Climate and Weather Extremes in the Volga Federal Region

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Abstract. Climate and weather extremes observed in the Volga Federal Region (VFR) are studied in relation to the climatic changes taking place in the XX – XXI centuries. Weather observation data from 183 meteorological stations and ERA5 reanalysis data are used as a source material. It has been demonstrated that a significant jump in the annual temperature mean was registered, the number of large-scale positive anomalies exceeded the number of negative ones, the quantity of hot days grew, while the quantity of ice days dropped in the VFR at the turn of the XXI century. The dynamics of hazardous weather events (strong winds, convection phenomena) was characterized by a positive trend on the territory of the VFR within the period from 1991 to 2018.

1. Introduction.
Present-day climate changes accompanied by more and more frequent and intense natural disasters turn out to be especially sensitive for nature, economy, and population of certain regions. Assessment of the impact of natural (the thermal state of the ocean surface, atmospheric circulation, solar and geomagnetic activity) and anthropogenous factors on the formation of weather and climatic anomalies, including extreme ones, has become a crucial task.

A number of papers devoted to this topic have been published over the last years. Thus, paper [1] studies changes in the near-surface temperature over the dryland of the Earth, as well as changes in the precipitation regime on the territory of Russia during the current warming period. Papers [2,3] present results of a statistical analysis for the frequency of hazardous hydrometeorological events which occurred on the territory of Russia and caused socio-economic damage within the period from 1998 to 2017. They also describe the influence of climatic changes on the frequency of extreme hydrometeorological events. When it comes to regions, these questions were discussed [6-12] as well. Much attention is given to the problems relating to the development of climate change response strategies, creation of an information basis for adaptive programs in the Russian economy. For this purpose, a probabilistic climate forecasting technology is being developed on the basis of mass ensemble calculations with a high-resolution model system [3,4].

The article discusses spatiotemporal variability of the air temperature, atmospheric precipitation, and extreme hydrometeorological phenomena on the territory of the Volga Federal Region (VFR) against the background of climatic events that took place on the territory of Russia within the period from 1955 to 2018 according to meteorological network and ERA5 reanalysis data.
2. Results
From 1850 to the present day the general trend of air temperature rise has been observed both in the region and on the territory of the Northern Hemisphere (NH). However, till the mid-1970s these changes were of oscillatory nature. Thus, in certain periods the temperature change processes were going on in antiphase on the territory of the VFR and the NH, which is clearly seen from Figure 1. Only since the 1970s an intensive air temperature rise has been observed throughout the entire NH, the NH land and VFR.

![Figure 1. Low-frequency component with a period exceeding 25 years for anomalies of annual near-surface air temperature means averaged for the territory relative to the norms for 1961-1990. (1 – the Northern Hemisphere, 2 – the Northern Hemisphere land, 3 – the Volga Federal Region).](image)

Large-scale normalized anomalies of the near-surface air temperature (ΔT/σT) averaged for the territory of the VFR were estimated according to the data obtained from 183 meteorological stations within the period between 1955 and 2018. Table 1 presents the results of calculations made for two subperiods: 1955-1998 and 1999-2018.

