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ANALYSIS OF TENDENCIES IN THE SPATIAL AND TEMPORAL DISTRIBUTION OF TEMPERATURE AND PRECIPITATION ACROSS CHELYABINSK REGION AND THE FORMATION OF HEAT AND MOISTURE AVAILABILITY ZONES

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The document shows the tendencies in the spatial and temporal distribution of air temperature and precipitation in the Chelyabinsk region for the period from 1936 to 2019. Average annual temperatures and precipitation were analyzed for 21 meteorological stations in the Chelyabinsk region. The results allowed differentiating the study area according to the conditions of thermal regime and moisture regime. The temperature growth zones are identified, the boundaries of moisture zones are determined. They play a leading role in the development of agricultural production in the Chelyabinsk region.
Keywords: climate, air temperature, precipitation, azonal factors, ecoclimatic zoning, methods of multidimensional statistics in climate research.

INTRODUCTION

Climatic parameters are determinant for the development of industrial and especially agricultural production and the comfort of living conditions for the population.

At Ural's 19 meteorological stations analysis of changes of the annual temperature shows an increase from 2–3°C / 100 years for the south Ural and Trans-Ural region and up to 0.7–0.8°C / 100 years for the Northern Urals [1, 2]. At the end of the 20th century there is an increase in the amplitudes of temperature fluctuations [3]. This is observed until now. Positive temperature amplitudes are in the north and north-west of the Urals, when the negative values of the amplitudes are in the north-eastern Urals [4].

Significant climatic changes have been observed in the Southern Urals over the past time. For the territory of Russia the most intense warming has been observed since 1976 at an average annual rate of about 0.43°C / 10 years [5], and the average annual air temperature increased by 0.4°C between 1990 and 2005 [6]. Average and extreme temperatures are rising globally and in most regions of our country. This is the case in the Southern Urals [7].

Temperature growth is confirmed by studies for 21 meteorological stations for the period from 1960 to 2005 for the Chelyabinsk region [6]. Temperature trends for a longer period according to 5 meteorological stations show an average temperature increase of 1.83°C [8]. In the mountain forest zone, the average annual temperature increases more intensively. It is typically for winter and summer. In the steppe zone warming occurs mainly in winter [9].

Assessment of temperature tendencies in the Southern Urals for the entire observation period [10]. showed lack of direct relationship between absolute temperature increase and the increase in the series of dynamics, with the exception of the steppes of the Southern Urals, where there is a linear increase in temperatures. The best result is not an analysis of annual indicators, but a comparison of decadal and close periods to them. In this case, the temperature peaks of the early 20th century for the Trans-Ural region were comparable with the temperature peaks of the early 21st century, and for the last decade may fall the average annual temperature or at least the lack of their growth [10]. There is also a different distribution of temperature and precipitation for the Southern Urals in the initial period of the 21st century than previously presented [11, 12]. The expected role increasing of warm and dry seasons against the warming tendency may increase the aridization of the steppe area of the Southern Urals and may be more chaotic than before [13].

Thus, the aim of this project is to assess the dynamics of temperature and precipitation regimes and the nature of changes in their spatial distribution in the Chelyabinsk region during the second half of the 20th century and the beginning of the 21st century.

RESEARCH METHODS

In this work we have assessed the nature of the dynamics of average annual temperature and average annual precipitation and changes in their spatial distribution over the following periods. The first period is from 1936 to the beginning of 60s, the data for this period were taken from the "Spravochnik po klimatu USSR"[14, 15]. The second period is from 1966 to 1978 and it is based on observations by the Chelyabinsk Hydrometeorological Observatory. The third period is the data of daily monitoring of Chelyabinsk Center of hydrometeorology and monitoring of environment - a branch of FGBU "Ural'skoe UGMS". The data were processed by using generally accepted statistical and climatological methods.

We used meteorological data from 19 meteorological stations in the Chelyabinsk region. Monitoring data was processed by using mathematical and statistical methods [13], calculating monthly averages of temperature and precipitation. Temperature and precipitation indicators for meteorological stations were analyzed by methods of multivariate statistics [16, 17] — cluster analysis by correlation coefficient with grouping into clusters by Ward method, evaluation of selected clusters by discriminant analysis and nonparametric multivariate scaling by correlation matrix with highlighting and interpretation of axis [9, 8], using nonparametric tau Kendall coefficient [18]. Spatial distribution of temperature and precipitation regimes was evaluated by Inverse Distance Weighted (IDW) [19, 20]. with subsequent classification to identify zones of heat and moisture availability.

RESULTS AND THEIR DISCUSSION

Analysis of the spatial dynamics of temperatures allows us to choose 5 cluster groups (fig. 1), forming several zones and subzones of heat availability in the South Urals and distinguished by specific indicators of average monthly temperatures (tab. 1).

