Climatic Changes on the Territory of the Volga Federal District

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Abstract. Climatic changes in the Middle Volga District observed from 1828 to 2018 are examined. Long-term air temperature variations are monitored using observation data from Meteorological Observatory of Kazan University (MO KU) (1828-2018), and from 5 meteorological stations located in Orenburg, Penza, Perm, Saratov, Ufa (1885—2018). Spatiotemporal variability of the air temperature and atmospheric precipitation is researched in the Volga Federal District (VFD) on the basis of data from 200 meteorological stations (1954-2018) and NCEP/NCAR, ERA-Interim, ERA5 reanalysis data (1979-2018). The general tendency towards the air temperature rise has been identified for the period considered (in Kazan the annual air temperature mean increased by 4°C from 1828 to 2018). It has also been revealed that the number of days with the minimum temperature (below -20°C) tends to decrease throughout the year, while the number of days with the maximum temperature (over 25°C) tends to increase. The dynamics of the low-frequency component with the period exceeding 15 years is studied for normalized air temperature and atmospheric precipitation anomalies in the VFD between 1954 and 2018. Distribution of great air temperature anomalies within the studied period is evaluated.

1. Introduction

The climate of the Middle Volga District has been studied for 200 years, starting from 1812, when a Meteorological observatory was opened in Kazan University on the initiative of Professor F. K. Bronner. The key historical milestones are described in [5]. It has been shown that the territory of the region is characterized by a strongly pronounced annual cycle of the principal climate-forming factors: solar radiation, underlying surface pattern, circulation factor regimes [1]. In recent decades the interest to regional climatic changes has been growing thanks to the active phase of the global warming. Development of modern information and computational technologies, free access to reanalysis, results of ensemble calculations using CMIP5 program etc. promote this interest, as well. The papers [2, 3] present the research findings for the processes taking place in the troposphere and stratosphere.

The present paper is primarily focused on analysis of long-term variations of the air temperature and atmospheric precipitation characteristics on the territory of the region, based on the data of MO KU (1828-2018), and long-range stations in Penza, Saratov (the west of the region), Perm, Ufa, Orenburg (the east of the region) from 1885 to 2018. The analysis of spatiotemporal indices of the climatic regime throughout the VFD is made on the basis of the observation data obtained from the meteorological network (over 200 stations) within the period from 1954 to 2018. NCEP/NCAR, ERA-Interim, ERA5 reanalysis data for the period between 1979 and 2018 have been used to identify
extreme characteristics of the climate and get height distributions of the air temperature. Furthermore, CRU data for the period from 1850 to 2018 have been used to obtain comparative characteristics.

Statistical manipulations with basic series have been made to find: mean values and anomalies of the air temperature and atmospheric precipitations ($\Delta T$ and $\Delta P_r$), mean square deviations (MSD) of the air temperature and atmospheric precipitations ($\sigma_T$ and $\sigma_{P_r}$), normalized anomalies of the air temperature and atmospheric precipitations ($\frac{\Delta T}{\sigma_T}$ and $\frac{\Delta P_r}{\sigma_{P_r}}$), linear trends for the temperature and extreme characteristics of the air temperature and atmospheric precipitations in the VFD. Low-frequency component (LFC) has been selected in the meteorological series with the help of Potter low-frequency filter, with the cutoff point being 15 years and more. The validity has been assessed using F test.

2. Results

Let us first study the nature of the long-term air temperature variations in Kazan on the basis of the weather observation data obtained by MO KU in the XIX-XXI centuries. Figure 1 presents multiyear curve of the annual air temperature means (AATM) in Kazan, according to which the anomalies of the air temperature (AT) has been tending to rise for many years already (approximately by $4^\circ$C within the period under consideration). The basic series was smoothed using Potter filter, which permitted to identify a low-frequency component (LFC) in it, comprising oscillations with the period exceeding 30 years. The LFC variations show a significant heterogeneity of AATM changes with time. Time series approximation with a step trend allowed evaluating the linear trend slope coefficient (LTSC) at individual segments, along with the determination coefficient $R^2$. Thus, according to the built step trends, in the earliest period (1828-1862) the AT was sharply increasing with the rate of $a = 0.24^\circ$C/10 years ($R^2 = 7\%$), from 1863 to 1891 its slight decrease was observed ($a = -0.04^\circ$C/10 years, $R^2 = 0.1\%$), from 1892 to 1924 a significant warming occurred ($a = 0.31^\circ$C/10 years, $R^2=11\%$), from 1925 to 1969 the AT slightly grew ($a = 0.03^\circ$C/10 years, $R^2 = 0.2\%$), and, finally, during the rather long closing part of the considered period, from 1970 to 2018, an intensive climate warming was observed, and the AATM was growing with the rate of $0.4^\circ$C/10 years ($R^2 = 29\%$).