| Period | Month | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|--------|-------|---|----|-----|----|---|----|-----|------|----|---|----|-----|
| 1955-1998 | a n | 5 | 4 | 5 | 7 | 9 | 9 | 6 | 6 | 5 | 3 | 5 | 5 |
| | b n, % | 11.36 | 9.09 | 11.36 | 15.91 | 20.45 | 20.45 | 6.82 | 9.09 | 13.64 | 11.36 | 6.82 | 11.36 |
| | e Sum, | 6.16 | 5.84 | 6.39 | 11.20 | 11.54 | 13.54 | 4.79 | 6.57 | 8.51 | 8.11 | 3.98 | 5.74 |
| | f Av, | 1.23 | 1.46 | 1.28 | 1.60 | 1.28 | 1.50 | 1.60 | 1.64 | 1.42 | 1.62 | 1.33 | 1.15 |
| 1999-2018 | a n, % | 18.18 | 15.91 | 27.27 | 20.45 | 13.64 | 15.91 | 22.73 | 11.36 | 15.91 | 15.91 | 18.18 | 15.91 |
| | e Sum. | -13.58 | -11.26 | -17.22 | -13.38 | -9.03 | -10.18 | -15.25 | -6.59 | -13.34 | -11.76 | -13.52 | -12.01 |
The number of negative large-scale anomalies was anomalously warm. The mean anomaly intensity varied within the range of 1 to 1.15 (December) to 1.44 (August). The number of negative anomalies was approximately the same as that of positive ones, but their intensity often exceeded the intensity of positive anomalies. The subperiod from 1999 to 2018 is very indicative, since in this period the number of positive anomalies considerably outnumbered the negative ones. In addition, the time share of positive anomaly existence significantly increased percentagewise (often up to 30%), which is the evidence of significant climate warming in the VFR in the XXI century. At the same time, the intensity of positive normalized anomalies varied from 1.26 (June) to 1.81 (August). The intensity of negative normalized anomalies varied within the range of -1.20 (October) to -2.51 (December). Simultaneously, no cases with large-scale negative anomalies were registered in April and September over the last twenty years.

Variance of diurnal air temperature deviations from the annual cycle was considered as a characteristic of temporal variability of the temperature conditions on the territory of the region. The air temperature variance was calculated for each of 183 stations in the VFR for the period from 1966 to 2018 in the following way: a smoothed mean annual cycle was calculated for diurnal values; diurnal temperature anomalies of the smoothed annual cycle were calculated; variance of the diurnal temperature anomalies (DTA) characterizing the interdiurnal temperature variability over the year was found. The linear trends were constructed for the studied period using the obtained DTA variances.

In the best part of the territory of the VFR the DTA trends are negative, which testifies to the regime stability augmentation. It is common knowledge that the AT variance is higher in the cold season than in the warm season, when a more stable radiation factor takes a dominant lead. That is why under the conditions of a well-pronounced climate warming trend the variance of diurnal temperature deviations from the annual cycle should decrease. The value of the variance of diurnal temperature deviations from the annual cycle is characterised by interannual oscillations.

A polynomial trend curve constructed for the Kazan station demonstrates that the variance was smoothly decreasing from 1966 to 1985 (from 28 to 23), then it increased to 26 (in 2004), and was significantly decreasing over the subsequent years (to 17 in 2018) (Figure 2). In such a way, the largest decrease in the variance characterising the interdiurnal temperature variability was observed within the period from 2004 to 2018. To prove the aforementioned phenomenon, the diurnal temperature anomaly trends were calculated separately for the cold (November – March) and warm (April – October) periods within two periods: 1966-1999 and 2000-2018 (Table 2).
As one can see from Table 2, for the above-mentioned twenty stations significant changes occurred in the cold season at the turn of the XXI century, the linear trend slope coefficients (LTSCs) of the diurnal temperature variance changed their sign from plus to minus, which is evidence of the thermal regime variability both on the interannual and interdiurnal scales.

![Figure 2](image-url)  
**Figure 2.** Variance of diurnal temperature deviations from the annual cycle (°C²), Kazan. (1 – basic series, 2 – polynomial trend).