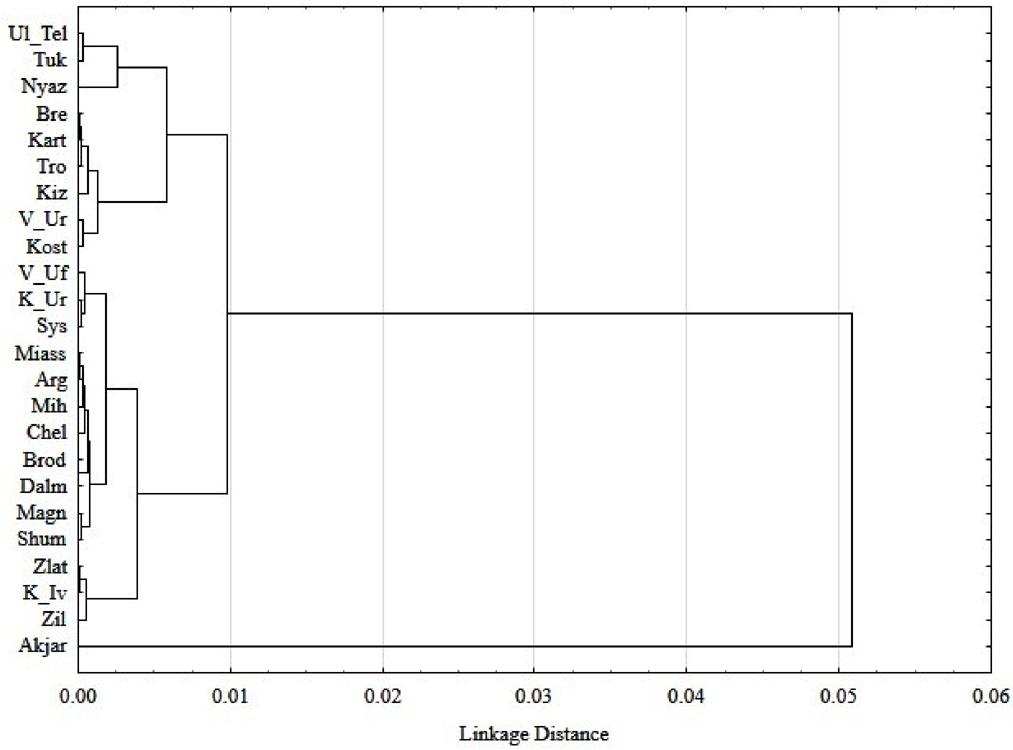

Fig. 1. Cluster analysis of air temperature by meteorological stations in the Southern Urals and adjacent territories.

Features of the spatial location of the zones are allocated according to the average monthly temperatures for the calendar year. They have difference from latitudinal and are characterized by meridional stretching for the territory of the Southern Urals. This is particularly obvious in the Southern Urals and Ural-Tau mountain systems. The meridional zone of the western macro-slope and western spurs of the Ural Mountain Range (cluster 5) is identified. It extends in north-south direction and is defined by meteorological stations Nyazepetrovsk-Ulu-Telyak-Tukan. The formation of this zone is related to the meridional transport of cold air masses along the eastern slope and western ridges of the southern Ural Mountains.

Changes in average annual temperatures for the early observation periods show significant dynamics not only of the average annual temperature of the zones upwards, but also the number of allocated zones for the Southern Urals. The classification of average annual temperature values for the three considered observation periods shows the process of differentiation of temperature conditions for the Chelyabinsk region. This process has been observed since the middle of the 20th century.

The second meridional zone (2) of the centre and eastern macroslope of the Southern Urals and Ural-Tau, extending in a north-south direction.

The azonal distribution of temperatures is due to the complex orographic situation in the study area. The Katav-Ivanovsk meteorological station area is located in a zone of higher average annual temperatures, close to the temperatures of the western macroslope of the Southern Urals. The formation of this zone is associated with the meridional transport of cold air masses along the mountain ranges. The plain part of the Southern Urals belongs to a similar temperature interval. Two temperature zones are formed in this part of the territory - a northern and a southern zone with a latitudinal distribution of temperatures, but it has a heterogeneous character of temperature conditions, and this determines the existence of local meridional temperature subzones.

Table 1.

Average temperature values (^{0}C) for selected heat availability zones of the Southern Urals

Zone	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	-12.4	-14.2	-15.8	6.1	14.8	19.6	21.2	20.4	12.9	3.9	-3.5	-11.7
2	-13.9	-12.0	-5.0	4.2	11.9	16.4	17.7	17.0	10.0	2.4	-4.5	-11.2
3	-15.9	-13.6	-5.4	4.8	12.2	17.3	18.4	17.3	10.7	3.2	-4.3	-12.4
4	-16.5	-15.1	-6.3	5.7	13.8	18.9	19.8	19.0	12.1	3.9	-3.9	-12.5
5	-15.0	-15.2	-7.8	2.4	11.1	15.9	16.6	16.2	9.3	1.6	-5.4	-12.1

Two humidification zones were identified according to studies (Smolensk) at the beginning of the 21st century. For Chelyabinsk region there was a period of increasing average annual precipitation, humidification zones acquired a close to submeridional location in the northeast-southwest direction.

