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Assessment of Changes in Agroclimatic Resources of the Republic of Bashkortostan (Russia) under the Context of Global Warming

Rita Kamalova [1,2], Ekaterina Bogdan [2,3,*], Larisa Belan [2,3], Iren Tuktarova [3], Alexey Firstov [1,2], Ildar Vildanov [1] and Irik Saifullin [1,*]

1 Laboratory of Climate Change Monitoring and Carbon Ecosystems Balance of the Decarbonisation Technology Center, Ufa State Petroleum Technological University, Kosmonavtov Str., 1, 450064 Ufa, Russia; galim-rita@yandex.ru (R.K.); alexfirstov777@gmail.com (A.F.); ildar.vildanov.89@mail.ru (I.V.)
2 Department of Geology, Hydrometeorology and Geoecology of Ufa University of Science and Technology, st. Zaki Validi, 32, 450076 Ufa, Russia; belan77767@mail.ru
3 Department of Environmental Protection and Prudent Exploitation of Natural Resources, Ufa State Petroleum Technological University, Kosmonavtov Str., 1, 450064 Ufa, Russia; umrko@mail.ru
* Correspondence: eavolkova@bk.ru (E.B.); irekle@mail.ru (I.S.)

Abstract: The process of climate warming significantly affects agroclimatic resources and agricultural production. We study the agroclimatic resources and their variability on the territory of the Republic of Bashkortostan (Russia). The Bashkortostan has a high agricultural potential and holds a leading position in the country in the production of grain crops, potatoes, milk, and honey. Currently, no detailed studies have been conducted for this area to assess the effects of global climate change on agro-climatic resources. World experience shows such research becomes strategically important for regions with powerful agricultural production. We used the sums of average daily air temperatures above 0 and 10 °C, the G.T. Selyaninov hydrothermal coefficient, and the Ped aridity (humidification) index as agroclimatic indicators. We used data of long-term meteorological observations of 30 meteorological stations for the period of 1961–2020. We revealed the long-term dynamics of the agroclimatic indicators and the spatial and temporal regularities in their distribution on the territory of Bashkortostan. There is a steady increase in the sums of average daily air temperatures above 0 and 10 °C. Against this background, aridity increases, which is especially manifested in the southern parts of the Republic of Bashkortostan. We assessed the impact of agroclimatic indicators on the main types of agricultural crops in the republic. We revealed that the greatest positive impact on the yield of oilseeds, cereals, and industrial crops is made by precipitation at the beginning ($r = 0.50$, $r = 0.44$, and $r = 0.52$, respectively) and in the middle of the growing season ($r = 0.55$, $r = 0.76$, and $r = 0.51$, respectively). Temperature and precipitation during the growing season have a complex effect on cereals. This is proven by correlations with HCS and the Ped index ($r = 0.45$ and $r = -0.56$, respectively). Aridity at the beginning of the growing season affects the yield of oilseeds and potatoes. This is confirmed by correlations with the Ped index ($r = -0.49$ and $r = -0.52$, respectively). In general, the aridity of the growing season has a significant impact on the yield of cereals ($r = -0.57$). Negative relationships have been found between the air temperature growing season and the yield of potatoes ($r = -0.50$) and cereals ($r = -0.53$). The results of the study were compared with data from the Copernicus Climate Change Service database. We identified climate trends under RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 scenarios. These scenarios should be taken into account when developing plans for the adaptation of agriculture in the Republic of Bashkortostan to changes in the regional climate. Maximum decrease in precipitation is established for the RCP 6.0 scenario. This can have an extremely negative impact on crop yields. This problem is especially relevant for the southern part of the Republic of Bashkortostan. The information presented in the study will allow for a more effective adaptation of the agricultural sector to current and future climate changes.

Keywords: agroclimatic resources; climate change; sums of positive air temperatures; precipitation; hydrothermal conditions; aridity index; crop yield

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1. Introduction

Current climate change has a direct impact on agricultural production. In different regions of the world, the responses of climate change are predominantly negative for the agricultural sector.

A large number of publications show that the effects of climate change mainly have a negative impact on agricultural production. One of the serious global climate problems currently is the intensification of aridity in various countries of the world. In Deng et al. [1], it has been established that in recent decades, droughts and heat waves have often occurred in Western Europe during the boreal summer. Similar conclusions for the European region are reflected in [2–4]. Based on the results of studies of forecast estimates [5], it was found that even in a low-emission scenario, a likely increase in the frequency and spread of heat and drought events in most of Europe is expected (60%). There are similar works for African countries [6–9] and Asia [10–12].

The combined effect of arid and hot phenomena leads to a large cumulative damage compared to individual dangerous natural phenomena [13]. Also, Hao et al. [14] concluded that combined droughts and hot weather events can lead to more serious consequences than individual droughts of the past. The negative impact of changes in heat and moisture availability is manifested not only on the potential of crop and livestock production, but also on working conditions and, mainly, on yields [15]. An analysis of different studies shows that changes in precipitation and water availability will have a significant impact on the demand of crops for water (for irrigation), productivity, an increase in the cost of water resources and, as a result, a decrease in agricultural production in Europe [16,17], Asia [10–12,18–21], Africa [6], and America [22,23].

Nevertheless, some researchers find positive effects from global warming that are beneficial for agricultural production. Thus, in the work of Barrio et al. [24], the possibility of increasing the area of cultivation of fruit trees in connection with a decrease in winter cold and frost is considered. A large number of works [25–30] show an increase in the length of the growing season and an increase in effective temperatures [27,30,31].

Thus, agriculture is very vulnerable due to the ongoing global warming [32]. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) shows that it affects regional changes in temperature and precipitation patterns. So, climate change affects crop growing conditions [32–35]. Consequently, the growing interest in research on climate change and its effects on agriculture is of great practical importance.

The consequences of climate change are noted both in Russia as a whole and in its subjects, including the Republic of Bashkortostan (hereinafter RB) [33–37].Consequently, the growing interest in the issues of regional climate change research is of great applied importance.

In particular, the RB ranks 11th among the subjects of Russia and 3rd in the Volga Federal District in terms of agricultural production by 2022. The RB is among the top 10 in terms of agricultural products produced in the country, including grain (11th place), potatoes (5th place), milk (3rd place), and honey (1st place) [38].

This study analyses the main agro-climatic indicators of the RB. At present, no such detailed studies have been conducted for its territory.

Thus, the purpose of this study was to analyse current and future changes in the agro-climatic resources of the RB in the period of 1961–2020. The study included an analysis of changes in agro-climatic parameters (sums of positive temperatures and hydrothermal indices), as well as an analysis of future changes in individual agro-climatic parameters based on the models HadGEM2-ES Model (UK Met Office, UK) and MIROC-ESM-CHEM Model (JAMSTEC, Japan) for scenarios of Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, and 8.5. The scenarios are composed of four pathways representative of the greenhouse gas concentrations along the 21st century which lead to a radiative forcing of 2.6, 4.5, 6.0, or 8.5 $W \cdot m^{-2}$ in 2100 [39].

2. Materials and Methods

The RB is a complex region both in terms of orography and climatic conditions. This is due to its location at the junction of the East European Plain and the Ural Mountains (Figure 1). Relief peculiarities form climatic differentiation of its separate parts. In physical and geographical terms, the republic is characterised by the flat Bashkir Pre-Urals, the Southern Urals (mountainous part), and the hilly and sloping Bashkir Trans-Urals.

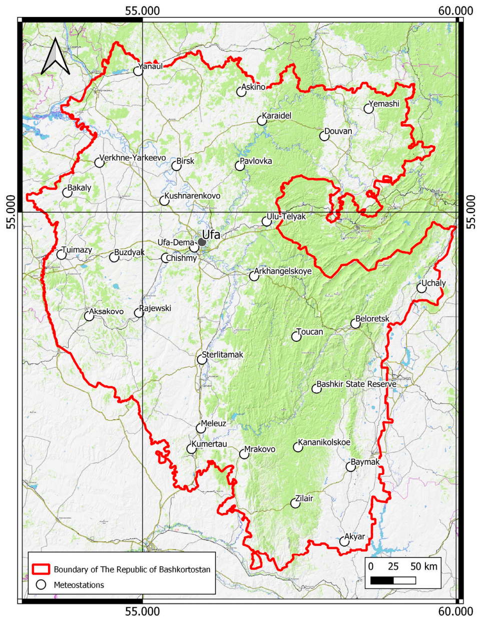


Figure 1. Location of the Republic of Bashkortostan.

Climatic conditions and their changes directly affect the agroclimatic potential. The paper assesses the impact of various climatic values and indicators on crop yields (centner/hectare) in the RB. The data on crop yields from the base of the Federal State Statistics Service of the Republic of Bashkortostan in the period of 2000–2020 were used for the analysis [40]. The selected agricultural crops are prioritised in terms of gross yields in the republic: cereals, industrial, oilseed (sunflower seeds) crops, and vegetables (potatoes).

Spatial and temporal series of the following characteristics were analysed as agroclimatic indicators: sums of mean daily air temperatures above 0 and 10 °C ($\Sigma T \geq 0$ °C and $\Sigma T \geq 10$ °C, respectively); humidification index and hydrothermal coefficients; and index of climate biological efficiency.

