Temperature and humidity regime of the Volga basin in the period 1976-2019

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Abstract. The features of the distribution of air temperature and atmospheric precipitation on the territory of the Volga basin in the periods 1976-2019 and 2001-2019 are given. A positive trend in air temperature at the stations of the region in the period 1976-2019 both in the central months of the seasons, and throughout the year as a whole was revealed. A decrease in January air temperature was noted in the period 2001-2019. In general, an increase in atmospheric precipitation in the period under consideration is observed.

1. Introduction
An important role in the formation of river runoff is played by climatic factors - atmospheric precipitation and temperature fluctuations due to both modern anthropogenic climate warming and the dynamics of atmospheric circulation. The work [12] considers long-term fluctuations in the hydrometeorological regime of the Volga basin in the period 1891-1993. As a result of a comprehensive analysis of long-term fluctuations in annual precipitation, runoff and air temperature (AT) of the Volga Basin (VB), quasi-cyclicality was revealed in fluctuations in annual precipitation amounts (3-4 and 13 years), Volga runoff - about 17 years, air temperature 2 and 10 years. A significant correlation was found between the amount of precipitation and the Volga runoff with the western and eastern forms of the Wangenheim-Girs circulation. In a later work [13], according to the network of meteorological stations and reanalysis in the period 1955-2009 it was found that the annual air temperature averaged over the territory of the Volga Federal District increased by about 1.8°C. The long-term dynamics of the annual amount of precipitation turned out to be more complicated: from 1955 to 1972. The annual amount of precipitation decreased by 28 mm, then it increased by 45 mm until the end of the 1980s and at the beginning of the 21st century again there was a tendency to decrease them.

Much attention is paid to the hydrological regime of the vast Volga-Kama basin on the part of hydrologists, geographers and climatologists. So, in work [1] revealed the dependence of the variability of the total annual runoff of the river. Volga from annual precipitation, the state of moisture and evaporation on the territory of the Volga and Kama basins. In particular, in work [4] it is shown that 65% of the annual runoff of the Volga is formed in the Kama basin.

According to [2], the intra-annual distribution of river runoff is determined as a result of a complex interaction of three groups of factors: climatic, meteorological, and factors of the river basin (relief,
vegetation, water bodies, soil, etc.). In work [6] it is noted that the observed modern changes in the annual runoff in the rivers of the Volga basin are conditioned by climate. The role of atmospheric circulation in the dynamics of annual precipitation in the region is indicated in [7].

Foreign literature [8-10] analyses the state of the surface temperature of the Atlantic Ocean, the dynamics of the Atlantic multi-decadal oscillation, which affect the seasonal changes in moisture conditions in Europe. In particular, it is shown that in the 1990s in the north of Europe humid places became wetter, and in the south it became hotter and drier [6]. In [18], a successful attempt was made to calculate not only the future values of meteorological quantities, but also the values of river runoff using the models of the general circulation of the atmosphere and the ocean at the nodes of a three-dimensional spatial grid.

The general state of climatic changes in the modern period on the territory of the globe and Russia is contained in the latest assessment reports of the IPCC and Roshydromet [3, 9].

Regional problems of changes in meteorological fields and climatic characteristics were previously considered also in works [11, 14, 15, 17].

In this article, the main attention is paid to the peculiarities of the temperature and humidity regime in the Volga basin in the periods 1976-2019 and 2001-2019, which have an impact on changes in the hydrological characteristics of the rivers in the Volga basin and, first of all, on the seasonal nature of river flow.

2. Materials and methods
To analyse the spatial and temporal variability of air temperature (AT) and atmospheric precipitation in the Volga basin, the data from 183 stations from the RIHMI – WDC fund located in the basin and near its boundaries, which served as the basis for constructing maps and tables were used. The mean values and linear trends of the specified climatic parameters in the periods 1976-2019 were found and 2001-2019. The main territory of the river basin. The Volga is geographically located within 52° N latitude - 60°, 35° E - 60° E, which roughly corresponds to the schematic maps of this territory given in [2].

To assess the influence of atmospheric circulation (AC) on the thermal regime, the correlation coefficients were found between the AC indices and the air temperature values at individual stations.

3. Results and discussion
Let us consider the features of the spatio-temporal change in air temperature on the territory of the Volga basin in the periods 1976-2019 and 2001-2019 in the central months of the seasons and throughout the year as a whole. As can be seen from table 1, the values of the mean long-term annual AT, as well as the temperatures of the central months of the seasons in the period 2001-2019 significantly exceed the corresponding climatic indicators calculated for the entire period 1976-2019, which indicates a noticeable warming in the basin in the 21st century. There is a noticeable increase in AT from north to south and its decrease from west to east.

