Research of synoptic processes in the south-east of the Russian plain during different climatic periods

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Abstract. This article examines the annual and seasonal (winter and summer) changes in the frequency of occurrence of the main types of synoptic processes in the Lower Volga region in two natural climatic periods of the state of the earth climatic system - the stabilization period and the second wave of global warming. The frequency of occurrence of some types of synoptic processes revealed both climatic and seasonal differences. In the second wave of global warming, in comparison with the stabilization period, the frequency of cyclone impact on the Lower Volga region developed on the Arctic front and the number of Arctic anticyclones increase, and the frequency of polar-front cyclones and cases of the impact of the western periphery of the winter Asian anticyclone decreases. Seasonal differences in the frequency of occurrence were revealed in the Arctic anticyclones. During the second wave of global warming, these anticyclones penetrate into the Lower Volga region in summer more often than in winter. It is concluded that the contribution of the transformation factor to the observed warming increases and the role of summer seasons in the observed climatic changes increases, which is not typical for processes in the earth climatic system. It is indicated that obtained result is of great climatological significance and will serve the further development of the physical theory of climate.

1. Introduction
The main trend in the global climate change is a steady progressive increase in the surface air temperature with some fluctuations [2, 14]. It is known that in the Northern Hemisphere over the past 100–120 years, during the mean surface air temperature, climatic periods such as the first wave of global warming, the period of stabilization, and the second wave of global warming are distinguished [2, 11, 13, 14]. However, at the regional level, climatic changes may have their own characteristics and do not always coincide with global trends. For example, in the Lower Volga region, the first wave of global warming did not manifest itself at all, and the development of the second wave of global warming began in the mid-1980s, and not from the mid-1970s, as in the hemisphere as a whole [4, 5, 7, 9].

Undoubtedly, regional climatic variability is formed under the influence of the general circulation of the atmosphere, namely, synoptic processes developing over the region. The recurrence of certain synoptic processes forms the regional climatic background.

The purpose of this work was to objectively identify the boundaries of climatic periods and identify
the prevailing types of synoptic processes in different climatic intervals. The study area was the southeast of the European part of Russia, namely the Middle and Lower Volga regions.

2. Materials and methods
Since the most striking indicator of modern climatic changes is air temperature, the initial material of the study was the data on the anomalies of the near-surface air temperature in the Northern Hemisphere, taken from the website (http://www.cru.uea.ac.uk/cru/data/temperature/#datdow).

For an objective identification of the boundaries of climatic periods, the stepwise trend method was applied to the available time series using the Kolmogorov statistics [3, 6, 8]. To further substantiate the statistical significance of changes in the near-surface air temperature to the selected climatic intervals, the method of confidence intervals was used using Student's statistics (95% significance level). The calculations were carried out according to the following formula (1)

$$\bar{x} \pm t_{\gamma} \frac{s}{\sqrt{n}}$$  

where $\bar{x}$ is an average value; $t_{\gamma}$ - Student's statistics, $\gamma$ - Significance level indicator (95%); $s$ - mean square; $n$ - Number of members of the series.

The regional typification of synoptic processes developed by professor V.L. Arkhangelsky [1], and refined by E.A. Polyanskaya [12] was chosen as a characteristic of the circulation conditions. According to the research of V.L. Arkhangelsky and E.A. Polyanskaya, all the diversity of synoptic processes in the Lower Volga region is divided into seven main types.

I. Cyclonic activity in the Arctic front.
II. The impact of the Arctic anticyclone.
III. Impact of the Asian winter anticyclone.
IV. Impact of the subtropical anticyclone.
V. Low-gradient fields of high and low pressure.
VI. Cyclonic activity in the polar front.
VII. Deformation field.