The study uses the hydrothermal coefficient of G.T. Selyaninov (HCS), developed and implemented for agricultural climate assessment in the 1920s–1930s, as an indicator of heat and moisture availability in the territory of the active growing season. In addition, HCS is included in the World Meteorological Organization (WMO) Handbook of Indicators and Indices of Aridity published in 2016 [41]. With the help of this indicator, arid or overwatered conditions can be identified. The HCS is calculated using the following formula:

$$\mathrm{HCS} = 10 \times \mathrm{R}_{\geq 10^{\circ}\mathrm{C}} / \Sigma \mathrm{T}_{\geq 10^{\circ}\mathrm{C}}, \quad (1)$$

where R is the sum of precipitation for the period with average daily temperatures above 10 °C (mm), and $\Sigma T \geq 10$ °C is the sum of average daily air temperatures for the same period (°C). A period is considered as dry when HCS is less than 1.0 and arid when HCS is less than 0.5.

The Ped index takes into account abnormal weather conditions that are most important for drought formation, such as anomalies of air temperature, precipitation, and soil moisture [42,43]. Subsequently, the index was refined for warm (summer) and cold (winter) conditions [44]:

$$S_{Si} = \frac{\Delta T_i}{\Delta \sigma_{Ti}} - \frac{\Delta R_i}{\Delta \sigma_{Ri}} \quad (2)$$

$$S_{Wi} = \frac{\Delta T_i}{\Delta \sigma_{Ti}} + \frac{\Delta R_i}{\Delta \sigma_{Ri}} \quad (3)$$

where S_S—summer Ped index, S_W—winter Ped index, ΔT—air temperature anomaly, ΔR—precipitation anomaly, σT and σR—mean square deviations of air temperature and precipitation at point i, respectively. Aridity conditions in the warm period are characterised by values of SS $\geq$ 2, and when SS ≤ -2, excess moisture availability is observed. If in the cold period SW > 2, the winter is considered mild (warm and snowy), if SW < −2, it is severe (cold and snowy). Gradations of the S index are given in detail in Table 1.

Table 1. Gradations of the Ped aridity index [45].

Season of the Year	S_i Gradations	Weather and Climate Conditions
Warm period	$S_i \geq 3$	severe drought
	$3 > S_i > 2$	average drought
	$1 < S_i \leq 2$	dry conditions (mild drought)
	$-1 \leq S_i \leq 1$	normal moisturising conditions
	$-2 \leq S_i < -1$	humid conditions (low excessive moisture)
	$-3 < S_i < -2$	medium excessive moisturisation
	$S_i \leq -3$	severe overhydration
Cold period	$S_i > 2$	warm and snowy winter
	$S_i < -2$	cold and snowy winter

For the calculations of agroclimatic indicators, the data of observations are derived from 1961 to 2020 at 30 meteorological stations of the Republic. They are part of the network of the Bashkir Department of Hydrometeorology and Environmental Monitoring [46].

To analyse the temporal variability of the studied meteorological quantity, its main statistical characteristics were calculated for the main study period (1961–2020), as well as for the base periods recommended by WMO (1961–1990, 1981–2010, and 1991–2020): mean values (climatic norms), maximums, and minimums.

We used trend analysis and correlation analysis to assess changes in the regional climate. The trend line slope coefficient (TLSC) was used to estimate the rate of change in the studied value, its growth (increase), or decrease. The value of the determination coefficient r^2 assessed the contribution of the linear trend to the total variability of the indicator. The reliability of the results was assessed using Fisher's criteria. In the calculation table (Table 2), significant coefficients are highlighted in bold (at the confidence level of $p < 0.05$).

In order to adapt the agricultural sector to climate change, it is important to make a forecast of future changes. The results obtained in our study were compared with the data presented in the database Copernicus Climate Change Service «Agroclimatic indicators from 1951 to 2099 derived from climate projections» [47] (Figure 2).

Table 2. Agro-climatic indicators on the territory of the Republic of Bashkortostan (1961–2020). Data source [46].

Agro-Climatic Indicator	Mean, °C	Maximum, °C (Year)	Minimum, °C (Year)	TLSC, °C/10 Years
$\Sigma T \geq 0$ °C (°C)	2575	3228 (2012)	2181 (1969)	**58.4**
$\Sigma T \geq 10$ °C (°C)	2250	2926 (2012)	1804 (1986)	**54.4**
HCS	1.12	2.0 (1994)	0.4 (2010)	0.003

Note: Bold font indicates statistically significant TLSC at the $p < 0.05$ confidence level.

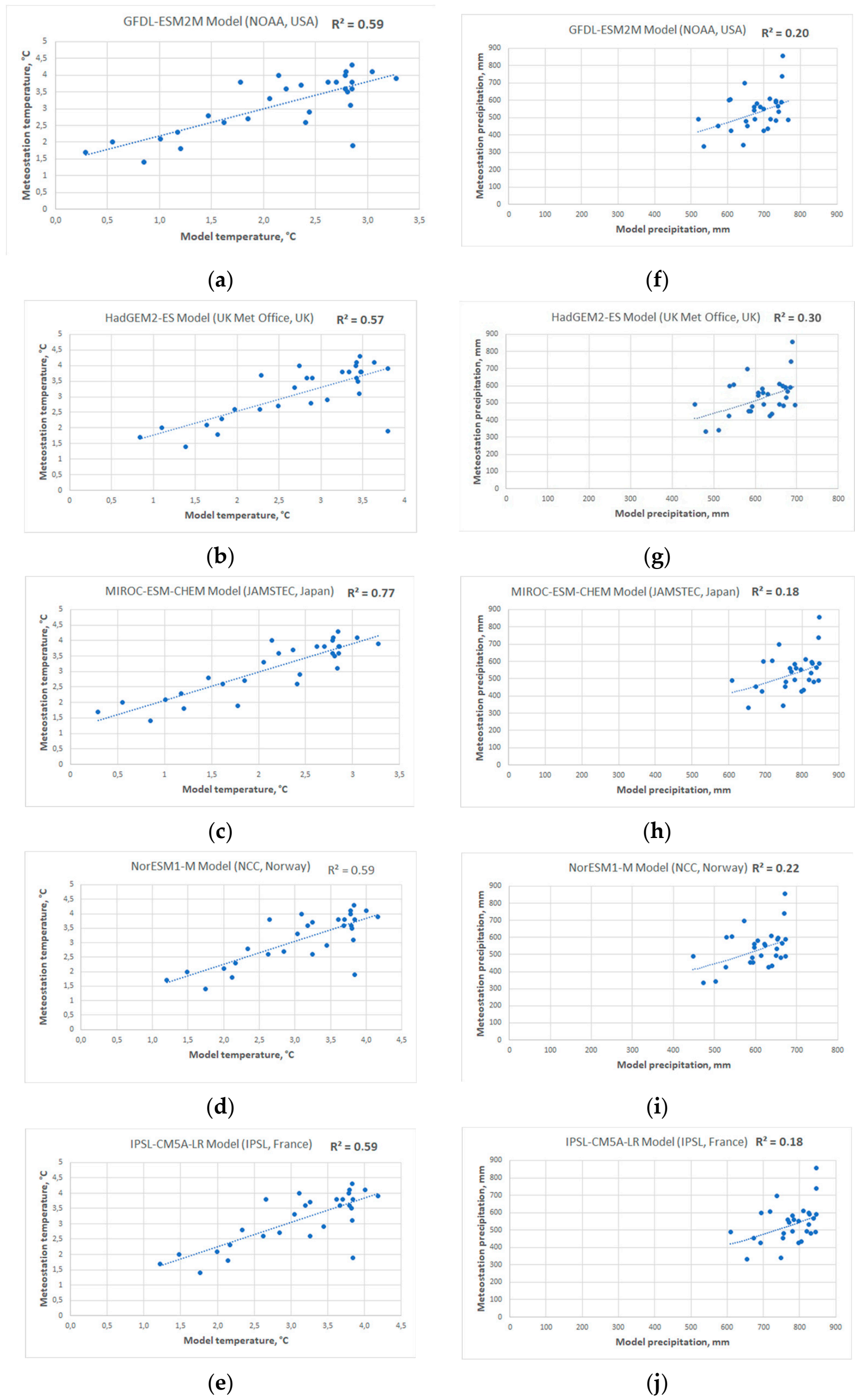


Figure 2. Correlation of the RB meteorological station data and climate models for annual mean temperature (**a**–**e**) and annual precipitation sum (**f**–**j**) for 1981–2010. Data source [47].

The data were uploaded to the geoinformation project (QGIS 3.14.16). Raster statistics were extracted. The correlations between our data and the data from the database "Agroclimatic indicators from 1951 to 2099 derived from climate projections" were estimated. Such indicators, such as precipitation sum and mean temperatures, were estimated for both the period of 1961–2010 and the periods of 2011–2040, 2041–2070, and 2071–2099 for scenarios RCP 2.6., RCP 4.5., RCP 6.0, and RCP 8.5.

The spatial resolution of the data was $0.5^\circ \times 0.5^\circ$. Previously, for each of the models presented in the dataset, a regression analysis of the relationship with the results of our research for the period of 1981–2010 was carried out. The greatest correlation with our data was demonstrated by the HadGEM2-ES Model (UK Met Office, Exeter, UK) (Figure 2g) for the amount of precipitation ($r^2 = 0.30$). The MIROC-ESM-CHEM Model (JAMSTEC, Tokyo, Japan) (Figure 2c) was more suitable for the average annual temperature ($r^2 = 0.77$).