According to [1], in the recent period (1870–2015) the variability of the near-surface daily temperature mean decreased in winter within the inter-day and synoptic ranges in the overwhelming majority of Russian regions, which correlates with the obtained results.

| Station                | Cold Period     | Warm Period      |
|-----------------------|-----------------|------------------|
|                       | 1966-1999       | 2000-2018        | 1966-1999       | 2000-2018 |
| Nyrob                 | 0.622           | -0.681           | 0.102           | 0.020     |
| Kirov                 | 0.368           | -1.012           | -0.002          | -0.241    |
| Lalsk                 | 0.421           | -1.009           | 0.05            | 0.204     |
| Perm                  | 0.321           | -0.788           | -0.092          | -0.130    |
| Izhevsk               | 0.365           | -0.941           | -0.033          | -0.269    |
| Nizhny Novgorod       | 0.347           | -0.857           | -0.039          | -0.209    |
| Cheboksary            | 0.304           | -1.021           | -0.04           | -0.315    |
| Kazan                 | 0.191           | -0.949           | -0.106          | -0.280    |
| Saransk               | 0.412           | -0.838           | -0.051          | -0.233    |
| Bugulma               | 0.566           | -0.836           | -0.036          | -0.205    |
| Ufa                   | 0.440           | -0.856           | -0.029          | -0.323    |
| Ulu-Telyak            | 0.396           | -0.798           | -0.055          | -0.290    |
AND indices as factorial indicators, demonstrates that within the period between the summer period, plays a prominent role in the temperature oscillations. The correlation with changes in the monthly temperature mean, and the circulation factor, in contrast to the indicator does impact of predominant, in March the impact of both indices is approximately the same, while in December the impact of these indices makes 0.34 and 0.35, respectively, whereas the temperature variance is described by circulation variations, the coefficient is significant at 0.01, as well as in October (the correlation coefficient is significant at 0.27 and higher at the reliability level of 0.95). The most strong correlation is identified in January and February (r = -0.60), in summer it is non-significant.

To estimate the contribution of the atmospheric circulation to the formation of the thermal regime in the region, the authors calculated the coefficients of correlation between the monthly temperature means averaged for the region and for individual stations, and the circulation indices NAO, AO, SCAND. The calculations were made for the period from 1954 to 2018 (65 years) by month (Table 3).

### Table 3. Coefficient of correlation between the air temperature averaged for the VFR and atmospheric circulation indices.

| Index | I  | II | III | IV | V  | VI | VII | VIII | IX | X  | XI | XII |
|-------|----|----|-----|----|----|----|-----|------|----|----|----|-----|
| NAO   | 0.34 | 0.38 | 0.44 | -0.10 | -0.29 | -0.32 | -0.08 | -0.15 | 0.11 | -0.07 | -0.12 | 0.47 |
| AO    | 0.43 | 0.33 | 0.39 | 0.06 | -0.06 | -0.13 | 0.25 | 0.01 | 0.15 | 0.11 | 0.28 | 0.41 |
| SCAND | -0.62 | -0.63 | -0.35 | -0.31 | -0.28 | -0.03 | 0.09 | -0.14 | -0.17 | -0.48 | -0.22 | -0.29 |

As is clear from Table 3, the annual cycles of the coefficients of correlation between the temperature mean in the VFR and AO and NAO indices are similar, which is caused by a quite strong correlation between these indices, especially in the cold period (the coefficient of correlation between these indices makes 0.71-0.80 between December and March). The closest positive correlation is observed in December through March between the temperature and both the NAO index (in December r reaches 0.47) and the AO index (r = 0.43 in January).

A significant negative correlation is found between the temperature averaged for the region and the SCAND index in the period between December and May, as well as in October (the correlation coefficient is significant at 0.27 and higher at the reliability level of 0.95). The most strong correlation is identified in January and February (r = -0.60), in summer it is non-significant.

The linear regression of the temperature averaged for the region as a resulting indicator, and jointly the NAO and SCAND indices as factorial indicators, demonstrates that within the period between December and March 27 to 47% of the temperature variance is described by circulation variations, with this value making about 21% in October. At the same time, in January and February the impact of the SCAND index is more than two times as strong, in October the impact of this index is predominant, in March the impact of both indices is approximately the same, while in December the impact of the NAO index dominates. The AO index added to the regression model as a factorial indicator does not exert any substantial influence on the model characteristics for the reason of a rather strong correlation between the AO and NAO indices.