The type of synoptic process is determined according to the methodological recommendations of V.L. Arkhangelsky [1] based on a set of synoptic material, including daily weather maps, baric topography maps and thermobaric maps. For each type of process, V.L. Arkhangelsky and E.A. Polyanskaya give examples of weather maps, the distribution of the geopotential values characteristic of this type, the location of altitudinal zones, and the thermobaric field of the middle troposphere [1, 12]. The type of process is determined separately for each selected item, taking into account the history of the development of the process and its transformation over time. It is a visual analysis maps.

To analyze synoptic processes during the stabilization period, the authors used an archive of types of synoptic processes of V.L. Arkhangelsky based on synoptic material received by the forecast center in Saratov via facsimile channels. Facsimile weather maps, baric topography maps and other maps were compiled at the Hydrometeorological Center (Moscow) and broadcast by fax. The archive of types of processes based on the available synoptic material covers the period from 1949 to 1969. This time interval falls on the stabilization period. The authors of this study believe that this working sample is quite representative for the characterization of processes in this climatic interval.

The sample of synoptic material characterizing atmospheric processes during the second wave of global warming was formed by daily downloading of synoptic maps, which are regularly posted on the ftp-server of the Hydrometeorological Center of Russia in the GRIB code. Since the definition of the type of synoptic process is very difficult, the Calendar of synoptic processes was compiled by E.A. Polyanskaya only for 2011. Therefore, to analyze synoptic processes during the second wave of global warming, we used a sample containing information on the circulation conditions from 1998 to 2013, which the authors consider to be representative for characterizing the circulation conditions during the second wave of global warming.

Let us point out that in Tables below, the stabilization period is designated as SP, the second wave of global warming as SW. For each period, the frequency of synoptic processes was calculated, expressed in the number of days with a process of this type, i.e. absolute frequency. Samara, Saratov, Volgograd and Astrakhan were taken as reference points in which the type of synoptic process was
determined. The type of synoptic process was determined by the surface weather map (or 00 hours GMT).

3. Results
The study of the time series of surface air temperature anomalies in the Northern Hemisphere for uniformity revealed years of disturbance in uniformity. These years were 1908, 1944, 1975. The significance level was assumed to be 95%. The procedure made it possible to objectively determine the boundaries of climatic intervals. Table 1 shows the boundaries of climatic intervals and an assessment of the statistical significance of temperature changes.

Table 1. Assessment of the statistical significance of changes in the average annual temperature anomalies in the Northern Hemisphere

| Period, year                  | Statistical characteristics of changes | Confidence interval |
|-------------------------------|----------------------------------------|----------------------|
|                               | $\alpha$ | $\bar{x}$ | $\sigma$ |                              |                      |
| 1) Little Ice Age (1850-1907) | -0.0014  | -0.283    | 0.147    | $[-0.508; -0.315]$            |
| 2) first wave (1908–1943)    | 0.0163   | -0.185    | 0.194    | $[-0.240; -0.130]$            |
| 3) stabilization (1944–1974)  | -0.0058  | -0.020    | 0.124    | $[-0.078; 0.038]$             |
| 4) second wave (1975–2016)   | 0.0240   | 0.356     | 0.320    | $[0.273; 0.439]$              |

The alternation of positive and negative values of the coefficients of linear trends, as well as the absence of overlapping of the boundaries of the confidence intervals, allows the changes to be considered statistically significant. S.V. Morozova [10, 15, 16] proposed to name these time intervals the natural climatic periods of the state of the Earth climatic system.

Figure 1 shows a graph of the change in the surface air temperature of the Northern Hemisphere with the drawn trend lines. This graph clearly shows the natural climatic periods of the state of the Earth climatic system.

Figure 1. Variability of the average hemispheric air temperature

The characteristics of the circulation conditions in two natural climatic periods are given in Table 2. This Table shows the average annual number of days with processes of each type at four points of the Lower Volga region - Samara, Saratov, Volgograd, and Astrakhan during the stabilization period and during the second wave of global warming.