Table 2 shows the average long-term values of monthly (January, April, July, October) and annual amounts of atmospheric precipitation (mm) for 2 periods 1976-2019 and 2001-2019. As can be seen from table 2 there is a significant decrease in the amount of precipitation from north to south. At the same time, at most stations, the amount of precipitation in January in 2001 - 2019 slightly exceeds the amount of January precipitation for the entire period 1976-2019. In general, the picture is ambiguous, which is also confirmed by the data of the calculated trends in the amount of precipitation (mm/10 years) for the central months of the seasons and the year for 2 periods. Naturally, much more precipitation falls in the summer than in the winter.

Let us consider the results of the analysis of the spatial-temporal distribution of linear trends in air temperature and atmospheric precipitation in the Volga basin (VB), calculated for the central months of the seasons and the year as a whole in the periods 1976-2019 and 2001-2019.
Table 1. Average air temperatures (°C) of the central months of the seasons and for the year over the intervals 1976-2019 and 2001-2019 by stations of the Volga basin.

| № | Station               | January 1976-2019 | January 2001-2019 | April 1976-2019 | April 2001-2019 | July 1976-2019 | July 2001-2019 | October 1976-2019 | October 2001-2019 | Year 1976-2019 | Year 2001-2019 |
|---|----------------------|-------------------|-------------------|----------------|----------------|---------------|---------------|------------------|------------------|----------------|----------------|
| 1 | St. Petersburg       | -5.9              | -5.4              | 5              | 5.4            | 18.6          | 19.6          | 6                | 6.2              | 5.8            | 6.5            |
| 2 | Vologda, Priluki     | -10.9             | -10.2             | 3.4            | 3.7            | 17.4          | 18.1          | 3.1              | 3.5              | 3.1            | 3.8            |
| 3 | Syktyvkar            | -14.3             | -13.5             | 1.7            | 2.2            | 17.3          | 17.9          | 1.3              | 1.8              | 1.3            | 1.9            |
| 4 | Kirov, AMSG          | -12.2             | -11.7             | 3.8            | 4.1            | 18.6          | 19.3          | 2.5              | 3                | 3              | 3.6            |
| 5 | Kostroma             | -9.8              | -9.2              | 4.8            | 5.1            | 18.4          | 19.4          | 3.9              | 4.3              | 4.2            | 4.8            |
| 6 | Izhevsk              | -12.8             | -12.2             | 3.7            | 4              | 18.8          | 19.1          | 2.9              | 3.4              | 3              | 3.5            |
| 7 | Yekaterinburg        | -13               | -13               | 4.4            | 4.7            | 18.8          | 19.8          | 2.8              | 3.2              | 3              | 3.4            |
| 8 | Moscow, VDNKh        | -7.1              | -6.8              | 6.6            | 7              | 19.1          | 20.2          | 5.3              | 5.8              | 5.8            | 6.5            |
| 9 | Nizhny Novgorod, AMSG| -9.2              | -8.8              | 5.9            | 6              | 19.2          | 19.9          | 4.5              | 5                | 4.8            | 5.4            |
| 10| Smolensk             | -6.8              | -6.4              | 6.3            | 6.8            | 17.7          | 18.6          | 5.1              | 5.6              | 5.6            | 5.4            |
| 11| Kazan, cgms          | -10.8             | -10.2             | 5.3            | 5.9            | 20.1          | 20.9          | 4.5              | 5.3              | 4.6            | 5.4            |
| 12| Ufa, Duma            | -12.9             | -12.5             | 5.3            | 5.7            | 19.6          | 20            | 4.1              | 4.7              | 3.7            | 4.3            |
| 13| Samara, OGMS         | -10.4             | -9.9              | 7              | 7.5            | 21.4          | 22.1          | 5.6              | 6.4              | 5.6            | 6.4            |
| 14| Kursk, AE            | -6.8              | -6.3              | 7.8            | 8.4            | 19.5          | 20.8          | 6.2              | 6.9              | 6.5            | 7.5            |
| 15| Saratov, cgms        | -8.4              | -8.2              | 8.2            | 8.6            | 22.5          | 23            | 6.6              | 7.1              | 6.9            | 7.5            |
| 16| Orenburg, ZSMO       | -12.3             | -12.2             | 7.1            | 7.7            | 22.3          | 22.7          | 5.5              | 6.2              | 5.3            | 6              |
| 17| Elista, AMSG         | -4.4              | -4.1              | 10.3           | 10.1           | 24.9          | 25.5          | 9.6              | 10.2             | 9.9            | 10.5           |
| 18| Astrakhan, GMO        | -4.1              | -3.9              | 11.4           | 11.3           | 25.7          | 26.3          | 10.1             | 10.9             | 10.6           | 11.2           |

Note: tables 1, 2 show data only for individual stations.