With that said, in the cold period the atmospheric circulation indices have a rather strong correlation with changes in the monthly temperature mean, and the circulation factor, in contrast to the summer period, plays a prominent role in the temperature oscillations.
Using ERA5 reanalysis data for the period from 1980 to 2018, the distribution of extremal indices of the temperature-humidity conditions (the number of days with high and low temperatures, heavy precipitation) was calculated for the Volga Federal Region.

The number of days per year on which the minimum diurnal temperature $t_{\text{min}}$ is below $-20^\circ\text{C}$ is unevenly distributed over the territory of the VFR: in the far north-east (Perm Territory) their number reaches 50 days, while in the south-west, in Saratovskaya Region, their number makes 15 only. The number of ice days grows up to 25–35 days per year in the south-east of the VFR (Orenburg Region) and in the east of Bashkortostan, in the area of the Ural Mountains. The number of ice days characterising the cold period, when $t_{\text{min}}<0$, grows on the territory of the VFR from the south-west to the north-east from 135 to 225 days per year.

The linear trend slope coefficient (LTSC) for this characteristic has a negative value ($-0.3$ – $-0.4$ days/per) everywhere, meaning that the number of days with minimum temperatures $<-20^\circ\text{C}$ has been reducing by 3 – 4 days over the decade.

The number of summer days with the maximum diurnal temperature ($t_{\text{max}}$)$>25^\circ\text{C}$ is notable for a zonal distribution, with the exception of the mountain area in the east of Bashkortostan. While the number of hot days reaches 110 in the south of the VFR, in the far north-east this number makes 10 only. Hot days are also few (10–20) in the east of Bashkortostan (the influence of the Urals is thus manifested). Tropical nights, when $t_{\text{min}}>20^\circ\text{C}$, are registered predominantly in the southern part of the VFR (35). They have not been registered in the far north-east of the VFR.

The trend of the number of days with $t_{\text{max}}>25^\circ\text{C}$ is positive everywhere. The number of days with the maximum temperature grows with the rate of 1–2 days/10 years from the north-east to the south-west up to 6–7 days/10 years.

In the north-eastern parts of the VFR and Pre-Urals the number of days with heavy precipitation of more than 20 mm/day grows. Here the influence of the orographic factor is vividly seen, as far as humid air masses come from the west (in the south of the VFR, one day with large-particle precipitation is registered, while in Bashkortostan their number is three). The LTSC is positive, but its value is low.

In the last few years, much attention has been focused on the problem of the influence produced by hazardous hydrometeorological phenomena on the economy and vital activities of the population of Russia. There were 510 hazardous events (HE) and unfavourable weather conditions registered on its territory in 2010 [5]. Since 1997, the Russian Research Hydrometeorological Institute - World data center has been collecting and accumulating information about hazardous events registered by hydrometeorological stations. According to expert estimates, the annual damage by emergency situations in Russia makes 1.5 to 2% of the annual gross domestic product. In 2010, the damage made 675 to 900 bln rub. Paper [13] presents information about the HE in constituent territories of the RF within the period from 1991 to 2018.

Let us study the dynamics of hazardous events on the territory of the VFR within the period between 1991 and 2018 using data about the HE distribution in constituent territories of the Russian Federation located in the VFR [8]. As Figure 3 shows, a positive trend is observed on the whole for the growth of the number of HE cases on the territory of the VFR (28 cases/10 years). The determination coefficient $R^2$ of the linear trend reaches 27%, which testifies to reliability of the consistent pattern revealed. The largest number of HE was registered within the period from 2007 to 2015, the latter being connected with the air temperature rise in the XXI century. In 2010 their quantity in the region achieved 170. Table 4 presents characteristics of the HE in the constituent territories of the VFR.
Figure 3. Multiyear curve of the number of all hazardous events in the VFR.