According to Table 2, three types of processes are decisive in the formation of weather and climatic instability at all reference points of the Lower Volga region. These are cyclonic activity in the Arctic and polar fronts (types I and VI) and the impact of Arctic anticyclones (type II).
For the entire studied period, including two natural climatic periods, in Samara and Saratov, cyclonic activity on the Arctic front and the impact of Arctic anticyclones prevail of the above three types of synoptic processes. In Volgograd and Astrakhan, located to the south, the weather is most often determined by Arctic invasions and polar front cyclones. It can be explained by the fact that polar front depressions are pumping fresh portions of cold Arctic air into their rear to the extreme southeast of the European Russia, while a new cyclonic series has already formed in the Arctic front to the north, in the Middle Volga region. The arctic air is stationary over the territories for a long time according to the type of anticyclonic circulation. A detailed description of such phenomena with an analysis of daily synoptic situations can be found in [9].

Table 2. Frequency of synoptic processes (year)

| Process type | Period | Point        |
|--------------|--------|--------------|
|              |        | Samara | Saratov | Volgograd | Astrakhan |
| I            | SP     | 84.2   | 74.1    | 56.5      | 42.1      |
|              | SW     | 95.4   | 98.6    | 63.5      | 43.6      |
| II           | SP     | 73.2   | 69.9    | 61.9      | 58.8      |
|              | SW     | 105.6  | 99.5    | 103.0     | 100.0     |
| III          | SP     | 40.9   | 38.3    | 33.8      | 35.6      |
|              | SW     | 36.2   | 27.5    | 30.5      | 32.1      |
| IV           | SP     | 38.0   | 45.6    | 56.5      | 64.2      |
|              | SW     | 21.0   | 26.4    | 32.5      | 35.9      |
| V            | SP     | 23.7   | 28.5    | 25.9      | 30.6      |
|              | SW     | 51.4   | 53.7    | 64.4      | 87.3      |
| VI           | SP     | 84.5   | 90.8    | 111.4     | 95.4      |
|              | SW     | 34.3   | 44.5    | 51.5      | 42.5      |
| VII          | SP     | 7.8    | 17.7    | 19.2      | 8.8       |
|              | SW     | 21.0   | 18.5    | 20.2      | 23.2      |

Comparison of the frequency of synoptic processes during the stabilization period and the second wave of global warming revealed a change in the frequency of synoptic processes in these two climatic intervals.

In all points of the Lower Volga region, with the exception of Astrakhan, during the second wave of global warming, compared with the stabilization period, the frequency of cyclones developed in the Arctic front significantly increased. The absolute frequency of this process has increased by an average of 1.5 times. In Astrakhan, no change in the frequency of this type of process (I) from one natural climatic period to another was observed.

During the second wave of global warming, the influence of the Arctic anticyclones on the region almost doubled in comparison with the stabilization period. The difference in the frequency of these invasions between two natural climatic periods increases from north to south (from Samara to Astrakhan). Another feature associated with this type of process is that during the stabilization period, the frequency of Arctic invasions decreased from north to south (from Samara to Astrakhan), and during the second wave of global warming, the number of Arctic invasions in all points turned out to be approximately the same.

It should be noted that while the influence of the Arctic anticyclones on the region increased during the second wave of global warming, other anticyclones determined the weather in the Lower Volga region much less often. In the second studied climatic interval (the second wave of global warming), the territory was less often influenced by the western periphery of the winter Asian anticyclone and the eastern periphery of the Azores pressure maximum.

During the second wave of global warming, in comparison with the previous period (stabilization), the frequency of cyclones developed in the polar front decreased by almost two times. Moreover, this tendency is typical for all points. Besides, deformation (type VII process) and low-gradient (type V process) fields over the Lower Volga region were much more often than during the stabilization period.
According to Table 1, an increase in the number of impacts on the region of the Arctic anticyclones was found out. Undoubtedly, the question arises about the apparent discrepancy between the observed warming and the increase in the number of Arctic invasions. To resolve this paradox, let us consider the recurrence of processes in winter and summer (Table 3).