In the period 1976-2019 in January, AT increased in the extreme northwest of the VB at a rate of 0.60–0.79°C/10 years, in the west and in the center at a rate of 0.40–0.59°C/10 years, and in the east, warming slowed down (linear trend slope coefficient (LTST) = 0.20–0.39°C/10 years).

In April the picture turned out to be more homogeneous; in most of the territory, the CNLT was of the order of 0.20–0.39°C/10 years.

In July in the western and especially in the southwestern part of the VB, there was a rather strong warming at a rate of 0.60–0.79°C/10 years, and in the central (LTST = 0.40–0.59°C/10 years) and especially In the eastern part of the VB, warming took place at a slower pace, especially in the northeast, where LTST = 0.20–0.39°C/10 years. On the whole the July picture was homogeneous; it was increasing throughout the AT territory.

In October AT increased noticeably in the southern and southeastern parts of the VB (NLCT = 0.60–0.79°C/10 years). So, at the Samara station LTST = 0.86°C/10 years, this is the maximum. In the west of the VB, LTST = 0.40–0.59°C/10 years. As in July AT increased throughout the entire territory of the Volga basin.

An analysis of the spatial distribution of trends in the mean annual air temperature indicates that, in general, in the Volga basin in the period 1976–2019 a fairly uniform picture has developed: in the northwest, north, in the center of the VB, warming occurs at a rate of 0.40–0.59°C/10 years, in the east – 0.30–0.39°C/10 years, and only in the extreme south-western LTST = 0.60–0.69°C/10 years (figure 1).
Table 2. Average values of precipitation sums (mm) for the central months of the seasons and for the year over the intervals 1976-2019 and 2001-2019 by stations of the Volga basin.

| №   | Station       | January 1976-2019 | April 1976-2019 | July 1976-2019 | October 1976-2019 | Year 1976-2019 |
|-----|---------------|-------------------|-----------------|----------------|-------------------|----------------|
| 1   | St. Petersburg| 45 47 34 37 84 87 | 63 63 663 692   | 7         | 1         | 79         |
| 2   | Vologda, Priluki| 34 35 30 25 77 69 | 52 57 572 559   | 9         | 4         | 72         |
| 3   | Syktyvkar     | 41 47 34 39 74 74 | 60 59 626 674   | 8         | 6         | 21         |
| 4   | Kirov, AMSG   | 47 53 35 37 83 74 | 66 69 672 688   | 5         | 7         | 16         |
| 5   | Kostroma      | 42 41 34 36 77 75 | 62 66 631 627   | 3         | 9         | 23         |
| 6   | Izhevsk       | 31 33 28 29 65 71 | 51 54 520 547   | 2         | 10        | 11         |
| 7   | Yekaterinburg | 25 24 32 34 90 81 | 41 43 525 531   | 1         | 12        | 24         |
| 8   | Moscow, VDNKh | 52 53 38 39 87 82 | 66 70 713 710   | 0         | 14        | 26         |
| 9   | Nizhny Novgorod, AMSG | 38 37 34 35 78 74 | 58 58 597 579   | 8         | 16        | 28         |
| 10  | Smolensk      | 50 51 40 38 91 79 | 63 71 732 731   | 4         | 18        | 30         |
| 11  | Kazan, cgms   | 43 49 32 32 67 68 | 53 53 570 582   | 3         | 20        | 32         |
| 12  | Ufa, Dema     | 45 43 33 33 53 41 | 60 58 581 566   | 2         | 22        | 34         |
| 13  | Samara, OGMS  | 54 57 41 40 52 47 | 51 55 566 546   | 0         | 24        | 36         |
| 14  | Kursk, AE     | 48 53 42 38 79 74 | 55 54 645 629   | 9         | 26        | 38         |
| 15  | Saratov, cgms | 44 49 34 37 50 45 | 36 43 492 498   | 5         | 28        | 40         |
| 16  | Orenburg, ZSMO| 28 26 26 27 41 42 | 34 37 359 359   | 3         | 30        | 42         |
| 17  | Elista, AMSG  | 24 25 28 27 38 44 | 31 35 374 395   | 1         | 32        | 44         |
| 18  | Astrakhan, GMO | 15 13 23 27 21 15 | 19 21 232 233   | 1         | 34        | 46         |

Thus, in the period 1976-2019 in the territory of the Volga basin, there was a moderate warming of the climate.

