryness index, the Selyaninov's hydrothermal coefficient, the Sapozhnikova's moisture index. It is shown that there is a tendency toward an increase in the duration of the growing season, its heat supply and aridity in the region in summer. A statistical estimation of the dependence of spring wheat yield on the agroclimatic indices on the territory of the Republic of Tatarstan is given.

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Keywords: Climate change, correlation, air temperature, precipitation, agroclimatic indices, yield

1. INTRODUCTION

The Volga Federal District (VFD) belongs to the most developed regions of Russia. A fourth of industrial and agricultural products in the country are produced here. The VFD area is 1037.0 10^3 km^2 (6.1% of the territory of the Russian Federation), the population is 28.8 10^6 people (19.82% of the population of the country). Agricultural industry is most developed in the central and southern parts of the district, where the natural and climatic conditions for crop production and animal husbandry are more favorable. Systematic meteorological observations have been carried out in the region since the moment of establishment of the Meterological Observatory at Kazan University (1812), which has been indicated in numerous scientific publications [6]. The first climatic studies of the Middle Volga region include the monograph [2], in which the observational data for the period until the 1960s were used to evaluate the effects of atmospheric circulation, radiation, and Earth surface conditions on the temperature and humidity regime of the region.

A later publication described [8] the main climatic characteristics and their spatiotemporal variations in the VFD over 1966–2009 under conditions of global warming. The authors of [11–13] considered the regional climate changes against the background of the processes in the Northern Hemisphere, taking into account the influence of atmospheric circulation. Among more modern studies, the publications [7, 9] should be noted, in which the features of climatic and agroclimatic changes on the territory of the VFD and the Republic of Tatarstan in the recent decades were analyzed.

The objective of the present paper is to analyze the dynamics of climatic and agroclimatic resources in the VFD over the period 1966–2021 and to show the dependence of grain crop yield on specific meteorological factors on the example of the Republic of Tatarstan.

2. DATA AND METHODS

The monthly observational data from 17 weather stations homogeneously distributed over the territory of the VFD from the archive of All-Russian Research Institute of Hydrometeorological Information–World Data Center for the period 1966–2021, as well as the daily observational data from 13 weather stations in the Republic of Tatarstan for the period 1966–2021 were used as initial data. The ERA5 reanalysis data were taken to evaluate several agroclimatic parameters and the correlations between air temperature and the atmospheric circulation indices. The characteristics of solar radiation were calculated using the data from https://power.larc.nasa.gov/ for 1983–2020. The atmospheric circulation indices were taken from the database https://crudata.uea.ac.uk/.

The long-term data were statistically processed. The mean values, standard deviations (SD), linear trend slope coefficients (LTSC), coefficients of correlation between the meteorological parameters and atmospheric circulation indices were found.

The extraction of the low-frequency component in meteorological series was carried out using the Potter lowpass filter with a cutoff point of 15 years and more. The reliability of the results was estimated using the *F*-test.

The dates of the stable 0, 5, 10 and 15 C crossing for the average daily temperature (ADT) of air in spring and autumn, the length of the periods when the ADT was above the mentioned thresholds, the sums of temperatures were determined by the method developed by D.A. Ped' [5].

The Budyko's dryness index, Selyaninov's hydrothermal coefficient, and Sapozhnikova's moisture index were calculated to assess the moistening of the region using the formulas presented in [3].

The intensity of photosynthetically active radiation (PAR) was computed using the formula from [1].

3. RESULTS AND DISCUSSION

According to [1], the shortwave radiation in the wavelength range = 0.38–0.71 m called photosynthetically active radiation is of key importance for the growth of plants. It is among the major factors of agricultural crop productivity.

In the present study, PAR was calculated for the period of the ADT exceeding 5 and 10 C, since the average daily air temperatures at the beginning and end of vegetation are about 5 C for the winter and early spring grain crops and about 10 C for the late spring crops. This is how PAR is bound to the stages of the growing season of grain crops. According to Fig. 1, its distribution over the VFD is zonal. Total PAR decreased from south to north from 1720 to 1260 MJ/m^2 in the period with ADT > 5 C and from 1600 to 1080 MJ/m^2 in the period of active vegetation (ADT > 10 C). Consequently, most of the VFD in the growing season is provided enough with solar energy needed for crop production. The spatiotemporal distribution of sunshine duration over the territory was previously considered in [8].

Several statistical characteristics were calculated using the data of 17 weather stations to reveal the main features of the annual and seasonal distribution of air temperature and precipitation in the VFD for the period 1966–2021. As follows from the data, the average long-term annual air temperature decreases from southwest (the Marks station close to Saratov) to northeast (the Nyrob station) from 6.9 to 0.5 C. It is equal to 3.0–4.7 C in the center of the district and decreases from 5.4 to 3.7 C from west to east. The lowest temperatures were registered in the area of the Bugul'ma-Belebei Upland, in the mountain regions of Bashkortostan, and in the northeast of the Perm krai. The annual isotherms are directed from northwest to southeast.