![Figure 1. Multiyear curve of the annual air temperature means (AATM) in Kazan (1 – basic series, 2 – LFC with the period exceeding 30 years, 3 – step trend), 1828 – 2018](image-url)
It should be emphasized that long-term AT oscillations in Kazan rather well correlate with oscillations of the near-surface air temperature averaged for the entire territory of the Northern Hemisphere (NH). The low-frequency components of the near-surface AATM anomalies with the period exceeding 25 years, registered at Kazan, University station and in the Northern Hemisphere (the linear trend has been excluded from the series), and presented in Figure 2, testify that ΔT LFC curves are much similar, however, at the same time, the warming phase starts earlier in Kazan than in the Northern Hemisphere in the whole. Thus, in the early XX century the AT rise in Kazan took place 10 earlier, and the contemporary significant warming started in 1960 (15 years earlier than throughout the NH). In addition, ΔT value during the closing period made 1.2°C in Kazan, while throughout the NH it was equal to 0.8°C only.

![Figure 2. LFC of the near-surface AATM with the period exceeding 25 years (trend excluded) at Kazan, University station (Ku) against the temperatures of the Northern Hemisphere (Nh) and the NH land (NhL)](image_url)

Analysis of behavior of the first-order LFC differences, characterizing the rate of low-frequency change in the temperature, in different months of the year proved that the most abrupt changes in the temperature occurred in the cold season. The most unstable temperature changes were observed in November. As a whole, standing out of the air temperature rise background, shorter periods of the AT rise was followed by the periods of less intensive cooling in Kazan. During the warm seasons its slight decrease was observed till the early XXI century. However, from the beginning of the XXI century to 2018 the summer AT was substantially growing in Kazan. This process was especially active in August.

Analysis of the low-frequency components of the normalized near-surface AATM anomaly \( \frac{\Delta T}{\sigma_T} \) with the period exceeding 25 years, registered at Kazan University, Penza, Saratov stations (the west of the VFD) and Perm, Ufa, Orenburg stations (the east of the VFD) within the period from 1885 to 2018, demonstrated that the general picture is rather homogeneous (especially in the east), which is the evidence of the climate warming in the entire region. While in the west of the region the change from negative to positive values \( \frac{\Delta T}{\sigma_T} \) at the stations occurred within a short period of time, from 1965 to 1970, in the east this process firstly began in the south (Orenburg station) in 1965 and ended at Ufa station in
By 2018 the maximum value $\frac{\Delta T}{\sigma_T}$ was 1.5, according to figures from Penza station, but the figures from Orenburg station gave the value of 1.3, in other words, the warming was a bit more pronounced in the west than in the east.

![Figure 3](image)

**Figure 3.** Dynamics of the low-frequency component of normalized air temperature anomalies in the VFD with the period exceeding 15 years (1954–2018).

Figure 3 presents the dynamics of the low-frequency component of the normalized AT anomalies in the VFD between 1954 and 2018 for the year as a whole and by seasons (winter, summer). Within the period of 1976-2002 the AT was synchronously rising in winter and summer, however, between 2002 and 2010 the temperature fall was registered in winter; then it started growing again, meaning that the winters became warmer. Since 2012 summer temperatures have been slightly decreasing. However, the annual temperature mean has been tending to grow since the late 1960s, according to the behavior of the value $\frac{\Delta T}{\sigma_T}$.

A more detailed picture has been obtained for Kazan region. Thus, in Kazan the winter air temperature mean grew by 4.7°C, and the summer mean grew by 2.2°C between 1928 and 2018. The temperature variations in Kazan region were rather well correlated with the AT variations observed in the entire hemisphere both in winter and summer. At the same time, the contribution of the global processes to the AT variability in Kazan region made 37% in winter and 23% in summer.

