Spatial and temporal trends of atmospheric humidification in the steppe part of the Trans-Volga-Ural region

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Abstract. The results of the regional climate change research on the example of the Volga-Ural steppe region are presented. Spatial and temporal patterns in the long-term (1960-2020) dynamics of atmospheric humidification are analyzed. It was revealed that the long phase with increased precipitation, which lasted in the region from about 1980 to 2010, was replaced everywhere by a clearly represented dry phase, especially in the Southern Urals and the Trans-Urals. There is also an intra-annual redistribution of precipitation for all weather stations (an increase in the share of the cold period precipitation and a decrease in the warm period rainfall), which leads to the levelling of humidification conditions. Speaking about the calendar months, the transformation of atmospheric humidification for separate periods of 1960-2020 at weather stations is quite multidirectional. The transformation of atmospheric humidification conditions occurs at the background of significant changes in the temperature regime: there is an increase in average annual indicators everywhere (on average by 1°C over 40 years) and average monthly temperatures in the first half of the year (from January to May). It is stated that against the air temperature background, changes in the humidification parameters can lead to the necessity of adapting various types of steppe environmental management to changing weather and climatic conditions.

1. Introduction
Climate continentality is typical for vast regions of inner Eurasia. It implies not only the considerable amplitude of daily and annual temperatures but, to no small extent, one or another degree of aridity. It is insufficient humidification thanks to which steppe landscapes were formed, and unique steppe land-use systems were developed in the south part of Russia, the east part of Ukraine, and most of Kazakhstan. A considerable increase in average monthly temperatures, and, consequently, average annual temperatures, have been noticed for the last decades [1]. Atmospheric humidification changes considerably in separate parts of Europe [2, 3, 4] and the steppe zone of Eurasia [5, 6, 7, 8]. Registered climatic changes cannot help but influence on parameters of ecological and functional stability of steppe landscapes and biocenoses everywhere gone through excessive anthropogenic influence.

A special feature of the climate in the steppe regions of North Eurasia is an extreme variability and trend to increase anomalies of long-term and annual climatic indicators that define the complexity of prediction to secure stable ecological and economic development. Many problems of steppe nature management are closely connected with humidification. They are problems of water consumption in the condition of extremely changeable long-term and seasonal river flow [9, 10], intensification of fire danger [11, 12], the formation of an economically reasonable system of agricultural production [13,
14, 15, 16] and others. A particular topicality is expressed in a necessity to explain and introduce climatically adapted methods of natural resources' use (land, soil, water, vegetation, etc.).

2. Materials
The study's principal task was an assessment of modern trends in the regional aspect (the Trans-Volga-Ural steppe region) based on an analysis of atmospheric precipitation data [17]. Initial data served as the long-term dynamics (1960-2020) of atmospheric precipitation amounts and average monthly temperatures within six weather stations. These weather stations reflected a change of humidification conditions along the vector of reinforcement of continentality's gradient and regional specifics of the examined region (figure 1).

![Figure 1. Location of weather stations.](image_url)

Isolines of annual precipitation totals, mm [18]. A scheme of latitudinal and high-altitude zonality based on [19]: FS – forest-steppe, S1 – northern steppe, S2 – central steppe, S3 – south steppe, SU – an area of high-altitude zonality (South Ural).

3. Methods
The results received from Perelyub, Sorochinsk, and Orenburg weather stations reflect peculiarities of humidification in the plain-steppe Trans-Volga and Cis-Urals regions. Kuvandyk weather station is located within the low mountain forest-steppe part of South Ural, in the Sakmara river valley. Dombarovka and Bredy weather stations are in the steppe Trans-Ural; they are located in a meridional direction relatively each other. Thus, results from these two weather stations reflect special features of humidification in the extremely east (the aridest) sector of the studied region, considering a shift of latitudinal zonal conditions due to the emergence of a barrier-cyclonic role of the Ural mountains.