In winter, the average long-term temperature rises from –14.5 C in the northeast to –7.7 C in the southwest. In the winter months under conditions of negative radiation balance, the western areas of the VFD are more subjected to the warming effect of the North Atlantic, which generates noticeable temperature swings between the western and eastern areas. For example, the winter-averaged temperature is equal to –8.8 C at the Penza station (the west of the VFD) and drops to –12.2 C at the Ufa station (the east of the VFD). The lowest temperature background is observed in the northeast of the region. For example, the average winter temperature at the Nyrob station is –14.5 C.

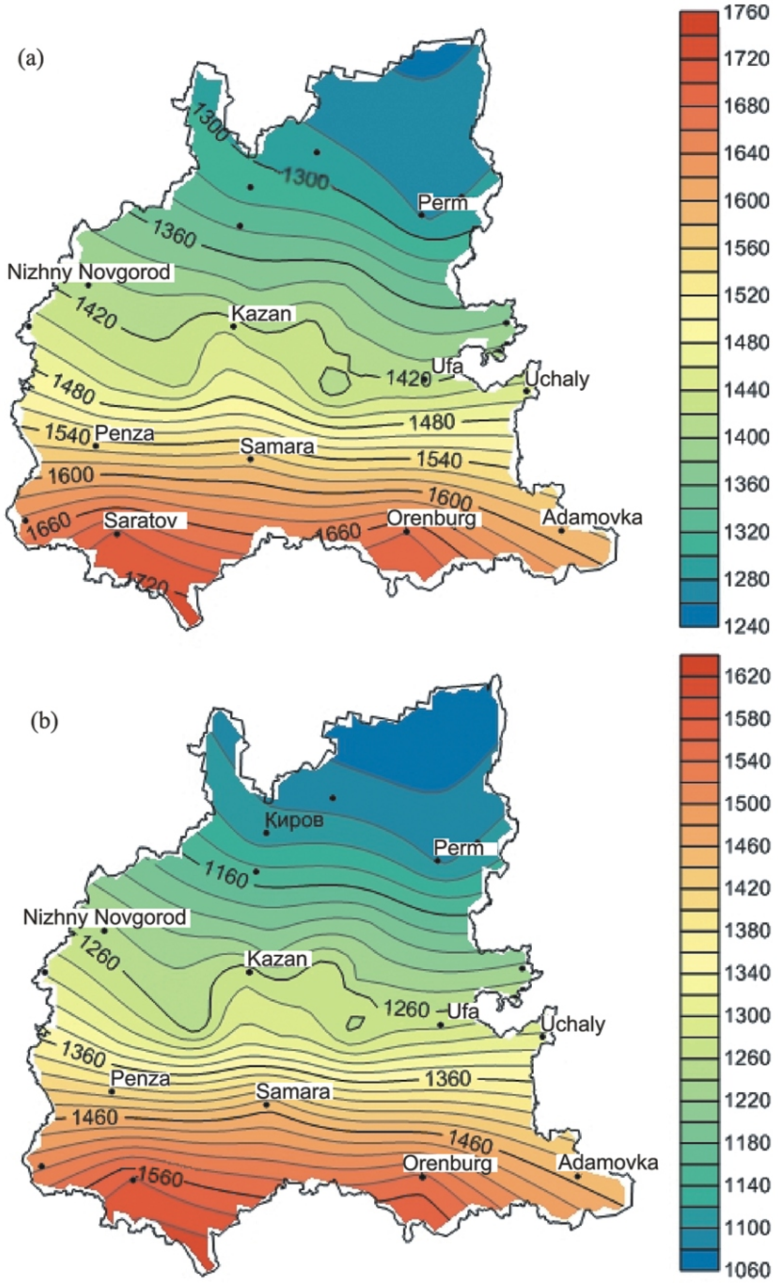

Fig. 1. The spatial distribution of the average long-term total photosynthetically active radiation (MJ/m^2) over the VFD territory during the periods with an average daily temperature of (a) >5 C and (b) >10 C.

In spring, a rapid temperature rise occurs, the temperature is positive everywhere and increases from 1.2 C in the northeast to 7.4 C in the southern areas.

In summer, under conditions of the maximum radiation heating, isotherms have a zonal pattern. The average long-term temperature increases from 15.1 C (the Nyrob station) to 21.5 C (the Marks station) in that period, i.e., the zonal difference is 6.4 C.