Regression equations were calculated for each model, according to which the forecast data for different climatic scenarios were refined.

Equation (4) was used to calculate the amount of precipitation:

$$Y = 200.09e^{0.0567x}, \quad (4)$$

Equation (5) was used to calculate the average annual temperature:

$$Y = 0.9179x - 249.58, \quad (5)$$

3. Results

The results of calculations of the sums of average daily air temperatures above 0 °C, presented in Table 2, show that the $\Sigma T \geq 0$ °C average on the territory of the Republic is 2575 °C. Its value increases from north to south from 2341 to 2839 °C, decreasing in the mountainous part to 2145 °C.

In the studied period, the minimum $\Sigma T \geq 0$ °C occurred mainly in 1969, at some meteorological stations in 1964, 1978, and 1992. In 1969, the values of this index were the lowest for most part of the territory and varied from 1794 °C in the mountainous part to 2407 °C in the southern part of the Urals. Maximum $\Sigma T \geq 0$ °C was almost observed everywhere in 2012 (except for 2010 and 2019—one case each): from 2818 °C to 3621 °C.

The main trend of $\Sigma T \geq 0$ °C in 1961–2020 is its significant increase at a rate of 58.4 °C/10 years (Figure 3). The largest increase was found at the southern meteorological stations of the Trans-Urals (83.7 °C/10 years) and the Pre-Urals (71.1–82.2 °C/10 years), while the lowest values were found in the northern parts of the Pre-Urals, Trans-Urals, and Southern Urals (TLSC from 39 to 48 °C/10 years). Accordingly, the maximum changes occur in the southern part of the republic and the minimum in the northern part. All trends are statistically significant, except for the meteorological station Meleuz.

When considering the WMO base over thirty years (Figure 3a), we came to the conclusion that the highest growth rate of $\Sigma T \geq 0$ °C was characteristic of the period of 1981–2010 and was 79.1 °C/10 years (Figure 3b).

The sum $\Sigma T \geq 10$ °C (or the sum of active temperatures) averages 2250 °C in the republic. Its lowest values are in the mountainous part (1771–1883 °C), which can be explained by a shorter warm period.

The minimum $\Sigma T \geq 10$ °C was detected mainly in 1986, and also in 1969, 1973, 1992, and 2002. The record low $\Sigma T \geq 10$ °C was observed in the mountainous part at the weather station of the Bashkir State Reserve and was 1278 °C (1969). The maximum $\Sigma T \geq 10$ °C occurred mainly in 2012, and also at some meteorological stations—in 1995, 1999, and 2016. The highest values of this indicator were found at the meteorological stations in the south of the Trans-Urals (3297 °C) and the south of the Pre-Urals (3239–3297 °C).

The trends of multiyear variations of $\Sigma T \geq 10$ °C indicate its steady increase by 54.4 °C/10 years. For all meteorological stations, the trends are statistically significant. TLSC values increase predominantly in the southern direction. The highest

TLSC ΣT ≥ 10 °C is typical for meteorological stations of the southern part of the Trans-Urals (77.4 °C/10 years) and the Pre-Urals (75.4 °C/10 years).

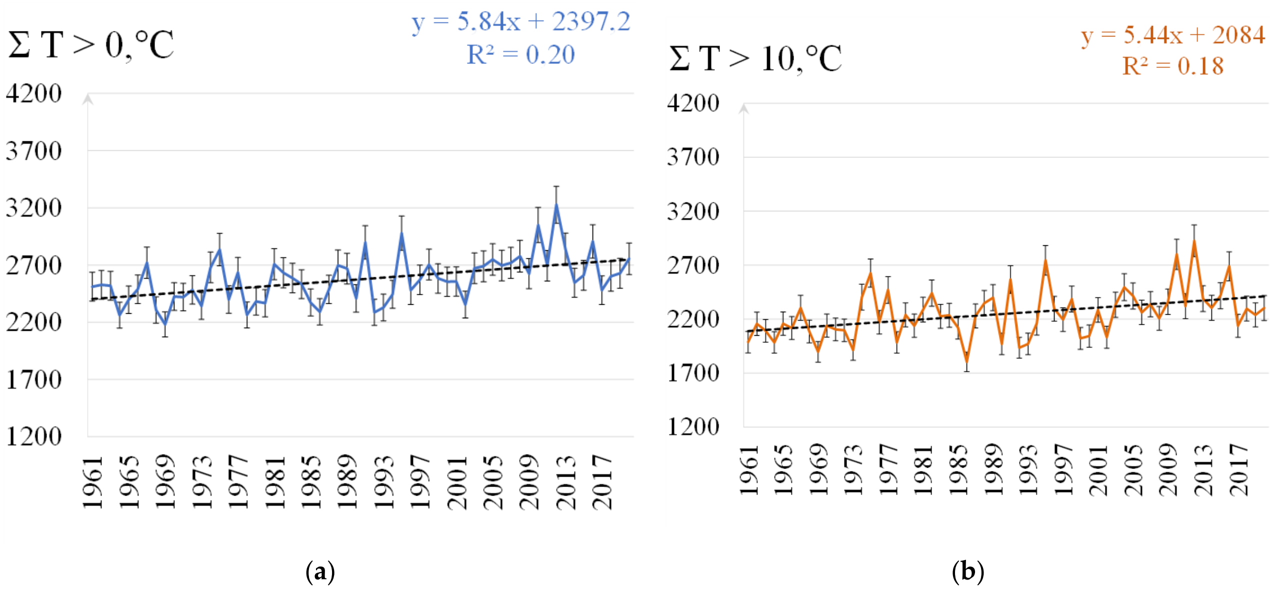


Figure 3. Multiyear course of ΣT ≥ 0 °C (**a**) and ΣT ≥ 10 °C (**b**), averaged in the Republic of Bashkortostan for different periods. The error bars is displayed as a %. Data source [46].

The main reason for the revealed tendency of ΣT ≥ 0 °C and ΣT ≥ 10 °C growth is both the steady increase in air temperature in the region and the increase in the duration of warm and summer periods.

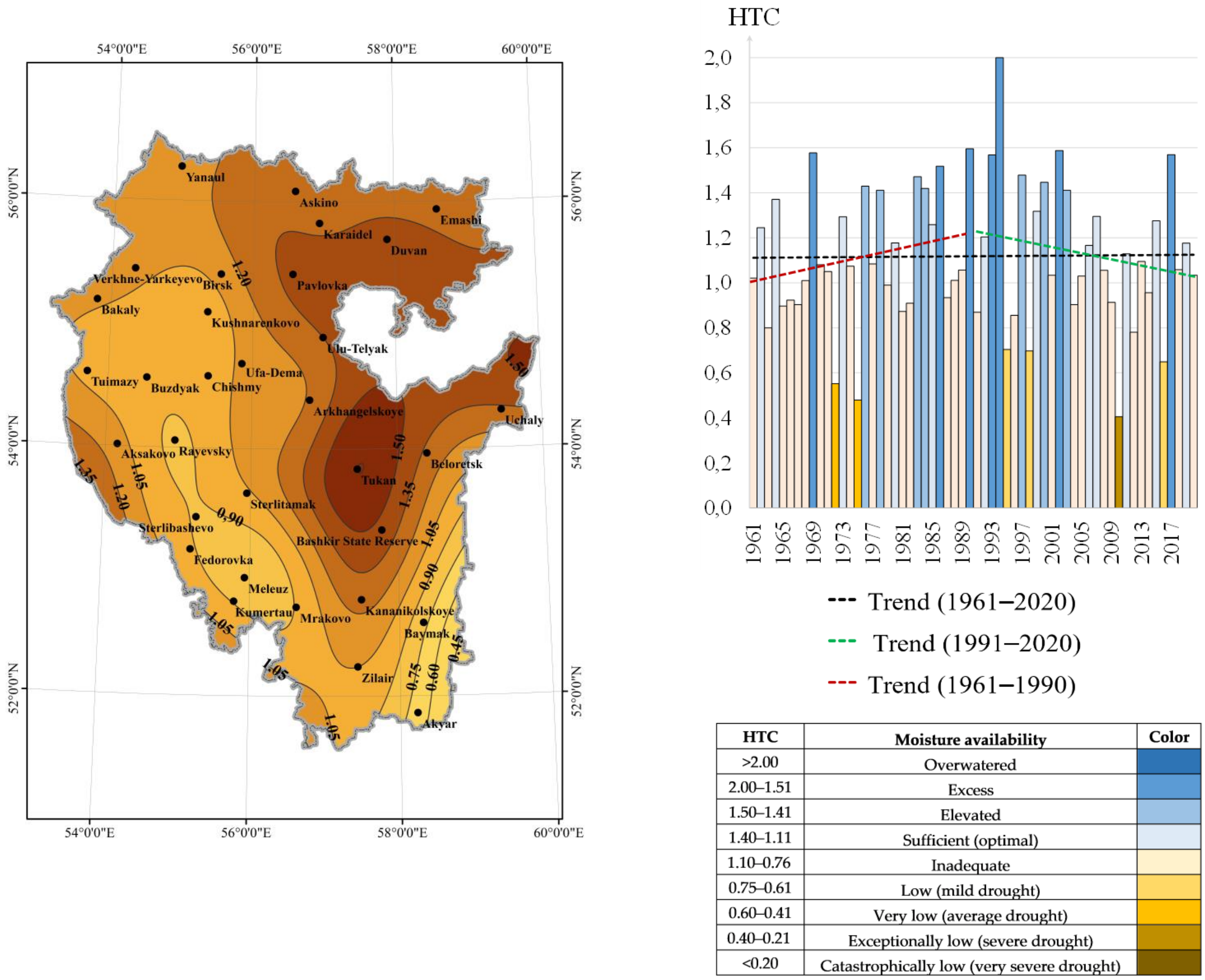
Increase in heat energy leads to an increase in the evapotranspiration potential. The evapotranspiration value affects the moisture availability of the territory and the conditions of moisture consumption by crops. Evapotranspiration or its dependent characteristics are mainly used in hydrothermal indices.