Data on atmospheric precipitation amount was analyzed, taking into account calendar months, the warm period (April – October), and the annual quantities for the last 60 years. Based on extreme heterogeneity of precipitation amount, there was an averaging of data by the moving 10-years average method to discover a direction of the long-term dynamics and the most general cyclicity signs.

4. Results and Discussion
The prepared diagrams of the annual precipitation dynamics (decade moving avarages) show long-term changes in atmospheric precipitation within the studied region (figure 2).

The diagrams show that atmospheric precipitation falls more frequently in the extreme west part of the Trans-Volga-Ural region (Perelyub) and in the area of the South Ural low mountains (which has a barrier function) than in the west transfer of air mass (Kuvandyk). These two regions (including a weather station located in the aridest sector of the territory, Dombarovka) show a small amplitude of long-term values 130-150 mm for the studied period.

The long-time course of values has as general features so differences. Weather stations of Trans-Ural and the mountain part of Ural registered an increase of precipitation to the middle part of the 1990s, then a considerable decrease was noticed. The most significant reduction of atmospheric precipitation has been seen in Kuvandyk – about 150 mm for 25 years. Within the aridest territories of
Trans-Ural, the climate aridization process was not so transient. For example, in Bredy, the annual precipitation has descended at 70 mm for the last 20 years. In the Trans-Volga and Cis-Urals region's weather station, the optimum of rain had finished in the 2000s, after that the annual precipitation was noticed. In Orenburg, a reduction of the yearly amount of rainfall with a speed of about 60 mm for ten years was registered.

Figure 2. The long-term dynamics of the annual amount of precipitation (mm).

Precipitation of the warm period (April-October), on the whole, repeats the long-term dynamics of annual values (figure 3). The last decades are characterized by low precipitation of the warm period everywhere. But, if in the west and the central parts of the region (Trans-Volga and the Cis-Urals region), this tendency has been noticed during the last 10-20 years, then to the east this trend had been seen earlier beginning from the end of the 1980s (Dombarovka), the middle part of the 1990s (Kuvandyk) and the 2000s (Bredy). A phase of increased atmospheric precipitation is expressed not in all weather stations, but, on the whole, it falls from 1990-2010. Notable that the most west weather station (Perelyub) had been in the fourth place, according to precipitation for the warm period, at the beginning of the examined period, and it came out on top thanks to the less expressed reduction of precipitation, passed ahead Kuvandyk weather station by the end of the period. Kuvandyk recipient increased precipitation (due to its orographic position) comes down to the third place, going past Perelyub and Sorochinsk.

Figure 3. The long-term dynamics of precipitation for the warm period (mm).
Taking into account a ratio of the warm (April-October) and cold (November-March) seasons in the studied region during the total period since the 1960s, a gradual reduction of the warm period’s precipitation is noticed (table 1). This trend is seen in Kuvandyk, where under the current tendency, the portion of precipitation of the warm and cold periods can be equal in the future.

Spatio-temporal heterogeneity in precipitation distribution is in detail noticed under the analysis of long-time annual values on months. The paper shows results as values proceeding from the months grouping according to typical periods of a year (table 2).

| Table 1. A ratio of precipitation for the warm and cold periods. |
|---------------------------------------------------------------|
| **Periods**         | **Cold period** | **Warm period** |
|                     | Precipitation amount, mm | A portion of annual precipitation amount, % | Precipitation amount, mm | A portion of annual precipitation amount, % |
| Perelyub             |                     |                     |                          |                          |
| 1961-1990           | 167                | 40.0                | 245                     | 60.0                     |
| 1971-2000           | 175                | 40.7                | 257                     | 59.3                     |
| 1981-2010           | 187                | 41.2                | 286                     | 58.8                     |
| 1991-2020           | 187                | 41.8                | 261                     | 58.2                     |
| Kuvandyk            |                     |                     |                          |                          |
| 1961-1990           | 189                | 39.1                | 296                     | 60.9                     |
| 1971-2000           | 212                | 42.6                | 289                     | 57.4                     |
| 1981-2010           | 221                | 43.3                | 291                     | 56.7                     |
| 1991-2020           | 206                | 44.2                | 259                     | 55.8                     |

The growth of humidification during the first 3-5 months of a year and reduction of precipitation amount during the rest months of the year have been the real tendency for all weather stations for the last 20 years within the studied region (a raw "n3-n2" in the Table). The most increase of humidification was noticed at the end of the winter-the beginning of spring. The most significant negative trend was seen in the second half of the summer, the most often in July-August. Thus, annual long-time values of precipitation amounts for August in Kuvandyk shortened at 9 mm for ten years.