In autumn, the temperatures in the VFD are lower than in spring, but the temperature averaged over three autumn months remains positive. The lowest autumn temperature has been recorded at the Nyrob station (0.4 C), the highest temperature has been registered at the Marks station (6.9 C).

The value of the standard deviation of air temperature (SD) characterizing the interannual variability varies in the VFD within the following limits: varies from 1.0 to 1.2 C for the average annual value, from

2.4 to 3.2 C for winter, from 1.4 to 2.0 C for spring, from 1.2 to 1.6 C for summer, from 1.4 to 1.6 C for autumn, i.e., the territorial differences are not so great. The temperature variability is highest in winter and minimal in summer.

The analysis of the distribution of annual and seasonal coefficients of the inclined trend *b* over the territory of the VFD calculated for all 17 stations over the period 1966–2021 has demonstrated that the positive annual values of *b* spatially vary within small limits: from 0.33 C/10 years (southeast, the Zernosovkhoz Ozernyi station) to 0.50 C/10 years (the Kazan station). The highest positive values of *b* are registered in the winter months. The value of *b* increases from 0.49 C/10 years in the southeast of the VFD to 0.80 C/10 years in the northwest (the Lal'sk station). Significant warming occurs for the territory as a whole in winter. The increasing temperature trend is also maintained in the other seasons. However, the warming rate is significantly lower than in winter. For example, the value of *b* within the district varies from 0.19 to 0.38 C/10 years in spring, from 0.17 to 0.45 C/10 years in summer, and from 0.23 to 0.43 C/10 years in autumn. The linear trends in temperature are statistically significant at the 5% level with the coefficient of determination R^2L ? 3%. Thus, at most stations, the revealed increasing temperature trends are significant.

The estimation of future air temperatures in Kazan was carried out using the results of ensemble simulations with 40 climate models performed under four main CMIP6 scenarios: ssp126, ssp245, ssp370, ssp585, corresponding to the value of global anthropogenic radiative forcing achieved in 2100 and equal to 2.6, 4.5, 7.0, and 8.5 W/m^2, respectively. In accordance to a modern increasing trend in the atmospheric concentration of CO_2, the most probable scenario is ssp245 (the CO_2 concentration will grow up to ~600 10^{-6} by the end of the 21st century). The simulations were performed both for the entire period 2021–2100 and for the consecutive 20-year subperiods: 2021–2040, 2041–2060, 2061–2080, and 2081–2100.

According to the projections, the warming in winter will be characterized by higher rates than in summer. According to the most likely scenario ssp245, the air temperature rise for different seasons and per year in the concluding 20 years of the 21st century (2081–2100) as compared to 2021–2040 will be equal to 2.9 C in winter, 2.4 C in spring, 2.1 C in summer, 2.2 C in autumn, and 2.4 C per year. Higher warming rates are expected in case of the realization of the toughest scenario (ssp585), but it is unlikely. In this case, at the end of the century, the annual temperature in Kazan will increase by 5.5 C, and the winter one will increase by 6.6 C. It should be noted that there is a high correlation between the temperature changes in Kazan and other parts of the VFD, so the results indicate a general situation in the region, which will require a future correction of the list of cultivated crops.

The precipitation regime in the VFD is characterized by the following values. Annual total precipitation averaged over 56 years (1966–2021) varies in the VFD from 272 mm (the Zernosovkhoz Ozernyi station) to 661 mm (the Kirov station). The greatest amount of precipitation is recorded in the northern part of the district, and the smallest one is observed in the south and southeast. According to [8, 9], local precipitation zones are formed in the areas of windward slopes of the Bugul'ma-Belebei and Volga uplands, Northern and Vyatka ridges, Ufa Plateau, etc. In winter, total precipitation in the southern areas is much smaller than in the northern regions: for example, it is equal only to 48 mm at the Zernosovkhoz Ozernyi station, 141 mm in Samara, and 133 mm in the Kirov station. The spatial distribution of precipitation is inhomogeneous, unlike the temperature distribution. In spring, total precipitation is slightly smaller than in winter (in spring, from 69 mm in the southeast to 126 mm in the northeast). The greatest amount of precipitation is recorded everywhere in summer: from the minimum of 94 mm in the southeast (the Zernosovkhoz Ozernyi station) to 234 mm (the Perm' station). In the northwest and northeast of the VFD, total precipitation is much greater than in the center and especially in the south. In autumn, the amount of precipitation across the VFD is greater than in spring, especially in the northern part of the district.

The temporal variability of precipitation was estimated using the coefficient of variation C_v. The value of C_v for annual total precipitation decreases from southeast to northeast from 23 to 13%. The value of C_v for different seasons varies within the following limits: from 38% (the Orenburg station) to 24% (the Lal'sk station) in winter, from 46% (the Zernosovkhoz Ozernyi station) to 28% (the Lal'sk station) in spring, from 47% (the Orenburg station) to 30% (the Kirov station) in summer, from 39% (the Perelyub station) to 24% (the Perm' station) in autumn. Thus, the variability of precipitation in summer is more noticeable than in the other seasons.