The analysis of HCS dynamics revealed that in the republic, its average TLSC in 1961–2020 is 0.003 units/10 years. At 19 stations located predominantly in the northern part of the republic, positive HCS trends were detected. At the southern stations, mainly negative TLSC HCS were detected. The value of this indicator varies in the republic from −0.07 to 0.05 units/10 years.

When comparing the changes in HCS in the periods of 1961–1990 and 1991–2020 (Figure 4), it is revealed that their trends are multidirectional. In the first thirty years, it is positive (0.08 units/10 years), and in the second, negative (−0.08 units/10 years). In the latter case, according to the data of 24 meteorological stations, the TLSC HCS are negative.

The recurrence of years with excessive moisture and droughts was calculated (Figure 5). The highest recurrence of years with excessive moisture is characteristic of the central part of the Southern Urals (15–20%). In the forest–steppe and steppe regions of the Urals and Trans-Urals, there are practically no years with such conditions. It was found that the highest frequency of years with droughts of different intensity is observed in the southern part of the Trans-Urals (up to 60%), as well as in the southern part of the Urals (20–30%).

The dynamics of the S index for the Republic in 1966–2020 for some months and for a year is presented in Figure 5, which shows its increase in all seasons. It was revealed that there is a steady increase in the annual S index in the republic (at 24 stations, the trends are statistically significant).



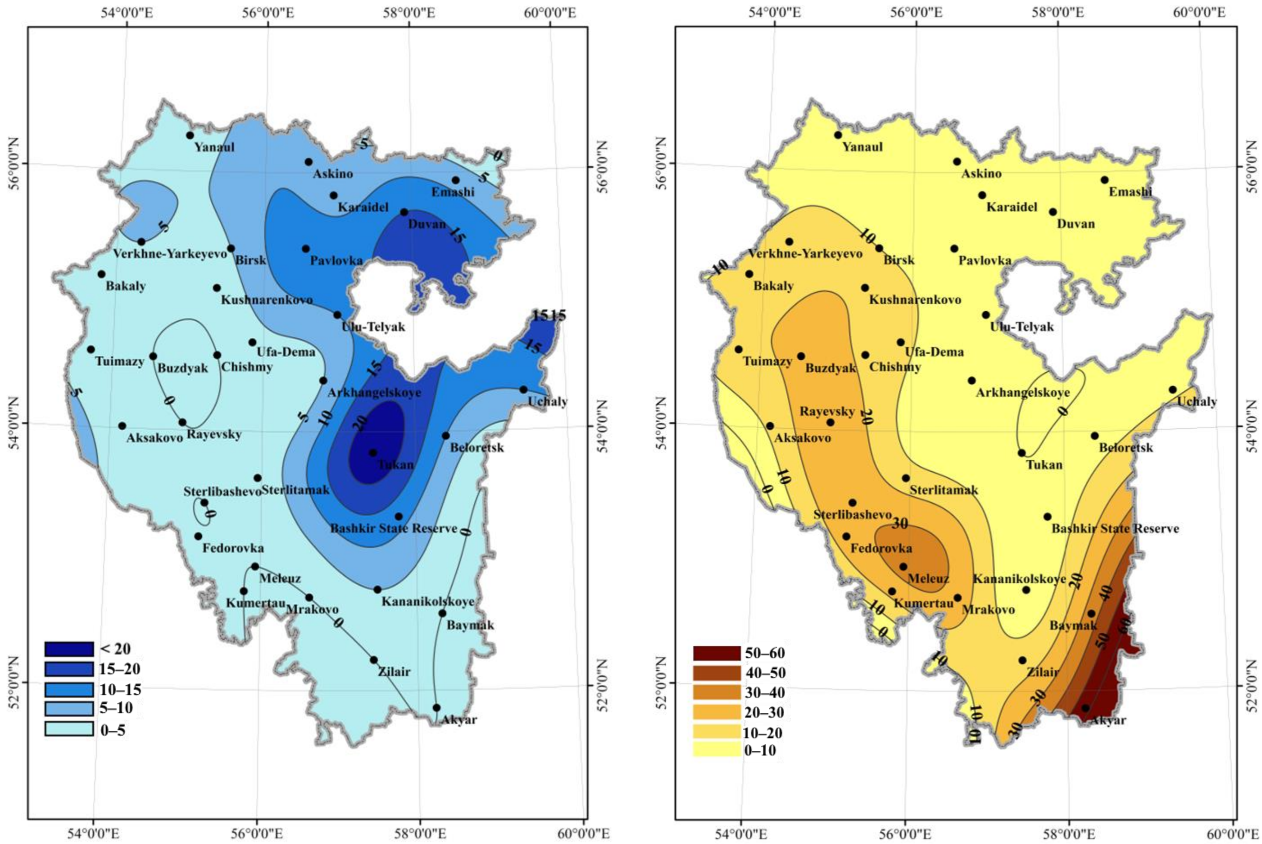
HTC	Moisture availability	Color
>2.00	Overwatered	
2.00–1.51	Excess	
1.50–1.41	Elevated	
1.40–1.11	Sufficient (optimal)	
1.10–0.76	Inadequate	
0.75–0.61	Low (mild drought)	
0.60–0.41	Very low (average drought)	
0.40–0.21	Exceptionally low (severe drought)	
<0.20	Catastrophically low (very severe drought)	

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

Figure 4. Spatial (**a**) and temporal (**b**) distribution of hydrothermal coefficient of G.T. Selyaninov in the Republic of Bashkortostan for 1961–2020. Data source [46].

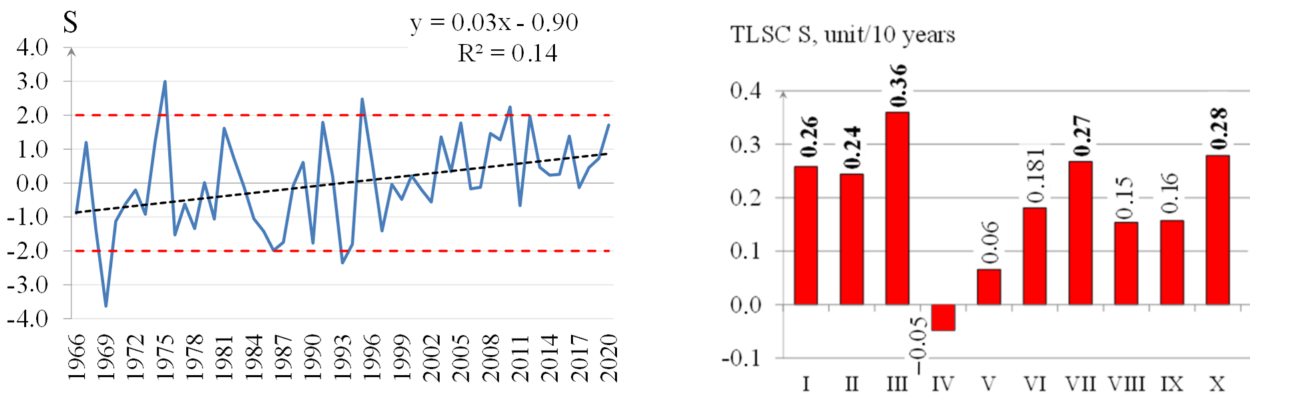
On the territory of the RB, the TLSC of S index values on average increase in the southern direction. The average value of TLSC of the S index for a year is 0.320 units/10 years. The most significant growth of the S index is observed within the range of the Southern Urals and is 0.426 units/10 years. In the Trans-Urals and Pre-Urals, the TLSC of the S index is 0.376 and 0.282 units/10 years, respectivel. The highest values of TLSC of the S index were observed at meteorological stations in the Southern Urals and Trans-Urals (from 0.419 units/10 years to 0.572 units/10 years).

Trends of the S index by months differ significantly (Figure 6). Statistically significant S index trends were found in March (0.360 units/10 years), October (0.279 units/10 years), July (0.268 units/10 years), January (0.258 units/10 years), and February (0.244 units/10 years). Negative TLSC values of the S index were found only in April (−0.048 units/10 years).



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

Figure 5. Repeatability (%) of years with excessive moisture (**a**) and droughts (**b**) in the Republic of Bashkortostan for 1961–2020. Data source [46].



Note 1:

- - - - - - *S criteria less than −2 and greater than 2*

Note 2: Statistically significant TLSC at the p < 0.05 level of confidence are in bold type

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

Figure 6. Perennial course averaged in the Republic of Bashkortostan Ped aridity index per year (**a**) and its TLSC (units/10 years) by month (**b**) for 1966–2020. Data source [46].