The time behavior of atmospheric precipitations in the VFD is more complex in nature (Figure 4). The low-frequency component curves $\frac{\Delta P_r}{\sigma_{P_r}}$ are oscillatory. Starting from the second half of the 1970s the winter precipitation intensity was growing till 2018. Having reached its maximum in the second half of the 1980s, the summer precipitations were decreasing over the last years till 2009, and only in more recent times they have started increasing again. After the minimum reached in 1973 the annual precipitation started intensively growing, while between 2000 and 2010 it was decreasing. However, from 2010 to 2018 both the annual values of $\frac{\Delta P_r}{\sigma_{P_r}}$, and its seasonal values were increasing, which is the testimony to the atmospheric precipitation intensification and moisture index growth throughout the region.
In addition to weather observation data obtained for the air temperature, reanalysis data were used in this paper. The reanalysis data averaged for the VFD are well-correlated with meteorological network data for the VFD, which permits to take the most recent years into account in our researches. In order to identify the fundamental patterns of climatic changes in the VFD the authors of the paper have studied the cycle of the near-surface annual air temperature mean, averaged for the territory of the VFD for the period between 1955 and 2018 and the two subperiods: 1955–1999, 2000–2018 (Table 1).

![Figure 4. Dynamics of low-frequency component of normalized total precipitation anomalies in the VFD with the period exceeding 15 years (1954 – 2018).](image)

As one can see from Table 1, a dramatic jump in the temperature mean (by 1.2°C) was registered in the early XXI century. At the same time, the interannual temperature variability halved, while the minimum value of the annual air temperature mean (AATM) sharply rose from 0.55°C to 3.58°C. All these facts evidence significant change in the thermal regime of the region at the turn of the century.

| Period, years | Mean value, °C | MSD, °C | Maximum, °C | Minimum, °C |
|---------------|----------------|--------|-------------|-------------|
| 1955–2018     | 3.49           | 1.04   | 5.49        | 0.55        |
|               |                |        | 1995        | 1969        |
| 1955–1999     | 3.14           | 1.00   | 5.49        | 0.55        |
|               |                |        | 1995        | 1969        |
| 2000–2018     | 4.34           | 0.47   | 5.33        | 3.58        |
|               |                |        | 2008        | 2011        |

Linear trends have been built for these three periods under consideration. Pursuant to them, the linear trend slope coefficient (LTSC) is equal to 0.32°C/10 years for the whole period (the adjusted coefficient of determination $R^2 = 31\%$, the trend determination reliability is over 0.99). In the earlier period, from 1955 to 1999, the LTSC = 0.23°C/10 years ($R^2 = 5\%$, the reliability is 0.96). In the latest period, from 2000 to 2018, the LTSC = 0.08°C/10 years ($R^2 = 0$, the reliability is 0.33). It means that no sizeable rise in the annual air temperature mean has been observed over the XXI century.
Calculations of the normalized anomalies of the near-surface air temperature made for the two subperiods (1955-1999 and 2000-2018) showed that the number of cases with negative temperature anomaly sharply decreased in the lattermost period (the mean value was taken for the period between 1955 and 2018, the normalized anomaly was determined by the formula: \( \frac{\Delta T}{\sigma} \), where \( \Delta T \) is temperature deviation from the mean temperature in the VFD, \( \sigma \) is the mean square deviation). Thus, in the XXI century their number per year has been changing from 0 (in April, September) to 4 (in May). The number of positive anomalies significantly grew. At the same time, during the earliest of the two periods considered (1955–1999) the number of great negative anomalies was higher than the number of great positive anomalies in the majority of the months.

To evaluate the extremeness of winters during Januaries and Feburaries on the territory of the Republic of Tatarstan (RT) the authors used the approach offered in [4], according to which the abnormality index is calculated by the formula:

\[
\alpha = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{2} \left( \frac{\Delta T_I}{\sigma_I} + \frac{\Delta T_{II}}{\sigma_{II}} \right),
\]

where \( \alpha \) – is an integral estimation of the winter AT abnormality degree (January, February) in the region, \( N \) – is the number of meteorological stations, \( \frac{\Delta T_I}{\sigma_I}, \frac{\Delta T_{II}}{\sigma_{II}} \) are normalized AT anomalies by the stations in Januaries and Feburaries, respectively, \( \sigma_I \) and \( \sigma_{II} \) – are mean square deviations of the AT, calculated for each station in January and February, respectively.

The calculations were made for 13 meteorological stations of the RT for the period from 1955 to 2019. At the same time, according to [4], extremely cold winters in the regions of the European Russia located to the south of 60° N are characterized by negative index values \( \alpha<0.9 \); during the extremely warm winters \( \alpha > 1.0 \).

