Trends in the spatial distribution of agrometeorological indicators on the territory of the Chelyabinsk region in the second half of the XX - early XXI century

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Abstract. The article examines the trends in the spatial distribution of air temperature and precipitation indicators on the territory of the Chelyabinsk region for the period from 1936 to 2019. The average annual temperatures and precipitation were analyzed for 24 meteorological stations of the Chelyabinsk region. The results obtained made it possible to differentiate the study area according to the conditions of the thermal regime and the regime of humidification. The amplitudes of temperature growth were determined with a tendency to an increase in the number of differentiated zones, while a shift of the warming boundary to the north was noted. In mountainous areas, low temperature zones are shrinking and shifting to the northwest. The precipitation regime is orographic in nature, but there is a tendency towards a decrease in the continuity of the identified zones, as well as greater moisture content in the territory of steppe (arid) landscapes, which play an important role in agricultural production in the Chelyabinsk region.

1. Introduction
Climatic parameters are decisive for the development of industrial and agricultural production, construction, assessment of the impact of economic and other human activities on the environment, as well as the comfort of living conditions of the population.

These estimates are used in various regulations and standards, but today these indicators are largely outdated technologically and informatively. This is because they were calculated because of climatic indicators obtained because of primary data from the middle and, at best, until the 90s of the last century.

At the same time, over the past time, both for the territory of Russia and in the South Urals, quite significant climatic changes have been noted. Thus, expert estimates show that around the globe, there is an increase in average annual temperatures of up to 1.5 °C compared to the pre-industrial period, including an increase in extreme temperatures in many regions, and global differences in average and extreme temperatures are expected [1-8]. For the territory of Russia, the most intense warming has been observed since 1976 with an average annual rate of about 0.43 °C / 10 years [3], and in the period 1990–2005 the average annual air temperature increased by 0.4 °C [7].

Analysis of changes in the average annual temperature for 16 meteorological stations in the Urals also shows its growth from 2–3 °C / 100 years for the south and the Trans-Urals and up to 0.7–0.8 °C / 100 years for the Northern Urals [9-16]. At the same time, there is a cyclical nature of climatic dynamics with interannual and intersecular fluctuations. Two cycles of climate change are
distinguished, which differ in the duration and nature of temperature changes [15] and the convergence of extreme temperatures against the background of their growth trend is determined, after which the amplitudes of temperature fluctuations increase, in particular, at the end of the 20th century [17]. Positive amplitudes of temperatures characteristic of warming are in the north and northwest of the Urals, while negative values of the amplitudes are in the northeast of the Urals [4]. For the Chelyabinsk region, the increase in temperatures is confirmed by studies for 19 meteorological stations for the period from 1960 to 2005 [7]. Temperature trends over a longer period according to data from 5 meteorological stations show an average temperature rise of 1.83 °C [10]. In the mountain forest zone, the average annual temperature increases more intensively, which is typical for winter and summer, and in the steppe zone, warming occurs mainly in winter [6]. Evaluation of trends in temperature changes in the Southern Urals for the entire observation period [9] showed that there is no direct relationship between the absolute increase in temperature and an increase in a number of dynamics, with the exception of the steppes of the Southern Urals, where there is a linear increase in temperatures. The best result is obtained by analyzing not annual indicators, but by comparing ten-year and similar periods. At the same time, the temperature peaks of the early XX century for the Trans-Urals turned out to be comparable to the temperatures of the peaks of the early XXI century, and for its last decade, a drop in average annual temperatures or, at least, no increase in them is possible [9]. In addition, for the Southern Urals for the initial period of the XXI century, a different from the previously presented character of temperature and precipitation distribution is noted [11-12]. The expected increase in the role of warm and dry periods against the background of a warming trend may enhance aridization of the steppe territory of the Southern Urals and may be more chaotic than before [5]. Thus, the task of this work is to assess the dynamics of temperature and precipitation regimes and the nature of changes in their spatial distribution on the territory of the Chelyabinsk region for the period of the second half of the XX - beginning of the XI century. 2. Materials and methods The work assessed the nature of the dynamics of average annual temperatures and average annual precipitation and changes in their spatial distribution over the following periods. The first period - 1936 until the beginning of the 60s, the data for which were taken from the "Handbook on the climate of the USSR" [13-14]. The second period - 1966-1978 - based on the results of observations of the Chelyabinsk Hydrometeorological Observatory. The third period - data of daily monitoring of the Chelyabinsk Central Hydrometeorological Service, a branch of the FSBI "Ural UGMS". The data were processed using generally accepted statistical and climatologically methods. In total, the work used meteorological indicators for 24 meteorological stations of the Chelyabinsk region. Since data for the selected observation periods are not presented for all considered meteorological stations, three cartographic layers were formed in the GIS, tied to a common topographic basis and with a single attributive database of average monthly temperatures and monthly precipitation totals. The nature of the spatial distribution of indicators was estimated based on the results of spatial interpolation by the Inverse Distance Weighted (IDW) method [1-2], followed by classification to identify zones of heat and moisture supply. 3. Results The nature of the spatial distribution of temperatures in the Chelyabinsk region in the period 1936-2019 allows you to define five temperature zones, different values of average annual temperatures (table 1). Firstly, this is a zone of the Southern Urals with low temperatures, located in the area of the Nyazepetrovsk meteorological station (1). The zone is characterized by two classes of average annual temperatures (figure 1) - in the immediate vicinity of the meteorological station with average annual temperatures below 1 °C, as well as adjacent territories, characterized by temperatures of 1–1.5 °C.
Table 1. The values of the average annual temperatures of the Chelyabinsk region and their dynamics, °C.