The highest number of droughts were recorded in June (eight occurrences), April (six occurrences), May, and August (five occurrences each), based on an analysis of aggregate S index data.

Summarising the results obtained on the changes in agroclimatic characteristics of the warm period, we can conclude that more arid conditions are increasing on the territory of the Republic, especially in the southern parts of the Urals and Trans-Urals. Droughts are more intensively manifested in the southern parts of the RB.

We also reviewed official statistical data on the application of mineral fertilisers for crops in the republic [40]. Unfortunately, data on fertilisation has been available only since 2008. Correlations between yield and the amount of fertilisers applied are not significant (with cereals r = 0.25; with industrial crops r = −0.002; with oilseeds r = 0.25; and with potatoes r = 0.05). A total of 39.8 thousand crops are irrigated in the republic. The ha of plots, which is only 0.5% of agricultural land (according to the 2021 data) [48], is a catastrophically small amount to maintain yields. Therefore, the main attention was paid to the interrelationships of productivity with agro-climatic indicators.

Calculations of the correlation coefficients between agro-climatic indicators and the yield of the main crops grown in the RB in the period of 2000–2020 are presented in Table 3.

Table 3. Correlation coefficients between crop yields and agro-climatic indicators in the Republic of Bashkortostan (2000–2020). Data source [38,40,46].

Indicator	Agricultural Crop	IV	V	VI	VII	VIII	IX	X	V.P.	T.P.	Year
Air temperature	Cereals	−0.40	−0.27	**−0.59**	−0.16	−0.21	0.09	0.31	**−0.53**	**−0.44**	−0.08
	Technical	−0.05	0.10	−0.04	−0.04	−0.13	−0.11	0.13	−0.08	−0.04	0.21
	Oilseeds	−0.21	−0.05	−0.04	−0.11	−0.23	−0.08	0.32	−0.23	−0.14	0.09
	Vegetables (potatoes)	**−0.49**	0.04	−0.36	−0.28	−0.35	−0.04	0.33	**−0.50**	−0.40	−0.18
Sum of temperatures	Cereals								**−0.43**	**−0.47**	
	Technical								−0.03	−0.12	
	Oilseeds								−0.14	−0.25	
	Vegetables (potatoes)								−0.39	−0.38	
Precipitation sum	Cereals	0.21	**0.50**	0.18	0.31	−0.23	0.14	−0.04	**0.43**	0.38	0.33
	Technical	**0.44**	−0.21	−0.21	**0.55**	**0.43**	0.18	−0.05	0.40	0.30	0.22
	Oilseeds	**0.52**	0.05	−0.21	**0.76**	0.25	0.14	−0.25	**0.53**	0.35	0.13
	Vegetables (potatoes)	0.33	0.06	−0.12	**0.51**	0.25	0.11	0.04	0.40	0.35	0.23
HCS	Cereals								**0.45**		
	Technical								0.04		
	Oilseeds								0.17		
	Vegetables (potatoes)								0.23		
Ped S index	Cereals	−0.36	**−0.42**	**−0.46**	−0.27	−0.08	−0.02	0.18	**−0.56**	**−0.47**	−0.24
	Technical	−0.35	0.16	0.09	−0.30	−0.25	−0.17	0.11	−0.24	−0.19	0.01
	Oilseeds	**−0.49**	−0.06	0.09	**−0.44**	−0.26	−0.13	0.34	−0.40	−0.27	0.01
	Vegetables (potatoes)	**−0.52**	−0.01	−0.16	**−0.46**	−0.35	−0.09	0.15	**−0.57**	**−0.43**	−0.18

Note 1: Statistically significant correlation coefficients at the $p < 0.05$ level of confidence are shown in bold. Note 2: V.P.—vegetation period (T > 5 °C), T.P.—warm period (T > 0 °C); Note 3: background—for the specified months (periods), the indicator is not calculated.

Analysis of calculations of Table 3 showed that the closest positive relationships were found between the sum of precipitation and the yield of technical, oilseed, and cereals, especially due to the strong relationship in July with oilseed and technical crops (r = 0.76 and r = 0.55, respectively), and in May, with grain crops (r = 0.50). Closer relationships for the first types of crops were found during the growing season. Potato yield has a significant correlation with precipitation in July (r = 0.51). Thus, the largest number of significant pairwise correlation coefficients were found for precipitation.

The strongest negative relationships were found between the yield of cereals, potatoes, and the Ped S index in the growing season (r = −0.56 and r = −0.57, respectively). For cereals, significant relationships were found in May and June, and for potatoes and oilseeds, in April and July.

Direct significant relationships were found between cereals yield and HCS (r = 0.45).

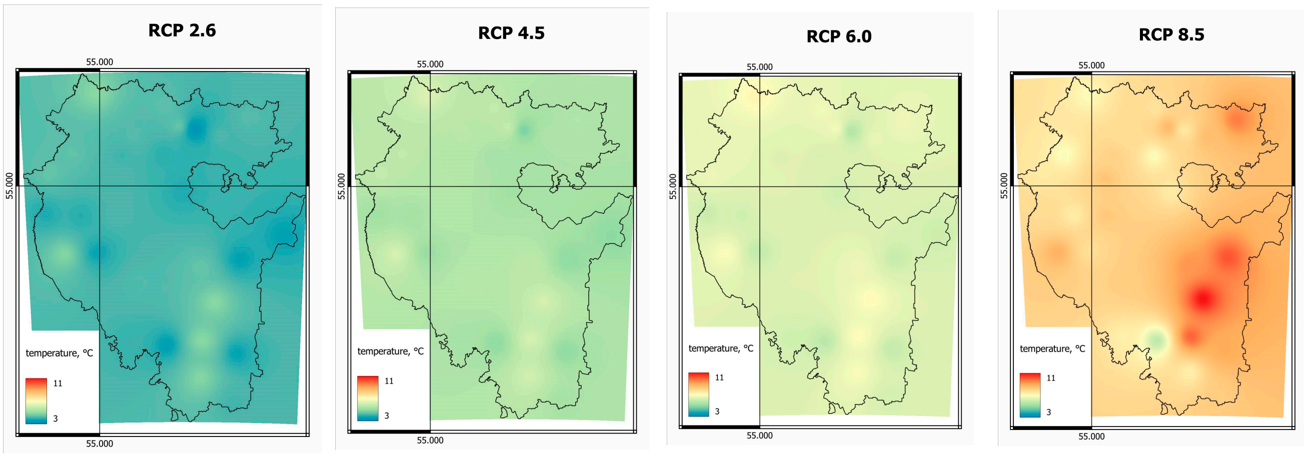
Between air temperature and yield of grain crops, significant negative relationships were established in June (r = −0.59), and for potatoes, in April (r = −0.49). Similar correlations were observed for these crops in vegetation and warm periods.

An analysis of the implementation of climate scenarios using the HadGEM2-ES Model (UK Met Office, Exeter, UK) and MIROC-ESM-CHEM Model (JAMSTEC, Tokyo, Japan) showed a steady increase in annual mean temperature in the republic for the period of 2071–2099 (Table 4). Only in the case of the RCP2.6 scenario, the increase in the first 30 years is higher than in the RCP 4.5 and 6.0 scenarios, but in the next 60 years, it is slower than in the other scenarios (Table 4). The spatial changes in the mean annual temperature relative to the period of the 1961–1990 temperature distribution for the RCP 2.6, 4.5, and 6.0 scenarios demonstrate a significant warming of the eastern part of the republic (Figure 7a–d). According to the RCP 8.5 scenario, the temperature distribution is uniform, except for small areas in the south of the RB (Figure 7d).

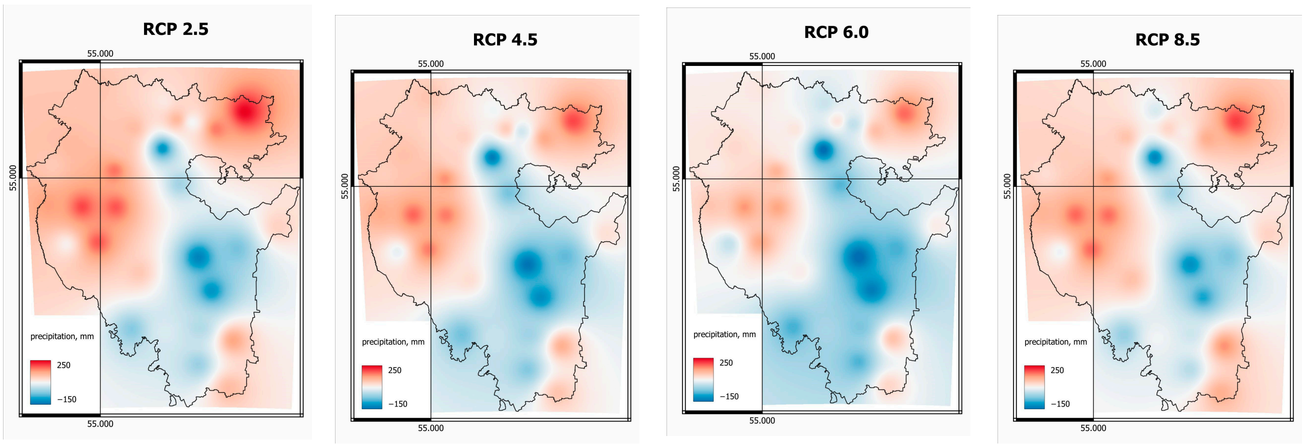
Table 4. The value of the mean annual temperature and mean annual precipitation sum under different climatic scenarios in the periods of 2011–2040; 2041–2070; and 2071–2099. Data source [47].