According to the total annual amount, five weather stations of six have experienced a reduction of atmospheric humidification, the most considerably expressed in Kuvandyk (at 44 mm for ten years), since the growth of the monthly amount of precipitation in this point was noticed only in February. The precipitation amount was either the same or decreased in the rest months of the year. Annual precipitation amount substantially reduced in Dombarovskiy – at 25 mm in a year. There, peak values of climate aridization were seen in July. The only station that kept the former precipitation amount for the last decade was Sorochinsk. However, annual changeability was noticed there. In the total, there was spatial heterogeneity in changes of humidification parameters. The more area was placed to the south-east, the more vital trends to climate aridization were noticed. It is worthy of mentioning that simultaneously partial leveling of the annual distribution of precipitation happened for the account of noticed differently directed trends; the aridest months (January-May) intensified their portions, and a part of the most humid months diminished (except separate weather stations and months).

The revealed transformations in the atmospheric humidification occur against the background of significant changes in the temperature regime. Despite the considerable distance of the extreme points in the studied region (Perelyub and Bredy), the trends of changes at these and other studied weather stations are very similar. Analysis of the long-term dynamics of the thermal regime in the studied area suggests that all weather stations show an increase in the average monthly temperatures of the spring months (March, April and May), as well as some summer and autumn months (August, October and November). The rest of the time, changes in the average monthly temperature parameters are not significant. As a result, the average annual air temperature at weather stations has increased by 0.3-0.5°C over the past 20 years, and by 0.4-1.1°C over the past 60 years.
5. Conclusion
Thus, the Trans-Volga and South Ural’s steppe zone have reduced atmospheric humidification for the last decades, mainly due to decreased precipitation in the second part of the year. The tendency to aridization in Trans-Ural started in the middle part of the 1990s, but in the Cis-Urals region and Trans-Volga at the end of the 2000s. As the authors consider [5, 6, 8], similar trends are seen in the other areas of Eurasia. As the reduction of precipitation amount for the warm period lays over an increase of annual temperatures in the studied region, so the complex indicator of climate usefulness to cultivate crops (the Selyaninov’s Hydrothermal Coefficient) decreases at the same time.

Table 2. Annual long-time amount of atmospheric precipitation (mm).