| No | Zone                     | until the 60s | 1966-1978 | 2005–2019 |
|----|--------------------------|---------------|------------|-----------|
| 1  | Nyazepetrovskaya         | < 0.5         | 1.5–2.0    | < 1.0     |
| 2  | Verkhneuralskaya         | 1–1.5         | < 1.0      | 1.5–2.0   |
| 3  | Mountain                 | 0.5–1.0       | 1.0–1.5    | 2.0–2.5   |
| 4  | Foothill-plain           | 1.0–1.5       | 1.5–2.0    | 2.5–3.0   |
| 5  | Plain                    | 1.0–1.5       | 2.0–2.5    | >3.0      |

Figure 1. Zoning of the territory of the Chelyabinsk region according to the values of the average annual temperature (1936–1960).

The second zone is Verkhneuralskaya (2), located in the south of the Ural ridge near the Verkhneuralsk meteorological station. The same indicators of average annual temperatures are typical for the territory of the northwestern part of the Chelyabinsk region, surrounding the Nyazepetrovsk zone. In fact, both zones are a broken (disjunctive) zone in the center of the South Ural mountain range with average annual temperatures of 1.5–2.0 °C and below.

The third zone (3) is also located in the complexly differentiated mountainous regions of the Southern Urals and has a meridional character with a direction along the Ural ridge. The zone is characterized by average annual temperatures of 2.0–2.5 °C.

The fourth (4) zone covers the foothills of the western and eastern macroslopes of the Ural ridge, going east into the lowland Trans-Urals, and also has a meridional nature of its location, going south of Verkhneuralsk to the vicinity of Magnitogorsk and, further, going into the southern regions of Bashkoria. The zone is characterized by average annual temperatures of 2.5–3.0 °C.

The fifth zone (5) is a "tongue" wedging into the flat part of the Chelyabinsk region from the south (from the east of the Orenburg region and the west of northern Kazakhstan) and covering almost the entire flat part of the Chelyabinsk region with a "top" in the area of the Chelyabinsk and Brodokalmak weather stations. The zone is the warmest with average annual temperatures over 3 °C.
Analysis of the dynamics of average annual temperatures for earlier observation periods shows for the Southern Urals significant dynamics not only of the average annual temperatures of zones in the direction of their increase, but also of the number of identified zones. The classification of the mean annual temperature for the three considered observation periods shows for the Chelyabinsk region the process of differentiation of temperature conditions, which has been observed since the middle of the 20th century. If at present there are five zones with six temperature classes, then in the period of the 1960-1970 of the last century, there are three such zones with five temperature classes (figure 2). Including the warmest zone. With further retrospective analysis, for the period up to the beginning of the 60s, only two zones (four temperature classes) are actually determined, and the temperature classes themselves are characterized by a shift in temperatures to lower values (figure 3). An increase in the average annual temperature for the flat zone over the past 50 years by 1.0 C.