Period	Mean of Daily Mean Temperature, °C	Precipitation Sum, mm
	RCP 2.6	
2011–2040	5.84 ± 0.14	575.00 ± 11.00
2041–2070	6.81 ± 0.14	590.95 ± 11.95
2071–2099	6.66 ± 0.14	601.37 ± 13.24
	RCP 4.5	
2011–2040	5.17 ± 0.14	551.58 ± 10.80
2041–2070	7.12 ± 0.14	573.82 ± 10.58
2071–2099	8.01 ± 0.15	582.48 ± 12.19
	RCP 6.0	
2011–2040	5.19 ± 0.14	583.40 ± 11.53
2041–2070	7.76 ± 0.14	569.05 ± 11.02
2071–2099	8.87 ± 0.13	558.07 ± 11.77
	RCP 8.5	
2011–2040	5.9 ± 0.14	586.70 ± 11.70
2041–2070	8.14 ± 0.14	579.82 ± 12.54
2071–2099	10.65 ± 0.14	594.79 ± 11.39

The behaviour of the changes in the annual precipitation sum is the same for all scenarios (Table 4, Figure 7e–h). A decreasing precipitation trend is observed for the south and east area of the RB. Precipitation is predicted to have the largest decrease for the RCP 6.0 scenario (Figure 7g). It is consistent with the results of our studies for the period of 1961–2020.



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



(**e**) (**f**) (**g**) (**h**)

Figure 7. Distribution of changes in the mean annual temperature and annual precipitation sum relative to the period of 1961–1990 and on the territory of the Republic of Bashkortostan in the implementation of scenarios RCP 2.6 (**a**,**e**), RCP 4.5 (**b**,**f**), RCP 6.0 (**c**,**g**), and RCP 8.5 (**d**,**h**) for the period of 2071–2099. Data source [47].

4. Discussion

Agriculture is one of the most climate-dependent areas of the economy. In many regions of the planet [49–53], as in the Republic of Bashkortostan, there is a simultaneous increase in air temperature and aridity, which negatively affects crop yields. A study [54] shows that high temperatures have a negative impact on the production of corn and wheat in North America. Our study also demonstrated negative associations between the yields of cereals and potatoes. The reasons may be the influence of higher temperatures at the reproductive stage of development, and that may lead to a decrease in yield by 80–90% [55]. Modern studies in China describe the dependence of rice on temperature conditions [53]. Grain yield decreased by 10% with each increase in the minimum temperature of the growing season by 1 °C in the dry season.

On the other hand, an increase in the aridity of the climate is also the cause of crop failure, which is confirmed by many studies. Such effects were noted in Canada, Georgia [51,56], and other regions.

The relationship of climate change with crop yields is even more vividly demonstrated by agro-climatic indices. It should be noted that correlations may differ depending on the season and crops [57,58]. Thus, for the conditions of Canada, it was noted that July rains have a greater impact on the yield of rapeseed and spring wheat than rains in June [59].

A detailed analysis of agro-climatic indicators allows us to adjust the agro-climatic zoning of the region. Thus, in the Czech Republic, the revision of agro-climatic indicators from 1961 to 2000 revealed a change in agro-climatic zones [60]. It turned out that the most productive areas for growing non-irrigated crops have shifted to warmer and drier conditions. This led to a decrease in yields.

The analysis of agro-climatic indices for the territory of Poland showed a warming climate, an increase in vegetation and frost-free periods, and the sum of vegetation degrees-days [61]. The great importance of these trends is typical for the period of 1991–2010. The results of these studies are consistent with our results for the Republic of Bashkortostan.

Russia is characterised by the heterogeneity of manifestations of global climate change and the response of agricultural crops to them. According to the results of research by V.N. Pavlova et al. [62], the greatest climatic risks caused by a lack of moisture were noted in the Tambov and Lipetsk regions at 12%. In Russia as a whole, warming trends caused a decrease in the climatically determined yield of spring wheat by about 12% from 1976 to 2015, i.e., the rate of its decline was ~3% per decade [63].

The results of the study for the Ulyanovsk region [64] revealed a steady increase in the average annual air temperature, especially in the cold season. This led to an increase in the growing season, which affected the increase in crop productivity: barley has the greatest potential (8.3 t/ha), and rye has the least (6.4 t/ha). Our studies also showed a positive correlation between precipitation in the middle of the growing season (July) and oilseeds, industrial crops and potatoes, and at its beginning (May), with grain crops. However, despite the increase in the duration of the growing season in the Republic of Bashkortostan, the tendency to increase aridity will lead to a decrease in yield. Thus, the applied agrotechnical measures should be aimed at maintaining the conditions of the moisture regime for agricultural crops.

The analysis of climate indices is important for forecasting future climatic conditions and yields of various crops. Thus, when implementing the climate scenarios of RCP 4.5 and RCP 8.5, an increase in the aridity of the Ethiopian climate will be observed in 2060 and this will lead to a decrease in coffee yields [9].

The third assessment report on climate change and its consequences on the territory of the Russian Federation [65], as in our study, predicts an increase in temperature with a precipitation deficiency for the territory of the Volga Federal District in the implementation of all scenarios. The Volga Federal District includes the RB. The presence of negative correlations with potato and grain yields threatens this area of agriculture in the future. All types of crops correlate with precipitation amounts (Table 3). However, this indicator behaves differently in different climatic scenarios (Table 4). For RCP 2.6 and 4.5, there is an increase in precipitation; for RCP 6.0—a decrease in precipitation, and for RCP 8.5—a decrease and then an increase. A large amount of precipitation in the RCP 8.5 scenario compared to the RCP 6.0 scenario was also detected for other regions, for example, for China. It is assumed that the amount of precipitation is influenced by evotranspiration [66]. For the UK, there is also a lower value of precipitation for the RCP 6.0 scenario in some areas compared to the RCP 8.5 scenario. The authors of the study [67] associate this phenomenon with the high variability of precipitation in the UK. For the RB, this issue requires additional study. Nevertheless, we note that the greatest decrease is observed in the mountainous part of the republic, which is characterised by great climatic variability. It should also be noted that there are insufficient correlations between the HadGEM2-ES Model climate model (UK Met Office, Exeter, UK) and the results of observations of meteorological stations in the RB − r^2 = 0.30. Another important fact is that in different regions of the planet, climate modelling predicts an increase in prolonged droughts with episodes of intense precipitation [51,59,61]. Also, the trends of increasing aridity of the territory of the republic are shown by the HCS and the Ped index. These indicators show an increase in the aridity of the climate of the RB. In the RCP 6.0 scenario, cereals, oilseeds, and potatoes are at risk.

5. Conclusions

One of the important sectors of the economy of the RB is agriculture. Due to changes in climatic conditions, the most important agroclimatic characteristics in the Republic of Bashkortostan are changing. In the period of 1961–2020, the sums of average daily temperatures above 0 and 10 °C have a significant growth in the entire study area (58.4 and 54.4 °C/10 years, respectively). The highest growth rate of these indices is found in 1981–2010. It was found that in 1961–1990, the trend sign of the hydrothermal coefficient of G.T. Selyaninov was positive, but in 1991–2020, it becomes negative. Thus, at present, there is an intensification of aridity in areas where there is a steady increase in air temperature and a decrease in precipitation amounts, which is especially evident during the growing season. Analysis of the dynamics of the Ped aridity index showed that conditions become warmer in the cold period, winters are snowy, and in the warm period, it is more arid. Positive significant trends of the Ped index were revealed in the cold season, where the highest growth rate was established in March (0.360 units/10 years). In the warm period, the highest growth rate of the Ped index was found in October and June (0.279 and 0.268 units/10 years, respectively).

Similar changes with the increasing temperature and aridity of the territory are typical for other countries. Many studies also show that there are episodic heavy rains at the same time that drought is increasing. This topic is relevant for Belarus and requires additional study.

The process of climate warming significantly affects agroclimatic resources of Bashkortostan. It was revealed that the greatest influence on the yield of oilseeds (r = 0.52), cereals (r = 0.50) and industrial (r = 0.44) crops has atmospheric precipitation at the beginning of the growing season, as well as in July (r = 0.76, r = 0.31 and r = 0.55, respectively). Negative relationships are mostly found between air temperature and yield, with the greatest closeness between cereal crops (r = −0.53) and vegetables (r = −0.50) with the air temperature of the growing season. Similar relationships are found for these crops with the Ped index.

In order to effectively adapt to the current and future climate impacts on yields, it is necessary to assess temporal and spatial agro-climatic changes.

Scenario analysis has shown that there is a decrease in precipitation for the RCP 6.0 scenario. In this case, the existing trends pointing towards an increase in aridity and an increase in temperature will increase the negative impact on the development of crops. In order to effectively adapt to global climate change, attention should be paid to the spatial representation of climate scenarios. A greater decrease in precipitation is predicted for the southern part of the RB.

The information presented in the study will make it possible to more effectively adapt the agricultural sector to current and future climate changes.