Analysis of the obtained results shows that the coldest winters were observed in Tatarstan from 1954 to 1982. Registered during this period were 5 extremely cold winters and not a single extremely warm winter. The winter 1969 was the coldest (\( \alpha = -2.23 \)), in the ensuing years due to the climate warming in the region [6] 5 extremely warm winters were registered within the period from 1989 to 2005 (especially in 2002, when \( \alpha = 1.63 \)) instead of extremely cold winters. Only between 2006 and 2011 cold winters returned to Tatarstan (2006, 2010, 2011) for a short while, but they were not as severe as in the 1950s and 1960s. Upper-level blocking anticyclones, interfering with the general western disturbance in the temperate latitudes, were the reason for the extremely cold winters. In their papers [7, 8] the authors examined anomalies in the air pressure and temperature fields in the troposphere of the Northern Hemisphere within 1900–2014, along with the influence of the zonal circulation on the air temperature variation.

Using ERA5 reanalysis data obtained in 1980–2018 for the Volga Federal District, the authors calculated distribution of extreme indicators for temperature and humidity conditions (number of days with high and low temperatures and heavy precipitation).

The number of frosty days per year, when the minimum daily temperature \( T_{\text{min}} \) is below -20°C, is unevenly distributed throughout the VFD: in the far North-East (Perm Territory) their number reaches 50 days, while in the South-West, in Saratov Region, their quantity makes 15 only. The number of frosty days grows up to 25–35 days per annum in the South-East of the region (Orenburg Region) and east of Bashkortostan, in the Ural Mountains area. The quantity of frosty days typical for the cold season, when \( T_{\text{min}} <0 \), increases in the VFD from the south-west to the north-east, making 135 to 225 days per year, respectively.

The LTSC of this characteristic has negative value everywhere (-0.3 – -0.4 days/year), meaning that the number of days with the minimum temperatures <-20°C decreases by 3–4 days over a ten-year period.

The number of summer days, during which the maximum daily temperature \( (T_{\text{max}}) >25°C \), is characterized by their 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 region, their quantity in the far north-east makes 10 only. Hot days are also few (10–20) in the east of Bashkortostan (the influence of the Ural Mountains). Tropical night, when $T_{\text{min}} > 20^\circ\text{C}$, are registered predominantly in the southern part of the region (35); they are not observed in the far north-east of the VFD.

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 south-west up to 6–7 days/10 years.

In the north-eastern areas of the VFD and near Ural areas the number of days with heavy precipitation exceeding 20 mm/day grows. The orographic factor’s influence here is vividly manifested, as humid air masses come from the west (in the south of the VFD one day with coarse-grain precipitation is registered, while in the eastern Bashkortostan they number three). The LTSC is positive, but its value is small.

To estimate the external factors’ effect on the processes observed in the VFD between 1955 and 2018 the authors determined correlation between the above studied climatic indices and natural factors, including among others: the North Atlantic Oscillation (the quantitative characteristic – NAO index), El Nino phenomenon – the Southern Oscillation (SOI index), day’s length (Earth angular rotation speed), as well as the relative sunspot number characterizing the solar activity (Wolf number) [9].

Table 2 presents the correlation coefficients registered between the anomalies of the air temperature and total precipitation in the VFD and temperature anomalies of the Northern Hemisphere, and anomalies of NAO index, SOI index, Wolf number and day’s length. Starting from $r = 0.28$ the correlation coefficient is significant at 95% level for this sample ($n = 55$). As one can see from the table data, a statistically significant long-term correlation is observed between the temperature anomalies in the VFD and Northern Hemisphere for winter, summer and year as a whole. Correlations are stronger in winter ($r = 0.62$) than in summer ($r = 0.41$). In fact, the global climate warming has been observed in the last decades (since 1976), which finds resonance in the Volga region, as well, especially in winter period. It is natural that the correlation between precipitations in the VFD and temperature anomalies of the Northern Hemisphere turned out to be incomparably weaker: $r = 0.30$ for winter, and for summer the correlation is practically non-existent. It should be pointed out that the warming has led to the increase in the amount of winter precipitation, which is clear from the physical standpoint (increase of cyclonic activity and air humidity).

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Period} & \textbf{Value} & $\Delta T_{NH}$ & NAO & W & D & SOI \\
\hline
\textbf{Year} & $\Delta T$ & 0.59 & 0.05 & -0.06 & -0.31 & -0.04 \\
 & $\Delta P_r$ & 0.25 & 0.21 & 0.12 & -0.21 & -0.15 \\
 & $\Delta T_{NH}$ & 1.00 & -0.17 & -0.11 & -0.66 & -0.27 \\
\hline
\textbf{Winter} & $\Delta T$ & 0.63 & 0.64 & 0.05 & -0.28 & -0.15 \\
 & $\Delta P_r$ & 0.30 & 0.11 & 0.24 & -0.25 & -0.05 \\
 & $\Delta T_{NH}$ & 1.00 & 0.31 & -0.05 & -0.61 & -0.37 \\
\hline
\textbf{Summer} & $\Delta P_r$ & 0.02 & 0.05 & -0.11 & -0.11 & -0.06 \\
 & $\Delta T_{NH}$ & 1.00 & -0.29 & -0.15 & -0.69 & -0.03 \\
\hline
\end{tabular}
\caption{Coefficients of correlation of the temperature anomalies $\Delta T$ and total precipitation anomalies $\Delta P_r$ in the Volga Federal District, and temperature anomalies in the Northern Hemisphere $\Delta T_{NH}$ with the North Atlantic Oscillation index NAO, Wolf number W, day’s length anomaly D and the Southern Oscillation Index SOI.}
\end{table}