Figure 2. Zoning of the territory of the Chelyabinsk region according to the values of the average annual temperature (1966–1978).

The nature of the dynamics and distribution of precipitation in the South Urals in the period under study differs quite strongly from the change and zoning of average annual temperatures (figures 4, 5 and 6).

Firstly, for the observation period up to the beginning of the 60s, three zones of precipitation are clearly distinguished, having a submeridional distribution (figure 4). The zones themselves are located in the direction of the perpendicular northeast - southwest.

The next considered period (1966–1978) is characterized by the lowest precipitation level, as well as a change in both the number and nature of humidification zones (figure 5).

There is a decrease in the number of precipitation zones from three to two, the zone of the highest amount of precipitation in the mountainous zone is practically not expressed, there are only local areas
of high precipitation in the area of the Zlatoust and Kropachevo meteorological stations, the amount of which is less than in the previous period (500–600 mm). The entire zone of the mountainous Southern Urals, as well as the foothills and the lowland forest-steppe part (practically the entire northern half of the Chelyabinsk region), is the only zone of moisture with an average annual precipitation of 400–500 mm. Moreover, the zone itself has a latitudinal nature of its location. The second zone occupies the entire southern half of the Chelyabinsk region and is characterized by a total precipitation of 400 mm or less.

![Figure 3](image.png)

**Figure 3.** Zoning of the territory of the Chelyabinsk region according to the values of the average annual temperature (2005–2019).

At the beginning of the XXI century, despite the fact that, in fact, there are also two zones of moisture, for the Chelyabinsk region there is a period of increase in the level of average annual precipitation, which is dispersed in nature (figure 6). In particular, the nature of the location of the zones resembles that for the observation period up to the 60s - the zones acquire a close to submeridional location in the northeast - southwest direction.

It is likely that this is a manifestation of the cyclical dynamics of precipitation, with a longer period compared to the plain part. The lowest precipitation for the mountainous zone (and region) for the early 2000s (which is not typical for the previous observation periods) is observed in the area of the Nyazepetrovsk meteorological station.
**Figure 4.** Zoning of the territory of the Southern Urals by the values of the average annual precipitation (1936–1960).

**Figure 5.** Zoning of the territory of the Southern Urals by the values of the average annual precipitation (1966–1978).
4. Discussion
Since the beginning of the 20th century, the values of average annual temperatures have a more generalized character and form two and three temperature zones, respectively. In this case, it is noted that, in terms of temperature, the climatic parameters of mountainous regions change towards warming, both in average long-term and, probably, in vegetation periods, which requires further research.

Over the period under study, for the territory of the Chelyabinsk region, there is an increase in average annual temperatures associated with global warming. So, for all periods of the study, the temperature in the southern part of the region increased from 1.0–1.5 °С to 3.0 °С, in the western part - from 1.0–1.5 °С to 3.0 °С, in the northeastern part - from 1.0–1.5 °С to 2.5–3.0 °С, in the mountainous zone - from 0.5–1.0 to 2.0–2.5 °С, in the area of Nyazepetrovsk (northern border) - 0.5 °С and below - 1.0 °С and below, in the area of Verkhneuralsk - from 1.0–1.5 °С to 1.5–2.0 °С. This increase in temperatures led to an increase in temperature differentiation, a change in the number of temperature zones and the nature of their spatial arrangement.

Figure 6. Zoning of the territory of the Southern Urals by the values of the average annual precipitation (2005–2019).