For agriculture, the information about the temporal trends in precipitation is of high interest. The analysis of the calculated values of linear trends has shown that annual total precipitation in most of the VFD, especially in its northern part, is increasing. The maximum rate has been registered at the Nyrob station (41.22 mm/10 years). However, at some stations (basically in the southern half of the VFD), an amount of precipitation is decreasing at a rate from –2.93 mm/10 years (the Penza station) to –14.51 mm (the Saransk

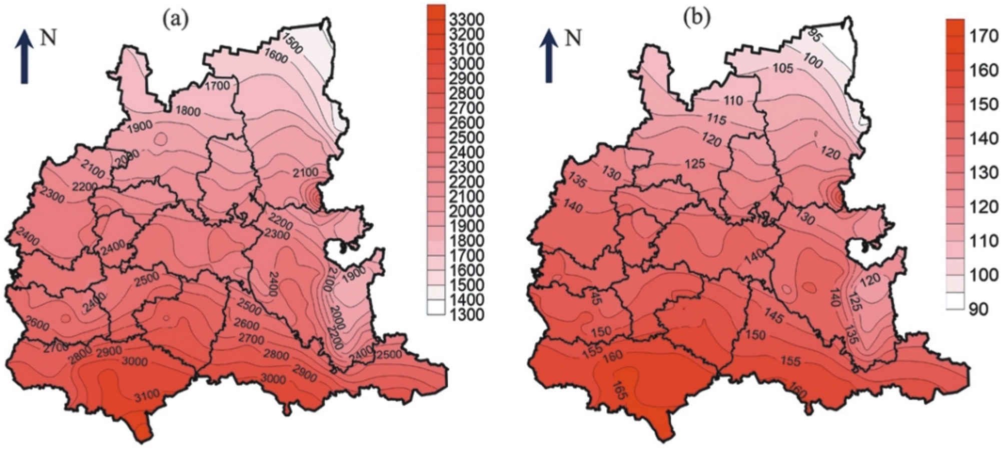

Fig. 2. The distribution of (a) the average number of days with an average daily temperature of >10 C and (b) the average sum of active temperatures on the VFD territory over 1966–2021.

station). In winter, the values of *b* vary from 0.28 mm/10 years (the Orenburg station) to 11.87 mm/10 years (the Nyrob station). A slight precipitation reduction is recorded at the Izhevsk and Bugul'ma stations (from –0.32 to –1.64 mm/10 years). In spring, the variation rates of precipitation are low, and the values of *b* are negative at two stations (Lal'sk and Saransk). At the other stations, a slight increase in total precipitation takes place: from 3.12 mm/10 years (the Zernosovkhoz Ozernyi station) to 11.08 mm/10 years (the Perelyub station). The summer amount of precipitation is increasing at a rate reaching 13.09 mm/10 years in the northern part of the district (the Lal'sk station), while there is a negative trend in the central and southern parts of the VFD, which creates conditions for the aridity growth (the Samara station, b = –10.31 mm/10 years). In autumn, this trend is intensifying: at 12 of 17 stations, *b* is negative. For example, at the Saransk station, *b* = –6.88 mm/10 years. Only at the northern stations, the precipitation trend is positive (at the Nyrob station, *b* = 12.39 mm/10 years). In general, the distribution of the coefficient *b* over the district is quite spotty, unlike the distribution of temperature. In addition, it should be noted that according to the calculated values of R^2L, the negative trends are statistically insignificant.

Several parameters were calculated to characterize the agroclimatic regime of the VFD based on the ERA5 reanalysis data for 1966–2021. Their distribution over the region is given below.

The length of the period with an average daily air temperature above 0 C increases from 185 days in the extreme northeast to 245 days in the extreme southwest, i.e., the difference is 60 days. The duration of the period with ADT > 5 C changes in the same direction from 145 to 200 days, the length of the phase of active vegetation with ADT > 10 C increases from 95 days in the extreme northeast to 165 days in the extreme southwest (Fig. 2a). In summer, the average daily temperature of >15 C is registered for 75 days in the northeast and 135 days in the southwest. It is natural that the spring 0, 5, 10, and 15 C crossing for ADT starts earlier in the southwest and ends the latest in the northeast.

The average annual sum of average daily temperatures above 0 C decreases over the VFD from southwest to northeast from 3500 to 2000 C (the LTSC decreases in the region from 70 to 56 C/10 years). The average annual sum of ADT > 5 C decreases from southwest to northeast from 3400 to 1900 C (the LTSC decreases in the same direction at a rate from 70 to 58 C/10 years). The average sum of ADT > 10 C decreases in the same direction from 3100 to 1500 C at a rate from 66 to 58 C/10 years (Fig. 2b). The sum of ADT > 15 C in summer decreases from the southwest from 2600 to 900 C at a rate from 60 to 44 C/10 years.