Observed is the dependence of the winter air temperature in the VFD from the North Atlantic condition. The latter fact is evidenced by the strong correlation between the temperature anomalies in winter and NAO index anomalies ($r = 0.64$). For summer such correlation is insignificant ($r = -0.15$).
In additions, the North Atlantic Oscillation has a certain effect on the temperature anomaly forming in the entire Northern Hemisphere \((r = 0.31\) in winter, \(r = -0.29\) in summer).

As one should expect, correlations with SOI index turned out to be significant only for the temperature in the Northern Hemisphere \((r = -0.37\) in winter). The correlation is negative, because negative SOI anomalies bring about the temperature rise. However, this phenomenon more vividly manifests itself in the Southern Hemisphere, where the basic events connected with the Southern Oscillation develop in the great spaces of the Pacific and Indian oceans.

The correlation of the temperature and amount of precipitation with the solar activity appeared to be non-significant. Solely for winter the correlation coefficient between the amount of precipitation anomalies and Wolf number was equal to 0.24. At the same time, nonuniformity of the Earth’s rotation finds an echo in the temperature field of both the VFD, and especially the Northern Hemisphere. Thuswise, \(r = -0.66\) for the annual values of the temperature anomalies in the Northern Hemisphere \((r = -0.61\) for winter, and \(r = -0.69\) for summer). The periodicity of the air temperature variations is 60-70 years, as in the case with the Earth rotation speed variations. Furthermore, the Earth rotation speed variations exert an impact on the atmosphere zonal circulation (and thereby, on the air temperature). It potentially could be the reason for the statistically significant correlation. As far as \(r < 0\), it means that the temperature rises with the day’s length reduction (the Earth rotation accelerates). For the VFD the considered correlation is definitely less significant \((r = -0.31\) for the whole year, and \(r = -0.28\) for winter).

3. Conclusions

The results of meteorological data analysis obtained for the VFD in 1828-2018 permitted to identify the following key features of regional climatic changes.

According to the data from MO KU, the annual air temperature mean increased approximately by 4°C within the period from 1828 to 2018. At the same time, the climate warming phases start 10-15 years earlier than in the Northern Hemisphere as a whole.

Analysis of the air temperature characteristics obtained within the period from 1885 to 2018 for 6 long-range stations of the VFD (Kazan, Penza, Saratov, Perm, Ufa, Orenburg) has revealed the general tendency towards the temperature growth from the 1920s to the present day.

Time variation of atmospheric precipitations between 1954 and 2018, averaged for the VFD, is of oscillating nature. During the latest period, from 2010 to 2018, their growth trend was observed in the region.

A catalogue of extreme winters of Tatarstan between 1955 and 2019, built using the method by A. V. Mescherskaya, demonstrated that extremely cold winters were registered on its territory during the periods from 1955 to 1982 and from 2006 to 2011 (the winter 1969 was the coldest). At the same time, all the cases of extremely warm winters were registered between 1989 and 2005.

Considerable spatial differences in distribution of extreme temperature and humidity indices have been identified on the territory of the VFD. Over the past few decades (1980–2018) the number of frosty days in the VFD (with the temperature below -20°C) was decreasing with the rate of approximately 3-4 days/10 years. In the meantime, the number of days with the maximum temperature (> 25°C) was growing from the north-east to south-west with the rate of 1 to 8 days/10 years. While the growth rate of the number of days with the minimum temperature is rather even throughout the VFD, the growth rate of the number of days with the maximum temperature demonstrates the pronounced decrease from the south-west to north-east. In the west and north-east of the VFD one can distinguish areas with a weak growth of the number of days with the total precipitation exceeding 20 mm (0.2 day/10 years).

A statistically significant negative correlation was found between the annual air temperature averaged for the VFD and the day’s length \((r = -0.66)\), along with the strong positive correlation between the winter temperature and NAO index \((r = 0.64)\).
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