Trends in the nature of the spatial distribution of temperature, the size and shape of the identified temperature zones have changed significantly. At the beginning of the 21st century, the meridional strike is noted only for the mountainous zone. The warmest zone also lacks not only meridional, but also latitudinal nature of the location, which may reflect the tendencies of climate warming in the Southern Urals by the type of "invasion" of heat from the southeast of the Ural ridge to the plains of the Southern Urals. At the same time, the southern spurs of the Ural Mountains serve as a barrier to the advance of the high temperature zone to the west. In the period of the 60s - 70s the zones have a
clear meridional strike associated with the location of the Ural ridge. Finally, for the period before the beginning of the 60s, there is no clear temperature zoning of the plain and foothill part of the Southern Urals - the coldest zone is a “tongue” associated with the penetration of cold air masses from the Middle Urals along the mountain ridge to the south into the center of the mountain zone of the Chelyabinsk area.

The territory of the foothill and lowland part of the Chelyabinsk region is one temperature zone with two enclaves of local warmer average annual temperatures - Chelyabinsk (most likely associated with the industrial development of Chelyabinsk and a corresponding increase in temperatures in the area of a large industrial center) and Kartalinsky (steppe enclave).

The zone with the highest level of annual precipitation is typical for the mountainous zone of the Chelyabinsk region with the maximum level of annual precipitation (> 700 mm) in the area of the Zlatoust and Medvedevskaya meteorological stations. Further, a zone of foothills and southern spurs of the Urals is noted, covering most of the forest-steppe zone and the entire north of the Chelyabinsk region, with an average annual precipitation of 500-600 mm. The rest (most of the plain of the South Urals) is the zone of the lowest precipitation level with an average annual amount of less than 500 mm.

At the beginning of the 20th century, the zone of the lowest precipitation level becomes more arid (400 mm or less), but less pronounced - it is not a single zone, but has a disjunctive (broken) character and represents several enclaves of minimum moisture: eastern (Oktyabrsky weather station), southern (meteorological station Bredy) and transitional (Yuzhnouralsk - Troitsk). As for the observation period up to the 60s, in the early 2000s, most of the territory of the Chelyabinsk region (the entire flat part and part of the foothills) is one humidification zone with a total precipitation of 400–500 mm. In fact, this means that most of the territory, according to moisture conditions, rhythmically repeats the period up to the 60s. Thus, for the level of average annual precipitation in the flat part of the Chelyabinsk region, cyclical dynamics with a half-century period is likely. Finally, the second humidification zone occupies a mountainous strip, foothills and part of the north of the Chelyabinsk region. However, unlike the period before the 60s, it is not divided into two zones, but has two small enclaves of high precipitation in the area of the Miass meteorological stations - Zlatoust and Katav-Ivanovsk, and is characterized by a slightly smaller - 500-600 mm - average annual sum precipitation.

5. Conclusion

Thus, for the Chelyabinsk region, temperature changes during the three studied periods are characterized by an increase in the mean annual temperatures and an increase in the complexity and contrast of the climate in terms of mean annual temperatures (an increase in the number of identified heat supply zones and temperature amplitude). The previously observed meridional nature of the spatial distribution of temperature zones is significantly transformed as a result of periods of warming.

For different regions of the Chelyabinsk region, the course of temperature growth is different, in mountainous regions it is less pronounced than in the plains, while the plains are of the greatest interest.

Precipitation trends are cyclical, with fluctuations over half a century. The relationship is traced between the change in the amount of precipitation and the appearance of pronounced zones with the highest or lowest values. At the same time, for the Chelyabinsk region, for the last time, there has been a tendency to an increase in the average annual precipitation with the disappearance of arid territories and the subsequent manifestation of more humid humid conditions in the southern regions. Most of the precipitation in the mountainous parts has an orographic nature of origin, namely, it is determined by circulation processes, therefore, changes within the mountainous territories are more pronounced.

Steppe plots already lacking sufficient moisture in such unstable conditions require additional irrigation, as well as a change in the range of cultivated plants. Obviously, a detailed analysis of seasonal changes in temperature and especially precipitation is required, where trends for the growing season will be clearly visible for the plain-steppe territories of the Southern Urals.
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