| Periods and declines | Months / Precipitation norm, mm | Year |
|----------------------|---------------------------------|------|
|                      | I-III  | IV-V  | VI-VIII | IX-X  | XI-XII |
| Perelyub             |        |       |         |       |        |
| 1961-1990 (n1)      | 85     | 41    | 127     | 77    | 82     | 417   |
| 1971-2000           | 92     | 47    | 128     | 82    | 83     | 430   |
| 1981-2010 (n2)      | 109    | 54    | 132     | 82    | 78     | 454   |
| 1991-2020 (n3)      | 112    | 66    | 115     | 80    | 75     | 447   |
| n3-n1               | 27     | 25    | -12     | 3     | -7     | 30    |
| n3-n2               | -3     | 12    | -17     | -2    | -3     | -7    |
| Sorochinsk          |        |       |         |       |        |
| 1961-1990 (n1)      | 60     | 50    | 121     | 69    | 63     | 360   |
| 1971-2000           | 67     | 50    | 131     | 68    | 66     | 375   |
| 1981-2010 (n2)      | 76     | 56    | 132     | 66    | 65     | 389   |
| 1991-2020 (n3)      | 80     | 63    | 123     | 66    | 62     | 391   |
| n3-n1               | 20     | 13    | -2      | 3     | 1      | 31    |
| n3-n2               | 4      | 7     | -9      | 0     | -3     | 2     |
| Orenburg            |        |       |         |       |        |
| 1961-1990 (n1)      | 69     | 54    | 110     | 73    | 69     | 374   |
| 1971-2000           | 68     | 52    | 106     | 64    | 68     | 356   |
| 1981-2010 (n2)      | 76     | 57    | 106     | 62    | 65     | 365   |
| 1991-2020 (n3)      | 78     | 58    | 99      | 59    | 59     | 354   |
| n3-n1               | 9      | 4     | 11      | 14    | 10     | -20   |
| n3-n2               | 2      | 1     | -7      | -3    | -6     | -11   |
| Kuvandyk            |        |       |         |       |        |
| 1961-1990 (n1)      | 93     | 66    | 128     | 102   | 96     | 484   |
| 1971-2000           | 107    | 66    | 130     | 93    | 105    | 498   |
| 1981-2010 (n2)      | 120    | 81    | 125     | 85    | 101    | 510   |
| 1991-2020 (n3)      | 116    | 74    | 108     | 77    | 90     | 466   |
| n3-n1               | 23     | 8     | 20      | 25    | 6      | -18   |
| n3-n2               | -4     | -7    | -17     | -8    | -11    | -44   |
| Dombarovskiy        |        |       |         |       |        |
| 1961-1990 (n1)      | 56     | 47    | 104     | 52    | 48     | 299   |
| 1971-2000           | 60     | 56    | 110     | 52    | 56     | 330   |
| 1981-2010 (n2)      | 67     | 64    | 107     | 47    | 53     | 334   |
| 1991-2020 (n3)      | 66     | 59    | 86      | 46    | 52     | 309   |
| n3-n1               | -10    | -12   | 18      | 6     | -4     | 10    |
| n3-n2               | -1     | -5    | -21     | -1    | -1     | -25   |
| Bredy               |        |       |         |       |        |
| 1961-1990 (n1)      | 57     | 53    | 146     | 55    | 53     | 364   |
| 1971-2000           | 58     | 59    | 142     | 49    | 53     | 361   |
| 1981-2010 (n2)      | 66     | 65    | 130     | 50    | 51     | 361   |
| 1991-2020 (n3)      | 68     | 67    | 115     | 49    | 47     | 346   |
| n3-n1               | 11     | 14    | 31      | 6     | 6      | -18   |
| n3-n2               | 2      | 2     | -15     | -1    | -4     | -15   |

Note: The average annual precipitation totals for a year are calculated by averaging the annual precipitation totals over thirty years.
Considering reasons for a significant reduction of the annual amount of precipitation, we should mention the growth of recurrence and duration of anticyclones [20] for the last two decades. It was blocking anticyclones placed under the central part of Kazakhstan and to the east (so-called Asian maximum), which do not permit Atlantic and Black Sea cyclones to pass through more south-east directions. The work [20] indicates the warm phase of the Atlantic long-time fluctuation as the principal reason for the increase of blocking periods on the European part of Russia, and, as a result, a reduction of atmospheric humidification and occurrence of atmospheric droughts. Parameters of surface humidification and the whole sufficiency of water supply in the steppe regions identify a vast spectrum of interactions between natural and socio-economical systems. Atmospheric, surface and groundwater are some of the leading factors of steppe landscapes' development, forming a volume of the river flow, the intensity of exogenous processes, a structure and productivity of vegetation communities, a formation of fire-dangerous situations, and others. Numerous steppe nature management problems are mainly connected with revealed trends of annual heterogeneity and cyclic dynamics of humidification [14]. The solution to these problems can be realized by adapting separate species of nature management to changeable weather-climatic conditions. Thus, the conducted study made a start integration between the most significant areas of the project realized by the Institute of Steppe UB RAS "Problems of steppe nature management in condition of modern challenges: optimization of the interaction between natural and socio-economical systems" and the results of studies of climatic orientation.

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