The absolute value of the sum of negative temperatures (below 0 C) increases from the southwest to the northeast of the VFD from 1000 to 1800 C. The absolute value of the sum of ADT < –15 C characterizing the coldest part of the winter significantly increases from southwest to northeast: from 400 to 1060 C. The values of the LTSC point to a decrease in the sum of negative temperatures at a rate up to 86 C/10 years, which indicates the climate warming.

For evaluating the contribution of atmospheric circulation into the changes in climatic indicators, the computations were performed for the coefficients of pair correlation between air temperature, precipitation, and the circulation indices: the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the East Atlantic/Western Russia pattern (EAWR), and the Scandinavia pattern (SCAND).

According to [10], the air temperature variations observed from the mid-20th century in Northern Eurasia can be explained by the anomalies of several circulation patterns. Here, in order to assess the role of the atmospheric circulation in the formation of the thermal regime of the VFD, the calculation was performed for the coefficients of correlation were between the monthly mean temperatures at the points of the regular grid with a resolution of 0.25 0.25 (ERA5 data) and the circulation indices for every month over the period 1979–2021 (for the sample volume $n = 43$ years and the 95% significance level ($r = 0.05$), the critical value of the correlation coefficient was equal to 0.35). The results of the calculations were mapped.

It has been found that the highest positive correlations between the temperature at the grid points and the NAO index are observed in the cold season (December–March). Isocorrelates are directed from southwest to northeast. In that period, almost the entire VFD, except for the southeast, is in the zone of positive and significant correlation coefficients. The highest values of r are registered in the northwest of the VFD, and then the correlation decreases in the southeastern direction. The maximum values of r are 0.55 in December, 0.60 in January, 0.55 in February, and 0.65 in March. In the other months, correlations are insignificant and, from April to August, negative. Thus, the NAO favors the air temperature rise in the VFD only over December–March.

The significant positive correlations between air temperature and the AO index also take place in December–March (in January, r increases from northeast to southwest from 0.40 to 0.55; in February, the maximum value of $r = 0.55$ is in the area of the Kirov station; in March, the correlations are the highest, they increase from southeast to northwest from $r = 0.35$ to $r = 0.65$ (isocorrelates stretch from southwest to northeast; in December, the significant correlations ($r_{\max} = 0.55$) are found only in the northern part of the VFD).

The calculations were also performed for the correlation coefficients between the monthly mean temperatures and precipitation at 17 VFD stations and the atmospheric circulation indices NAO, AO, SCAND, and EAWR for 1979–2021. The results of the calculations for temperature are consistent with the estimates based on the ERA5 data, but the coefficients of correlation between total precipitation and circulation indices turned out to be insignificant.

In January and February, the field of significant negative values of the correlation coefficient r between air temperature and the SCAND index is formed across the VFD. Isocorrelates are directed from southwest to northeast. The value of r increases from northwest to southeast from –0.40 to –0.70 in January and from –0.55 to –0.70 in February (Fig. 3a). All this indicates a strong cooling effect of the Scandinavia pattern on the territory of the VFD in winter. In March, the role of the SCAND is still manifested in the southeast of the VFD ($r = -0.60$). The correlation coefficient in the northeast of the VFD reaches –0.60 in May, and the one in the east of the region in October and December is –0.50. In the other months, the coefficients of correlation between the air temperature and the SCAND index are insignificant.

The East Atlantic/Western Russia pattern has a significant effect on the thermal state of the entire region in the warm season (April–September). The coefficients of correlation between air temperature and the EAWR index are negative and reach the maxima of –0.70, –0.75 in that period. For example, Fig. 3b shows the distribution of r in the VFD in May, the correlation in the other months is much lower. Thus, the mentioned pattern has a cooling effect in the growing season.

The Republic of Tatarstan is located in the center of the VFD. It belongs to the most developed industrial and agricultural subjects of the Russian Federation. Its area is 68000 km^2, the population is 3773 10^3 people. The main food plants on the territory of the republic are grain and leguminous crops and potato, whose development and ripening depend directly on climatic factors: light, heat, and moisture.