In the period 2001-2019 in the VB, there were noticeable climatic changes associated with the so-called pause in global warming. Thus, in January, throughout the entire territory of the Volga basin, a cooling took place, especially noticeable in the central southern and southeastern parts, where AT decreased at a rate of $-1.50 \div -1.99^\circ C/10$ years. Extreme cooling was noted at Saratov station (LTST $= -2.08^\circ C/10$ years). In the west and north, the temperature decreased at a slower rate of $-1.00 \div -1.49^\circ C/10$ years. In a narrow strip stretching from Vologda station to the east through Syktyvkar station and further LTST $= -0.50 \div -0.99^\circ C/10$ years.

In April, in the north of the VB, a cooling is noted (LTST $= -0.20 \div -0.49^\circ C/10$ years), and in the rest of the region, a slight increase in AT at a rate of $0.20 \div 0.49^\circ C/10$ years, with the exception of southern and south-eastern regions, where LTST can reach $0.97^\circ C/10$ years (Astrakhan).

In July, in most of the VB, AT decreased at different rates: with LTST values from $-0.20 \div -0.49^\circ C/10$ years (center) to $-1.00 \div -1.49^\circ C/10$ years (northwest). Only in the south and southeast of the VB there was an increase in AT (at the Orenburg station) LTST reached $0.71^\circ C/10$ years.

In October, in the western and central parts of the VB, the AT speed varied mainly within the range $-0.19 \div -0.19^\circ C/10$ years, in the eastern part the cooling was more intense (LTST $= -0.20 \div -0.49^\circ C/10$ years). Extreme cooling was noted at Izhevsk station (LTST $= -0.72^\circ C/10$ years). In the south of the VB (Astrakhan) LTST $= -0.29^\circ C/10$ years.

In the annual plan of intense warming in the period 2001-2019 on the territory of the VB did not happen. In the western part, AT grew at a rate of $0.50 \div 0.59^\circ C/10$ years, in the center and in the east, AT practically did not change.
Thus, in the period 2001-2019 there is no noticeable annual warming on the territory of the VB. But this period turned out to be warmer than the entire period 1976-2019.

Let us consider the distribution of atmospheric precipitation on the territory of the VB in the period 1976-2019.

In January, in the north-western and western parts of the VB, as well as in the center, their growth was noted at a rate of 1.0–1.9 and 2.0–2.9 mm/10 years. In the southern, eastern and south-eastern parts, on the contrary, their decrease is observed: LTST = -0.4 ÷ 0.4 mm/10 years, - 0.5 ÷ - 0.9 mm/10 years. At some stations, the LTST values were higher (or lower) than those indicated. So, at the Orenburg station LTST = -1.2 mm/10 years.

In April, in most of the VB, precipitation intensified (LTST = 2.0÷2.9 mm/10 years), and only in the north and southwest is their decrease noted (CLB = -1.0 ÷ -1.9 mm/10 years).

In July, practically throughout the entire territory of the VB, and especially in the southwest and southeast, their decrease is noted at a rate of -3.0 ÷ -3.9 mm / 10 years. Only in the north-eastern part are there growth foci (LTST = 2.0÷2.9 mm/10 years). LTST values vary across the VB territory within the range from -7.4 to 2.4 mm/10 years.

A spotty structure of the precipitation field is observed in October. In the northern half of the VB, their growth is observed at a rate of 2.0÷2.9 mm/10 years, in the central zone there are minor changes in the precipitation regime (LTST = -0.4÷0.4 mm/10 years). In the south, LTST = 2.0 ÷ 2.9 mm/10 years, and in the southeast, LTST = -1.0÷1.9 mm/10 years. At the station Orenburg, ZGMO LTST = -1.3 mm/10 years.

Trends plotted according to annual precipitation values indicate that in the central part of the VB, the amount of precipitation did not change, in the southwest they decrease at a rate of 5.0÷19.0 mm/10 years, and in the northeast there is an increase in atmospheric precipitation with a speed of 10.0÷29.0 mm/10 years). Their large space-time variation is observed (figure 2).
Figure 2. Trends in annual precipitation mm/10 years 1976-2019.