**Table 3.** Frequency of various types of synoptic processes in winter and summer.

| Process type | Period | Samara (winter) | Samara (summer) | Saratov (winter) | Saratov (summer) | Volgograd (winter) | Volgograd (summer) | Astrakhan (winter) | Astrakhan (summer) |
|--------------|--------|----------------|----------------|-----------------|-----------------|-------------------|-------------------|-------------------|-------------------|
| I            | SP     | 25.1           | 14.4           | 24.5            | 11.4            | 19.3              | 7.6               | 15.5              | 5.0               |
|              | SW     | 30.5           | 18.6           | 29.6            | 22.0            | 19.9              | 14.2              | 13.8              | 9.2               |
| II           | SP     | 15.9           | 15.3           | 15.3            | 13.5            | 14.4              | 11.2              | 13.5              | 10.3              |
|              | SW     | 12.3           | 30.0           | 10.2            | 26.8            | 12.9              | 27.3              | 12.6              | 26.2              |
| III          | SP     | 22.3           | -              | 20.6            | -               | 17.5              | -                 | 18.8              | -                 |
|              | SW     | 22.2           | -              | 16.6            | -               | 18.7              | -                 | 19.7              | -                 |
| IV           | SP     | 2.7            | 16.9           | 3.1             | 20.0            | 5.0               | 26.5              | 5.9               | 26.2              |
|              | SW     | 0.6            | 10.7           | 2.3             | 10.5            | 3.1               | 14.1              | 2.8               | 17.8              |
| V            | SP     | 4.4            | 11.4           | 5.6             | 11.9            | 4.8               | 11.4              | 5.0               | 13.1              |
|              | SW     | 10.6           | 20.6           | 11.9            | 18.6            | 13.9              | 22.9              | 21.0              | 28.7              |
| VI           | SP     | 14.8           | 29.5           | 16.8            | 30.8            | 24.8              | 34.2              | 21.8              | 30.0              |
|              | SW     | 8.6            | 9.0            | 13.1            | 9.5             | 12.4              | 11.5              | 11.5              | 7.5               |
| VII          | SP     | 1.8            | 1.2            | 4.5             | 4.4             | 4.5               | 3.9               | 3.5               | 1.5               |
|              | SW     | 5.3            | 4.8            | 4.4             | 3.3             | 4.7               | 3.9               | 4.9               | 4.9               |

According to Table 3, both in winter and summer, from the stabilization period to the second wave of global warming, at three points in the Lower Volga region (with the exception of Astrakhan), the number of cyclones developed in the Arctic front increases and the number of polar-front cyclones decreases. In Astrakhan, seasonal differences in the frequency of occurrence of this type of process are noticeable. In winter, from the first climatic period to the second one, the frequency of occurrence of the Arctic-front cyclones increases, in summer it decreases.

Strong seasonal differences were found out in the frequency of incursions into the region by arctic anticyclones. In winter, during the second wave of global warming, the frequency of penetration of the Arctic cores into the region is less than during the stabilization period. The increased temperature background of the winter seasons is quite explainable by the intensification of cyclonicity and a decrease in the number of intrusions of cold air masses from the Arctic.

In summer, the frequency of the invasion of Arctic anticyclones into the region during the second wave of global warming is more than twice as high as during the stabilization period. Let us recall that sharp and intense cold waves in the continental regions in summer are manifested by short-term cold snaps, followed by long periods of very hot weather. According to the research of V.L. Arkhangelsky and E.A. Polyanskaya [1, 12], in summer under the conditions of the Lower Volga region, fresh Arctic air is transformed into local tropical air within one or two days.

Circulation near the earth's surface cannot but manifest itself in the middle troposphere. Based on the NCEP / NCAR reanalysis data on the geopotential values at the AT-500 GPa level, the fields of geopotential anomalies were constructed in two climatic periods (stabilization and the second wave of global warming) for the central months of winter (Figure 2) and summer (Figure 3).