The analysis of the main parameters of the growing season computed for the territory of Tatarstan based on the daily data from 13 weather stations for the period 1966–2021 demonstrated that the differences between the stations are small. For example, the spring 10 crossing for ADT occurs in Tatarstan initially in May (on the 122th day from the beginning of the year) and then on the 126th day in the north. The sum of positive temperatures for the active phase of the growing season on the territory varies from 2319 to 2476 C, and total precipitation increases from the southwest from 227 to 262 mm (the Bugul'ma Upland). At the same time, the rate of the increase in the growing season length varies from the west from 0.6 to 3.4 day/10 years in the northeast. The sum of temperatures is growing on the territory at a rate from 51.1 to 77.6 C/10 years, total precipitation is increasing at a rate of 5.7 mm/10 years in the west of the Republic of Tatarstan and decreasing at a rate of 1.9 mm/10 years in the east. In general, soil and climatic conditions are most favorable for the development of agriculture in the southwestern and southern areas of the republic.

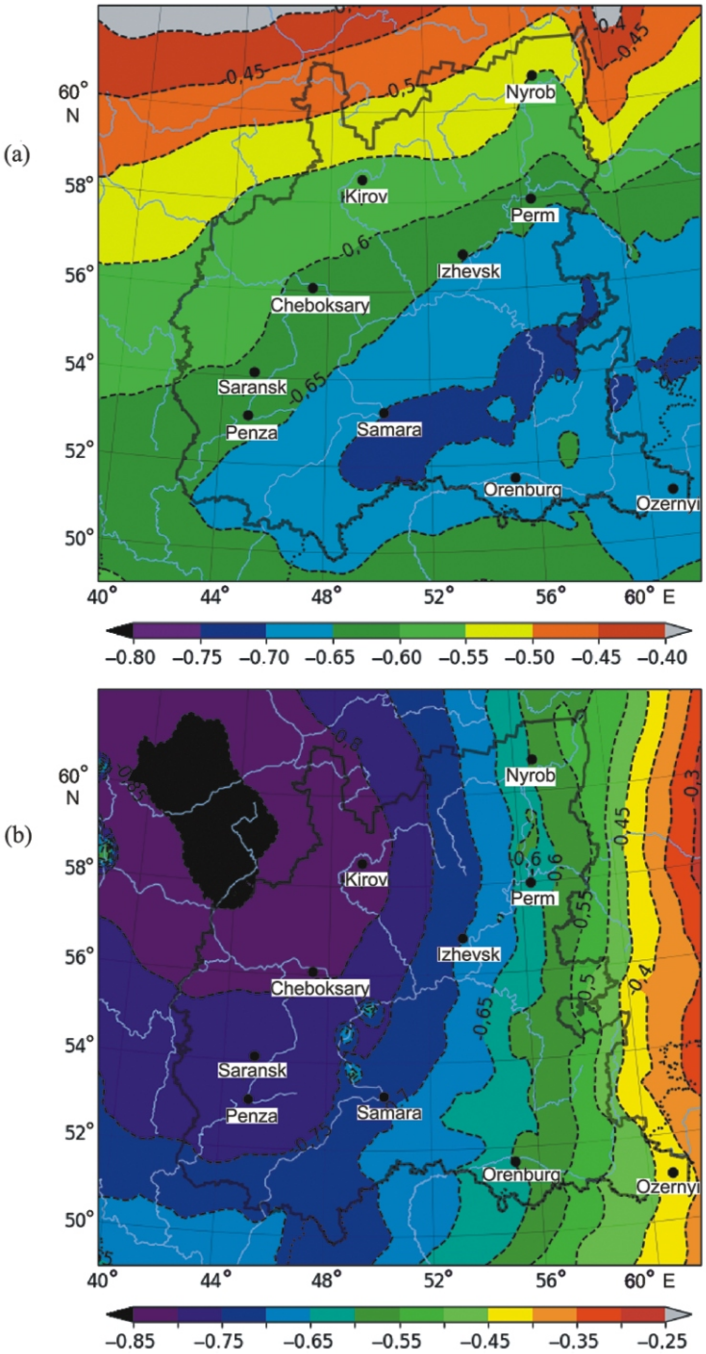

Fig. 3. The coefficients of the correlation between temperature and (a) the SCAND (February) and EAWR (May) indices.

The Budyko's dryness index, Selyaninov's hydrothermal coefficient, and Sapozhnikova's moisture index were calculated using the formulas from [3] to characterize the moistening of the territory based on the daily data from 13 weather stations in Tatarstan. According to the calculations, the dryness index in summer varies on the territory from 2.70 (the Kazan station) to 3.16 (the Kaibitsy station), the hydrothermal coefficient changes from 0.96 (the Kaibitsy station) to 1.16 (the Bugul'ma station), the moisture index varies from 0.84 (the Muslyumovo station) to 1.03 (the Bugul'ma station), which indicates a generally balanced inflow and outflow of moisture. The LTSC values are positive for the dryness index and negative