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References

1. Deng, K.Q.; Azorin-Molina, C.; Yang, S.; Hu, C.D.; Zhang, G.F.; Minola, L.; Vicente-Serrano, S.; Chen, D. Shifting of Summertime Weather Extremes in Western Europe during 2012–2020. *Adv. Clim. Chang. Res.* **2022**, *13*, 218–227. [CrossRef]
2. Akimov, L.M. Trends in the Change of the Thermal Regime in Arid and Adjacent Territories of the European Part of Russia in the Summer Period. *Arid Ecosyst.* **2021**, *27*, 3–12. [CrossRef]
3. Lysenko, S.A.; Loginov, V.F. Multidecadal Oscillations of Temperature and Humidity Characteristics on the Territory of Belarus. *Issues Probl. Hydrometeorol. Dr.* **2020**, *4*, 39–50.
4. Perry, K.; Legg, W. *Sustainable Management of Water Resources in Agriculture*; Organisation for Economic Co-Operation and Development: Paris, France, 2010; p. 120.
5. Dosio, A.; Spinoni, J.; Migliavacca, M. Record-Breaking and Unprecedented Compound Hot and Dry Summers in Europe under Different Emission Scenarios. *Environ. Res. Clim.* **2023**, *2*, 045009. [CrossRef]
6. Omar, M.E.D.M.; Moussa, A.M.A.; Hinkelmann, R. Impacts of Climate Change on Water Quantity, Water Salinity, Food Security, and Socioeconomy in Egypt. *Water Sci. Eng.* **2021**, *14*, 17–27. [CrossRef]
7. Liu, Y.; Liu, Y.; Wang, W.; Fan, X.; Cui, W. Soil Moisture Droughts in East Africa: Spatiotemporal Patterns and Climate Drivers. *J. Hydrol. Reg. Stud.* **2022**, *40*, 101013. [CrossRef]
8. Shiferaw, B.; Tesfaye, K.; Kassie, M.; Abate, T.; Prasanna, B.M.; Menkir, A. Managing Vulnerability to Drought and Enhancing Livelihood Resilience in Sub-Saharan Africa: Technological, Institutional and Policy Options. *Weather Clim. Extrem.* **2014**, *3*, 67–79. [CrossRef]
9. Chalchissa, F.B.; Diga, G.M.; Feyisa, G.L.; Tolossa, A.R. Geospatial Variabilities and Trends in Extreme Agroclimatic Indicators in the Jimma Zone, Southwest Ethiopia. *Theor. Appl. Climatol.* **2024**, *155*, 229–247. [CrossRef]
10. Karimi, V.; Karami, E.; Keshavarz, M. Climate Change and Agriculture: Impacts and Adaptive Responses in Iran. *J. Integr. Agric.* **2018**, *17*, 1–15. [CrossRef]
11. Nissan, H.; Muñoz, Á.G.; Mason, S.J. Targeted Model Evaluations for Climate Services: A Case Study on Heat Waves in Bangladesh. *Clim. Risk Manag.* **2020**, *28*, 100213. [CrossRef]
12. Angom, J.; Viswanathan, P.K.; Ramesh, M.V. The Dynamics of Climate Change Adaptation in India: A Review of Climate Smart Agricultural Practices among Smallholder Farmers in Aravalli District, Gujarat, India. *Curr. Res. Environ. Sustain.* **2021**, *3*, 100039. [CrossRef]
13. Yang, Y.; Maraun, D.; Ossó, A.; Tang, J. Increased Spatial Extent and Likelihood of Compound Long-Duration Dry and Hot Events in China, 1961–2014. *Nat. Hazards Earth Syst. Sci.* **2023**, *23*, 693–709. [CrossRef]
14. Hao, Z.; Hao, F.; Xia, Y.; Feng, S.; Sun, C.; Zhang, X.; Fu, Y.; Hao, Y.; Zhang, Y.; Meng, Y. Compound Droughts and Hot Extremes: Characteristics, Drivers, Changes, and Impacts. *Earth-Sci. Rev.* **2022**, *235*, 104241. [CrossRef]
15. Arnell, N.W.; Freeman, A. The Effect of Climate Change on Agro-Climatic Indicators in the UK. *Clim. Chang.* **2021**, *165*, 1–26. [CrossRef]
16. Pavlova, V.N.; Perevodchikov, Y.P.; Karachentsova, A.A.; Tagirov, M.S.; Mirsaeva, N.A. Assessment of Agro-Climatic Resources and Yield of Spring Wheat in the Republic of Tatarstan. *Meteorol. Hydrol.* **2023**, *1*, 90–102. [CrossRef]
17. Georgopoulou, E.; Mirasgedis, S.; Sarafidis, Y.; Vitaliotou, M.; Lalas, D.P.; Theloudis, I.; Giannoulaki, K.D.; Dimopoulos, D.; Zavras, V. Climate Change Impacts and Adaptation Options for the Greek Agriculture in 2021–2050: A Monetary Assessment. *Clim. Risk Manag.* **2017**, *16*, 164–182. [CrossRef]
18. Ajjur, S.B.; Al-Ghamdi, S.G. Towards Sustainable Energy, Water and Food Security in Qatar under Climate Change and Anthropogenic Stresses. *Energy Rep.* **2022**, *8*, 514–518. [CrossRef]
19. Guo, C.; Dai, H.; Liu, X.; Wu, Y.; Liu, X.; Liu, Y. Impacts of Climate Change Mitigation on Agriculture Water Use: A Provincial Analysis in China. *Geogr. Sustain.* **2020**, *1*, 189–199. [CrossRef]
20. Qi, W.; Feng, L.; Yang, H.; Liu, J. Warming Winter, Drying Spring and Shifting Hydrological Regimes in Northeast China under Climate Change. *J. Hydrol.* **2022**, *606*, 127390. [CrossRef]
21. Syed, A.; Raza, T.; Bhatti, T.T.; Eash, N.S. Climate Impacts on the Agricultural Sector of Pakistan: Risks and Solutions. *Environ. Chall.* **2022**, *6*, 100433. [CrossRef]
22. Agyeman, R.Y.K.; Huo, F.; Li, Z.; Li, Y. Projected Changes in the Hotspots for Agriculturally Relevant Compound Events in Western Canada Cropping Regions under the RCP8.5 Scenario. *Q. J. R. Meteorol. Soc.* **2023**, *149*, 830–842. [CrossRef]
23. Chipanshi, A.; Berry, M.; Zhang, Y.; Qian, B.; Steier, G. Agroclimatic Indices across the Canadian Prairies under a Changing Climate and Their Implications for Agriculture. *Int. J. Climatol.* **2022**, *42*, 2351–2367. [CrossRef]
24. del Barrio, R.; Fernandez, E.; Brendel, A.S.; Whitney, C.; Campoy, J.A.; Luedeling, E. Climate Change Impacts on Agriculture's Southern Frontier—Perspectives for Farming in North Patagonia. *Int. J. Climatol.* **2021**, *41*, 726–742. [CrossRef]
25. Camarero, J.J.; Campelo, F.; Colangelo, M.; Valeriano, C.; Knorre, A.; Solé, G.; Rubio-Cuadrado, Á. Decoupled leaf-wood phenology in two pine species from contrasting climates: Longer growing seasons do not mean more radial growth. *Agric. For. Meteorol.* **2022**, *327*, 109223. [CrossRef]
26. Szyga-Pluta, K. Assessment of Changing Agroclimatic Conditions in Poland Based on Selected Indicators. *Atmosphere* **2022**, *13*, 1232. [CrossRef]
27. Ruosteenoja, K.; Räisänen, J.; Pirinen, P. Projected changes in thermal seasons and the growing season in Finland. *Int. J. Climatol.* **2011**, *31*, 1473–1487. [CrossRef]