According Figures 2 and 3, climatically stable areas of negative and positive geopotential anomalies are distinguished on all maps, which indicates the predominance of certain types of processes. In January (Figure 2 a) during the stabilization period, two closed centers of negative geopotential anomalies indicate active cyclonic activity over eastern and southern Europe in the Arctic and polar fronts. During the second wave of global warming (Figure 2b), the disappearance of these foci and the formation of a single band of negative geopotential anomalies is an indicator of a change in the frequency of circulation forms, which was mentioned above.
In July (Figure 3a), during the stabilization period, the area of negative geopotential anomalies over southern Europe indicates the predominance of cyclonicity in this region. In the next climatic period (Figure 3 b), almost all of Europe is occupied by a center of positive geopotential deviations, which indicates the predominance of anticyclones in this region. An independent focus with the highest values of positive geopotential deviations is located in the south of ER. Such a geopotential field indicates an increase in the intensity and frequency of arid events in the south of ER.

![Figure 3a](image1.png) ![Figure 3b](image2.png)

**Figure 3.** Average long-term field of isanomalous of the surface geopotential of 500 GPa in July: a – stabilization period; b - second wave of global warming.

Taking into account the above, we can formulate a following conclusion: in the future, with a possible increase in the average global temperature, the contribution of summer seasons to an increase in the general temperature background may become more significant as a result of transformation processes - heating of dry cold air masses under anticyclone. If in the second wave of global warming, the increase in temperatures was mainly determined by milder winter seasons (advective factor), then in the future, possibly, summer seasons will influence the development of warming due to an increase in the meridionality of processes and an increase in the role of the transformation factor.

An increase in average annual temperatures due to an increase in temperatures in summer seasons is not typical for processes in the earth climatic system, at least in the era of regular meteorological observations. We believe that this provision can be of great importance for the development of the physical climate theory.

It also should be noted (Table 3) that during the period of stabilization both in winter and in summer, the number of Arctic invasions decreased from north to south (from Samara to Astrakhan). During the second wave of global warming in winter, Arctic anticyclones do not extend as far southward than in summer. The number of summer incursions of Arctic cores in Saratov, Volgograd and Astrakhan is the same, that is, summer sharp cold waves propagate further south than winter ones. This phenomenon is also unusual for the development of synoptic processes according to “climatic” rules.

Let us note that the preliminary climatic generalization of synoptic material by the types of synoptic processes (2014 - 2019) showed the preservation of the above trends.
4. Conclusions

In the course of the study, the following conclusions were obtained.

1. The number of cases of impact on the region of some types of synoptic processes differ significantly during the period of stabilization and the second wave of global warming. During the second wave of global warming, in comparison with the stabilization period, cyclones developed on the Arctic front and Arctic anticyclones began to be observed more often in the Lower Volga region. The repeatability of low-gradient and deformation fields has also increased.

During the second climatic period, the western periphery of the winter Asian anticyclone less often settled in the region, subtropical ridges spread less often, and there were fewer polar front cyclones.

2. There are seasonal differences in the frequency of occurrence of some types of synoptic processes in the Lower Volga region. In the second wave of global warming, compared with the stabilization period in winter, the number of Arctic invasions into the region increases, and in summer decreases. This feature allows one to assume an increase in the impact of the thermal features of summer seasons due to an increase in the role of the transformation factor, which is uncharacteristic for the development of processes in the earth climatic system. We believe that obtained result can be of independent importance for the development of the physical climate theory.

3. The features of the distribution of the Arctic cores in the Lower Volga region in two natural climatic periods have been revealed. During the stabilization period, the number of incidents of Arctic invasions into the Lower Volga region decreased from north to south. During the second wave of global warming, the Arctic cores spread throughout the entire territory.

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