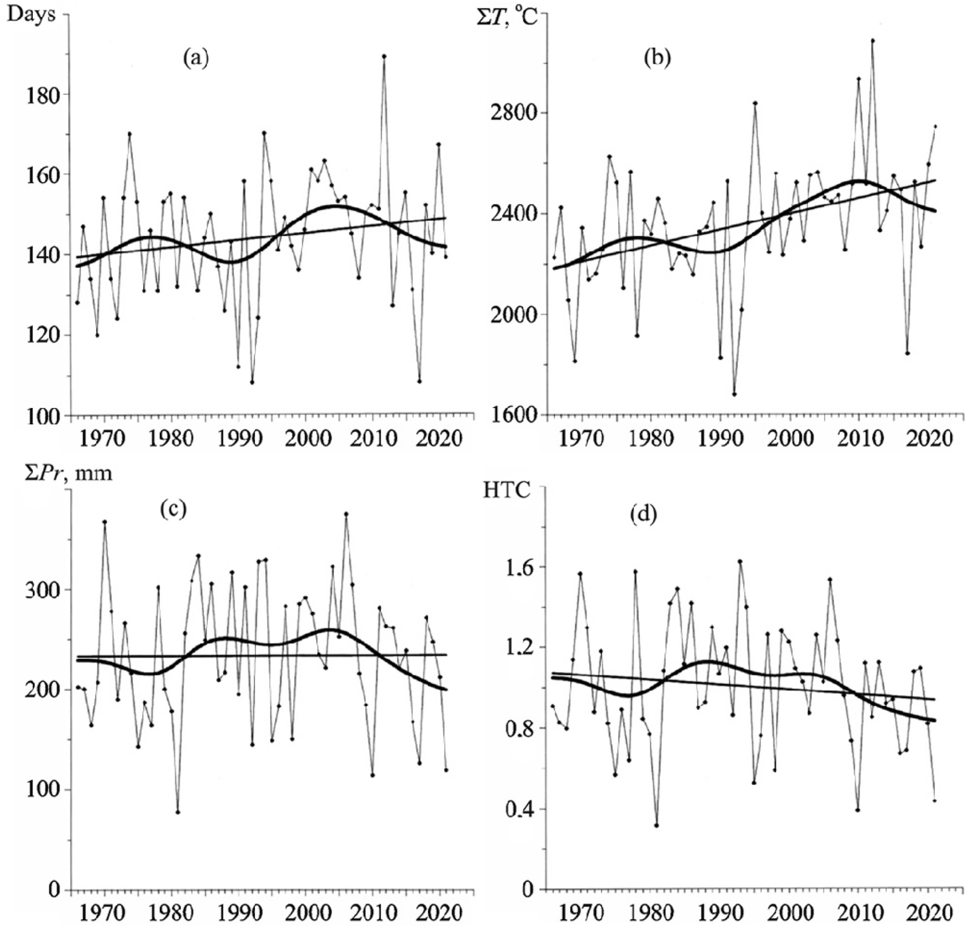

Fig. 4. The distribution of the low-frequency component for the Menzelinsk station in`the period with the temperatures above 10 C: (a) the duration of the period, (b) the sum of temperatures, (c) total precipitation, and (d) hydrothermal coefficient.

for the hydrothermal coefficient and the moisture index, which indicates a slight increasing trend in aridity of the region.

The slope coefficient of the linear trend in the dryness index varies from 0.09 to 0.38 unit/10 years, the LTSCs for the hydrothermal coefficient are everywhere negative (from –0.1 to –0.4 unit/10 years), and the ones for the moisture index are also negative (from –0.1 to –0.3 unit/10 years).

The Potter filter was used for each of 13 weather stations to extract low-frequency fluctuations in the time series of the analyzed indicators. The general features inherent in all regions of the Republic of Tatarstan were revealed: the duration of the growing season reached the maximum in the early 2000s and then started decreasing. The sum of temperatures reached the maximum approximately in 2010 and has decreased in the recent years. There has also been a reduction in precipitation since 2008. A decrease in the hydrothermal coefficient is observed everywhere. The dryness index is increasing, the moisture index is decreasing. The distribution of the low-frequency component according to the Menzelinsk station data is given as an example (Fig. 4).

For assessing the effect of meteorological factors on the agrosphere, the study was carried out concerning the correlation between the average spring wheat yield (A, centner/ha) over the territory of Tatarstan and some indicators of the temperature and humidity regime also averaged over the territory of the republic over the period 1991–2020. The following agroclimatic indices were used: the total precipitation of the hydrological year (R_{11-10}), November–June (R_{11-6}), May–June (R_{5-6}), the growing season (R_{5-8}), the average amount of precipitation over Tatarstan in June (R_6), the average temperature over Tatarstan for May–June (T_{5-6}), the air temperature for May (T_5), the air temperature for June (T_6). The time series of spring wheat yield and agrometeorological indices in the analyzed 3-year period were uniform.