Table 4. Characteristics of change in the total number of hazardous events in the Volga Federal Region (1991-2018).

| Constituent territory       | a Av | b Rms | c S   | d Av/S | e A | f R² | g α  |
|-----------------------------|------|-------|-------|--------|-----|------|------|
| Kirovskaya Region           | 9.29 | 3.68  | 120.8 | 0.08   | 0.27| 0.34 | 0.00 |
| Perm Territory              | 5.68 | 3.06  | 193.5 | 0.03   | -0.07| 0.00 | 0.33 |
| Republic of Udmurtia        | 3.82 | 2.51  | 42.1  | 0.09   | 0.08 | 0.04 | 0.17 |
| Nizhegorodskaya Region      | 8.61 | 4.15  | 74.8  | 0.12   | 0.21 | 0.14 | 0.03 |
| Republic of Mari El         | 4.36 | 2.33  | 23.2  | 0.19   | -0.03| -0.03| 0.64 |
| Republic of Chuvashia       | 4.46 | 2.95  | 18.3  | 0.24   | 0.01 | -0.04| 0.86 |
| Republic of Tatarstan       | 10.61| 5.51  | 68.0  | 0.16   | 0.31 | 0.18 | 0.01 |
| Republic of Mordovia        | 6.29 | 2.99  | 26.2  | 0.24   | 0.01 | -0.04| 0.89 |
| Ulyanovskaya Region         | 8.64 | 5.17  | 37.3  | 0.23   | 0.31 | 0.21 | 0.01 |
| Samarskaya Region           | 11.39| 6.12  | 53.6  | 0.21   | 0.36 | 0.21 | 0.01 |
| Republic of Bashkortostan   | 7.75 | 4.18  | 143.6 | 0.05   | -0.01| -0.04| 0.93 |
| Penzenskaya Region          | 6.11 | 3.72  | 43.2  | 0.14   | 0.13 | 0.04 | 0.15 |
| Saratovskaya Region         | 10.43| 5.29  | 100.2 | 0.10   | 0.27 | 0.15 | 0.02 |
| Orenburgskaya Region        | 8.43 | 4.16  | 124.0 | 0.07   | 0.33 | 0.39 | 0.00 |
| VFR                         | 105.86| 33.18 | 1068.8| 0.10   | 2.18 | 0.27 | 0.00 |

a Av – mean value, °C.
b Rms – standard deviation, °C.
c S – area (tsd km²).
d A – linear trend slope coefficient, events per year.
e Av/S – average value per unit area, °C/ tsd km².
f R² – linear trend determination coefficient (decimal quantity).
g α – significance, (decimal quantity).

The territorial distribution of hazardous events is very diverse. They are most frequently registered in the central and southern regions characterized by a more complex physico-geographical environment. The following hazards are most frequent on the territory of the VFR: strong wind, squall, tornado, heavy rain, hail, etc.
Conclusions
The following regional peculiarities of the climate change have been identified as a result of the above statistical processing and analysis of multi-year observations made on the territory of the Volga Federal Region:

Similar to the entire territory of the Northern Hemisphere, a general warming trend has been observed in the above-studied region since the fifties of the XIX century. However, until the mid-1970s the regional changes in the annual and hemispheric air temperature mean were characterized by certain oscillations, including those of antiphase nature. In the mid-1970s the active phases of both global and regional warmings began, which resulted in a considerable increase in the annual mean air temperature and a slight growth in the annual atmospheric precipitation.

A significant jump in the AATM in the VFR was registered at the turn of the XXI century, which manifested itself in more frequent large-scale positive temperature anomalies, a decrease in the variance of daily air temperature mean in the winter period, and an increase in the number of hazardous events on the territory of the VFR. At the same time, the number of positive temperatures increased and the number of negative temperatures decreased against an increase in the number of days with daily temperature means above 0 °C.

It is important to study the natural and social consequences of the regional climatic changes and develop measures aimed at adaptation of natural and socio-economic systems to these changes.

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