28. Kang, J.; Yang, Z.; Yu, B.; Ma, Q.; Jiang, S.; Shishov, V.V.; Zhou, P.; Huang, J.-G.; Ding, X. An earlier start of growing season can affect tree radial growth through regulating cumulative growth rate. *Agric. For. Meteorol.* **2023**, *342*, 109738. [CrossRef]
29. Khan, V.M.; Vilfand, R.M.; Tishenko, V.A.; Emelina, S.V.; Gritsun, A.S.; Volodin, E.M.; Vorobiova, V.V.; Tarasevich, M.A. Assessment of changes in the temperature regime of Northern Eurasia for the next five years according to the INM RAS Earth system model forecasts and their possible consequences for agriculture. *Russ. Meteorol. Hydrol.* **2023**, *9*, 14–28. [CrossRef]
30. Dai, S.; Shulski, M.D.; Hubbard, K.G.; Takle, E.S. A spatiotemporal analysis of Midwest US temperature and precipitation trends during the growing season from 1980 to 2013. *Int. J. Climatol.* **2016**, *36*, 517–525. [CrossRef]
31. Chen, X.; Pan, W. Relationships among phenological growing season, time-integrated normalized difference vegetation index and climate forcing in the temperate region of eastern China. *Int. J. Climatol.* **2002**, *22*, 1781–1792. [CrossRef]
32. AR6 IPCC. Climate Change 2021: The Physical Science Basis. Available online: https://www.ipcc.ch/assessment-report/ar6/ (accessed on 2 November 2023).
33. Cherenkovaa, E.A.; Semenova, V.A. A New Approach to Identifying the Influence of Climate Extreme on the Reduction of Wheat Yield in the South of European Russia. *Dokl. Earth Sci.* **2021**, *500*, 88–94. [CrossRef]
34. Semenov, S.M. (Ed.) *Methods for Assessing the Effects of Climate Change on Physical and Biological Systems*; Roshydromet: Moscow, Russia, 2012; p. 512.
35. Pavlova, V.N.; Karachenkova, A.A. Observed Climate Changes and Dynamics of Agro-Climatic Resources in the XX-XXI Centuries on the Territory of the Volga Federal District. *Proc. Main Geophys. Obs. Named A. I. Voeykov* **2016**, *583*, 112–128.
36. Sinitsina, N.I.; Goltsberg, I.A.; Strunnikov, E.A. *Agroclimatology*; Hydrometeoizdat: Leningrad, Russia, 1973; p. 344.
37. Galimova, R.G. Analysis of Changes in Temperature and Humidity Regime in the Republic of Bashkortostan in Recent Period. *Bull. Udmurt Univ. Ser. Biol. Earth Sci.* **2020**, *30*, 83–93. [CrossRef]
38. Territorial Body of the Federal State Statistics Service for the Republic of Bashkortostan. Available online: https://02.rosstat.gov.ru/storage/mediabank/Mesto-Respubliki-Bashkortostan-sredi-subektov-Rossiyskoy-Federacii-za-2022-god.pdf (accessed on 10 August 2023).
39. Lamy, K.; Portafaix, T.; Josse, B.; Brogniez, C.; Godin-beekmann, S.; Revell, L.; Akiyoshi, H.; Bekki, S.; Hegglin, M.I.; Deushi, M.; et al. Ultraviolet Radiation Modelling Using Output from the Chemistry Climate Model Initiative. *Atmos. Chem. Phys.* **2018**, *19*, 10087–10110. [CrossRef]
40. Federal State Statistics Service/Republic of Bashkortostan/Agriculture, Hunting and Forestry. Available online: http://bashstat.gks.ru/wps/wcm/connect/rosstat_ts/bashstat/ru/statistics/enterprises/agriculture/ (accessed on 1 August 2023).
41. Guidelines of the World Meteorological Organization for the Calculation of Climate Norms. Available online: https://library.wmo.int/doc_num.php?explnum_id=4168 (accessed on 1 August 2023).
42. Sadokov, V.P.; Neushkin, A.I.; Kozeltseva, V.F.; Kuznetsova, N.N. Summer Drought (May–August 1949–1999) on the Territory of the Former USSR. *Proc. GMC RF* **2001**, *336*, 3–33.
43. Edelgeriev, R.S.-H. *National Report "Global Climate and Soil Cover of Russia: Manifestations of Drought, Prevention, Control Measures, Elimination of Consequences and Adaptive Measures (Agriculture and Forestry)"*; Limited Liability Company "MBA Publishing House": Moscow, Russia, 2021; p. 700.
44. Galimova, R.G.; Perevedentsev, Y.P.; Yanaev, G.A. Agro-Climatic Resources of the Republic of Bashkortostan. *Proc. Vor. State Univ. Ser. Geogr. Geoecology* **2019**, *3*, 29–39.
45. Perevedentsev, Y.P.; Sharipova, R.B.; Vazhnova, N.A. Agroclimatic Resources of the Ulyanovsk Region and Their Impact on the Yield of Crops. *Bull. Udmurt Univ. Ser. Biol. Earth Sci.* **2012**, *2*, 120–126.
46. Nobakht, M.; Beavis, P.; O'Hara, S.; Hutjes, R.; Supit, I. *Agroclimatic Indicators from 1951 to 2099 Derived from Climate Projections*; 2019. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Available online: https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.dad6e055?tab=overview (accessed on 23 November 2023).
47. *Materials of the Bashkir Department of Hydrometeorology and Environmental Monitoring*, 1961–2020.
48. Komissarov, A.V.; Khafizov, A.R.; Ishbulatov, M.G.; Khazipova, A.F. Current State and Prospects for the Development of Irrigated Agriculture in the Republic of Bashkortostan. *Melior. Water Manag.* **2022**, *1*, 22–26. [CrossRef]
49. Meladze, G.; Meladze, M. Agroclimatic Zone Scenarios of the Distribution of Crops with Account of Global Warming. *Bull. Georgian Natl. Acad. Sci.* **2009**, *1*, 151–155.
50. Maurya, H.K.; Joshi, N.; Swami, D.; Suryavanshi, S. Change in Temperature Extremes over India Under 1.5 °C and 2 °C Global Warming Targets. *Theor. Appl. Climatol.* **2023**, *152*, 57–73. [CrossRef]
51. Agyeman, R.; Huo, F.; Li, Z.; Li, Y. Modeled Changes in Selected Agroclimatic Indices over the Croplands of Western Canada under the RCP8.5 Scenario. *Q. J. R. Meteorol. Soc.* **2021**, *152*, 4188. [CrossRef]
52. Chalchissa, F.B. Assessments of Extreme Agroclimatic Indicators and Climate. Ph.D. Thesis, Jimma University, Jima, Ethiopian, 2023.
53. Peng, S.; Huang, J.; Sheehy, J.E.; Laza, R.C.; Visperas, R.M.; Zhong, X.; Centeno, G.S.; Khush, G.S.; Cassman, K.G. Rice Yields Decline with Higher Night Temperature from Global Warming. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 9971–9975. [CrossRef]
54. Vogel, E.; Donat, M.G.; Alexander, L.V.; Meinshausen, M.; Ray, D.K.; Karoly, D.; Meinshausen, N.; Frieler, K. The Effects of Climate Extremes on Global Agricultural Yields. *Environ. Res. Lett.* **2019**, *14*, 054010. [CrossRef]
55. Hatfield, J.L.; Prueger, J.H. Temperature Extremes: Effect on Plant Growth and Development. *Weather Clim. Extrem.* **2015**, *10*, 4–10. [CrossRef]

56. Meladze, G.; Meladze, M. Influence of Global Warming on Agroclimatic Indices of Agriculture and Intensity of Droughts in Kakheti Region, East Georgia. *Bull. Georg. Natl. Acad. Sci.* **2016**, *10*, 97–104.
57. Carew, R.; Meng, T.; Florkowski, W.J.; Smith, R.; Blair, D. Climate Change Impacts on Hard Red Spring Wheat Yield and Production Risk: Evidence from Manitoba, Canada. *Can. J. Plant Sci.* **2017**, *98*, 782–795. [CrossRef]
58. Meng, T.; Carewa, R.; Florkowski, W.J.; Klepacka, A.M. Analyzing Temperature and Precipitation Influences on Yield Distributions of Canola and Spring Wheat in Saskatchewan. *J. Appl. Meteorol. Climatol.* **2017**, *56*, 897–913. [CrossRef]
59. Agyeman, R.Y.K.; Huo, F.; Li, Z.; Li, Y.; Elshamy, M.E.; Hwang, Y. Impact of Climate Change under the RCP8.5 Emission Scenario on Multivariable Agroclimatic Indices in Western Canada from Convection-Permitting Climate Simulation. *Anthropocene* **2023**, *44*, 100408. [CrossRef]
60. Trnka, M.; Balek, J.; Brázdil, R.; Dubrovský, M.; Eitzinger, J.; Hlavinka, P.; Chuchma, F.; Možný, M.; Prášil, I.; Růžek, P.; et al. Observed Changes in the Agroclimatic Zones in the Czech Republic between 1961 and 2019. *Plant Soil Environ.* **2021**, *67*, 154–163. [CrossRef]
61. Graczyk, D.; Kundzewicz, Z.W. Changes of Temperature-Related Agroclimatic Indices in Poland. *Theor. Appl. Climatol.* **2016**, *124*, 401–410. [CrossRef]
62. Pavlova, V.N.; Karachenkova, A.A. Assessment of Changes in Climate-Based Productivity of Summer Wheat in the Main Regions of Its Cultivation in Russia. *Fundam. Appl. Climatol.* **2020**, *4*, 68–87. [CrossRef]
63. Pavlova, V.N.; Karachenkova, A.A.; Varcheva, S.E. Regional Monitoring of Agro-Climatic Conditions of Crop Formation under Climate Change. *Proc. Main Geophys. Obs. Named A. I. Voeykov* **2020**, *596*, 55–77.
64. Nikitin, S.N.; Sharipova, R.B. Assessment of Change of Agroclimatic Potential of Ulyanovsk Region for Plant Production. *Vestn. Ulyanovsk. State Agric. Acad.* **2022**, *230*, 36–42. [CrossRef]
65. *The Third Assessment Report on Climate Change and Its Consequences on the Territory of the Russian Federation. General Summary*; High-Tech Technologies: St. Petersburg, Russia, 2022; p. 124.
66. Zhao, J.; Wang, Z. Future Trends of Water Resources and Influences on Agriculture in China. *PLoS ONE* **2020**, *15*, e0231671. [CrossRef]
67. Robinson, E.L.; Huntingford, C.; Semeena, V.S.; Bullock, J.M. CHESS-SCAPE: High-Resolution Future Projections of Multiple Climate Scenarios for the United Kingdom Derived from Downscaled United Kingdom Climate Projections 2018 Regional Climate Model Output. *Earth Syst. Sci. Data* **2023**, *15*, 5371–5401. [CrossRef]