Table 1. The statistics of the yield *A* and agrometeorological indicators in Tatarstan during 1991–2020

Score	A	R_{11-10}	R_{11-6}	R_{5-6}	R_{5-8}	R_6	T_{5-6}	T_5	T_6
Mean	22.93	500.59	294.62	100.19	210.41	59.4	14.97	13.63	17.83
Median	23.45	513.04	290.66	102.42	202.56	56.06	15.03	13.71	17.47
SD	7.66	75.02	51.36	34.27	49.20	27.71	1.52	2.17	2.05
Minimum	3.30	314.0	180.0	27.0	81.0	7.0	10.99	8.74	13.38
Maximum	36.90	632.0	414.0	164.0	278.0	112.0	17.68	16.78	21.28

Explanations are given in the text.

Table 2. The correlation matrix of the yield *A* and agrometeorological indicators in Tatarstan during 1991–2020

Indicator	A	R_{11-10}	R_{11-6}	R_{5-6}	R_{5-8}	R_6	T_{5-6}	T_5	T_6
A	1.00	0.35	0.54	0.75	0.48	0.59	–0.52	–0.23	–0.62
R_{11-10}		1.00	0.85	0.59	0.65	0.38	–0.02	–0.36	–0.29
R_{11-6}			1.00	0.69	0.46	0.52	0.11	–0.26	–0.42
R_{5-6}				1.00	0.76	0.84	0.10	–0.38	–0.61
R_{5-8}					1.00	0.54	0.01	–0.38	–0.48
R_6						1.00	0.29	–0.15	–0.57
T_{5-6}							1.00	0.82	0.79
T_5								1.00	0.30
T_6									1.00

Table 1 presents the statistical scores for the analyzed period, Table 2 provides the coefficients of correlation between the characteristics under consideration (the significant correlation coefficient r = 0.37 for the sample volume $n = 30$ and the 95% significance level $P = 0.05$). The table clearly shows the significant positive correlations between spring wheat yield *A* and total precipitation over November–June, May–June, the whole growing season, and June. A negative significant correlation between the spring wheat yield and June temperature has been revealed. Based on the results of the multiple correlation analysis between the yield and the agrometeorological indicators, the multiple regression equation was constructed that sets the dependence of the yield on total precipitation for May–June and temperature in June:

$$A \quad 27.18 \quad 0.26\ R_{5\ 6} \quad 0.98T_6. \tag{1}$$

This equation describes 57% of total variance. Figure 5 presents the data on the actual spring wheat yield in Tatarstan over 1991–2020 and on the one retrieved from the regression equation. The actual and computed values of the yield are in good agreement with each other, which allows using the obtained equation in the practical evaluation.

The pair correlation between the values of photosynthetically active radiation and spring wheat yield over 1991–2020 was also calculated. The correlation coefficients turned out to be significant and negative for the period of April–June (*r* was equal to –0.53, –0.55, and –0.41, respectively). Consequently, high radiation background in spring does not favor the formation of high spring wheat yields.

4. CONCLUSIONS

Finally, the following conclusions can be drawn. In the entire VFD, climate warming is going on in all seasons, which is especially noticeable in the winter-spring period. According to the anthropogenic scenario ssp245, an increase in the average annual temperature by 2.4 C is expected in Kazan by the end of the 21st century. At the same time, there are a complex pattern of the precipitation distribution and a clearly pronounced aridity trend for the summer-autumn season on a significant territory of the VFD. The study has revealed the role of the atmospheric circulation in the air temperature fluctuations. The NAO, AO, SCAND, EAWR have turned out to be most effective modes. The correlation of precipitation with the listed circulation oscillations has not been found. The dependence of spring wheat yield on the May–June total precipitation and June temperature has been shown.

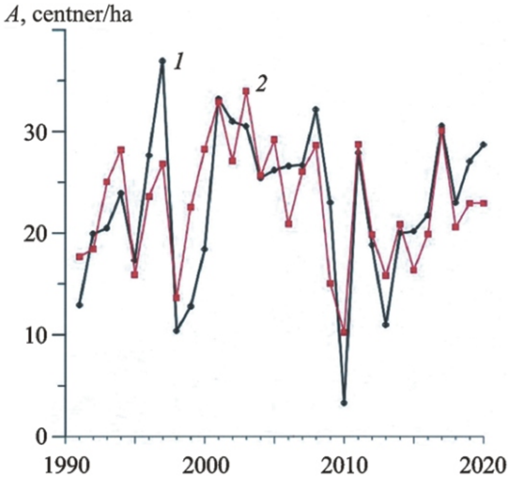

Fig. 5. The average spring wheat yield in the Republic of Tatarstan: (*1*) actual; (*2*) retrieved from the regression equation.

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