Period 2001-2019 differs markedly from the previously considered period of 1976 – 2019 in the nature of changes in atmospheric precipitation on the territory of the VB.

In January in the western and especially southwestern part of the VB, there is a positive trend of precipitation growth (LTST = 6.0 ÷ 7.9 mm/10 years), and in the eastern part, on the contrary, there is a shortage of precipitation (LTST = -4.0 ÷ -5.9 mm/10 years).

In April an increase in precipitation occurs throughout the Volga Basin, especially in the center and in the northeast, where the LTST reaches a value of 8.0 mm / 10 years. In the extreme south of the VB at Elista and Astrakhan stations, a negative trend is noted (LTST = -10.3 mm/10 years).

In July also in most of the VB, especially in the northeast, precipitation intensifies, where the LTST reaches a value of 25 mm/10 years, however, starting from Kazan and further south, their weakening is noted at a rate of 5.0 ÷ 9.0 mm/10 years. At Samara station LTST = -11.7 mm/10 years, which is an extreme value. In the extreme south of the VB (stations Elista and Astrakhan), the LTST is greater than zero.

In October the entire territory of the VB, with the exception of the northern and northeastern parts, experiences a precipitation deficit. For example, LTST in the center and in the west reach values of -8.0 ÷ -11.0 mm/10 years and -12.0 ÷ -15.0 mm/10 years, respectively, and only in the north and northeast is their growth observed at a rate 4.0 ÷ 7.0 mm/10 years; 8.0 ÷ 12.0 mm/10 years.

In general during the year in the north-west, north and north-east, atmospheric precipitation grows at a rate of 30.0 ÷ 39.0 mm / 10 years, to the south, in most of the territory of the VB, their deficit is observed (the values of LTST are of the order of -2.0 ÷ -2.9 mm/10 years).

Thus the field of atmospheric precipitation is distinguished by its spatial heterogeneity and the instability of their change over time.

To assess the effect of atmospheric circulation (AC) on the thermal regime of the Volga Basin, pairwise correlation coefficients (r) were calculated between the air temperature of meteorological stations and circulation indices NAO (North Atlantic Oscillation), AO (Arctic Oscillation), EAWR (East Atlantic - Western Russia Oscillation), SCAND (Scandinavian blocking) in the period 1976 – 2019. It was found that in January the North Atlantic Oscillation exerts the greatest influence on the thermal regime of the region: in the west of the Volga basin, the values of r reach 0.7, and in the east, connections weaken and r = 0.4. In July, the connections between AT and NAO fluctuations are weak (r=0.2). The Arctic oscillation also has a significant effect on the warm regime of the region only in January (r in the
west of the basin reaches 0.6), in July the correlations are insignificant. The EAWR circulation mode, on the contrary, acts more effectively on the Volga basin in July, while the connections are closer in its eastern part (r=0.7). The influence of the Scandinavian blocking anticyclone (SCAND index) is more pronounced in January in the center and especially in the east of the Volga basin (r=0.6). Thus, there is an ambiguous relationship between changes in the thermal regime of the Volga basin and circulation systems. The results generally correspond to those previously obtained by the authors in [13, 14].

4. Conclusion
1. Analysis of the distribution maps of air temperature trends in the Volga basin in the central months of the seasons and in general for the year in the periods 1976-2019 and 2001-2019 revealed noticeable spatio-temporal differences in the dynamics of the thermal regime. On an annual basis, the climate is warming in the whole territory of the World Bank; in the northern regions it is more intense. January 2001-2019 stands out, when a significant cooling was noted throughout the VB territory (LTST <0 everywhere), as well as July, when a decrease in AT was also observed in most of the VB (northern and central parts).

2. There is a significant heterogeneity across the territory of the VB in the distribution of atmospheric precipitation in time and space. If in the north and northeast of the VB the amount of precipitation increases, then in the southern regions their decrease over time is observed.

3. Atmospheric circulation has a significant effect on the temperature regime of the Volga basin. Correlation analysis showed that the circulation modes NAO and AO have the greatest effect in January to the west of the VB (r reaches 0.7), the circulation mode East Atlantic – Western Russia manifests itself most effectively in July in the eastern part of the VB, and the blocking anticyclone (index SCAND) has closer ties with the January AT fluctuations in the center and especially in the east of the VB.

The performed analysis of changes in air temperature and atmospheric precipitation in the periods 1976-2019 and 2001-2019 shows that climate warming and an increase in the amount of atmospheric precipitation are observed on the territory of the Volga basin, which leads to a change in the hydrological characteristics of the region's river system.

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