We can assume that this is a reflection of cyclical precipitation dynamics with long periods. For the mountainous area of the Chelyabinsk region in the early 2000s the lowest precipitation is recorded in the area of the Nyazepetrovsk meteorological station and is not typical of previous observation periods.

Thus, there is a colder meridional northern subzone within the northern temperature cluster of the Trans-Ural part of the Southern Urals (3). It is characterized by colder growing season conditions compared to the rest of the zone. This is due to the influence of cold air masses coming from the mountain ranges of the Middle Urals in the spring-summer-autumn period.

The general structure of temperature distribution in the study area differs from the typical latitudinal distribution and it is characterised by a more latitudinal extension in the Trans-Urals. It is observed especially in summer throughout the European part of the country [4]. In this case, the maximum temperature intervals are distinguished by a shift to the northeast. Also, the closer to the eastern slope, the more clearly defined is the meridional transition zone of foothills extending from northeast to southwest (along the line Dalmatovo-Argayash-Miass) and characterized by average annual temperatures up to 3°C. This zone is close to the more northern temperature cluster in the south of Sverdlovsk Region (Sysert and Kamensk-Uralsky meteorological stations), but the foothills of Chelyabinsk region have higher average monthly temperatures in February, March and December.

The flat part of the Southern Urals belongs to a single temperature interval (meteorological stations Troitsk-Kartaly-Kizilskoye-Bredy), and forms a southern temperature cluster (4) with a more latitudinal character of the northern border, characterized by a significant annual temperature amplitude. High temperatures of summer months here are combined with low temperatures of calendar winter, comparable with temperatures of cold mountain zones, but warmer compared to mountain temperature clusters in spring and the warmest calendar autumn in the region. According to temperature monitoring data, there are two temperature subzones for this zone. The first one covers areas of the steppe west of the Republic of Kazakhstan (Kostanay) and the second zone is the steppe foothills of the Southern Urals (Verkhneuralsk) with the greatest increase in continentality and the largest temperature variations over the calendar year, and a colder summer period.

The results of the analysis confirmed the correctness of the clustering of meteorological stations and identification of temperature zones. The classification precision is 100% for all groups of meteorological stations. The discriminant analysis model identifies three statistically significant functions determining the character of temperature distribution within the studied area. Analysis of the model structure (Table 2) showed that in the annual dynamics of temperatures, determining for the formation of heat availability zones in the territory of the Southern Urals are (in decreasing order) the average annual temperatures: January-September-March.

Table 2.

Temperature indicators included in the discriminant analysis model and their connection to the discriminant functions*

Factor	Discriminant Function Analysis Summary				Standardized Coefficients for Canonical Variables		
	Wilks' Lambda	Partial Lambda	F-remove	p-value	Root 1	Root 2	Root 3
IV	0.01	0.88	0.58	0.64	-0.43	-0.17	1.78
III	0.01	0.51	4.10	0.03	-1.84	0.46	-0.49
I	0.03	0.21	16.52	0.00	2.30	1.31	1.20
IX	0.02	0.41	6.36	0.01	4.58	-3.37	-1.24
VII	0.01	0.63	2.56	0.10	-1.06	3.29	1.45
average annual temperature	0.01	0.55	3.55	0.04	-5.07	-1.50	-1.16
XI	0.01	0.74	1.50	0.26	2.04	0.44	-0.26

*— statistically significant indicators are in bold.

Moreover, the factors determining the heat availability zones of the Southern Urals are: in the first function it is a decrease in the annual average temperature and the highest temperature in September; in the second function it is the warmest month of July and the coldest month of September; in the third function it is the warmest month of April and July.

Thus, the distribution of temperature indicators in the territory of the Southern Urals has a clear meridional character. It is connected with the influence of the southern part of the Ural Mountains, the meridional transport of cold in the direction of the ridges and the influence of cold air masses descending from the ridge. January, September and March temperatures are the determining factors, and, to a much lesser extent, July and April temperatures. Due to the complex orographic situation in the mountain ranges, a peculiar "necklace" of meridional temperature zones characterized by specific monthly and annual average temperature values is defined.

The monitoring of annual precipitation patterns and multidimensional classification also allow the identification of 5 clusters (fig. 2), spatially forming meridional humidification zones (fig. 3) characterized by specific indicators of mean monthly precipitation levels (tab. 3).

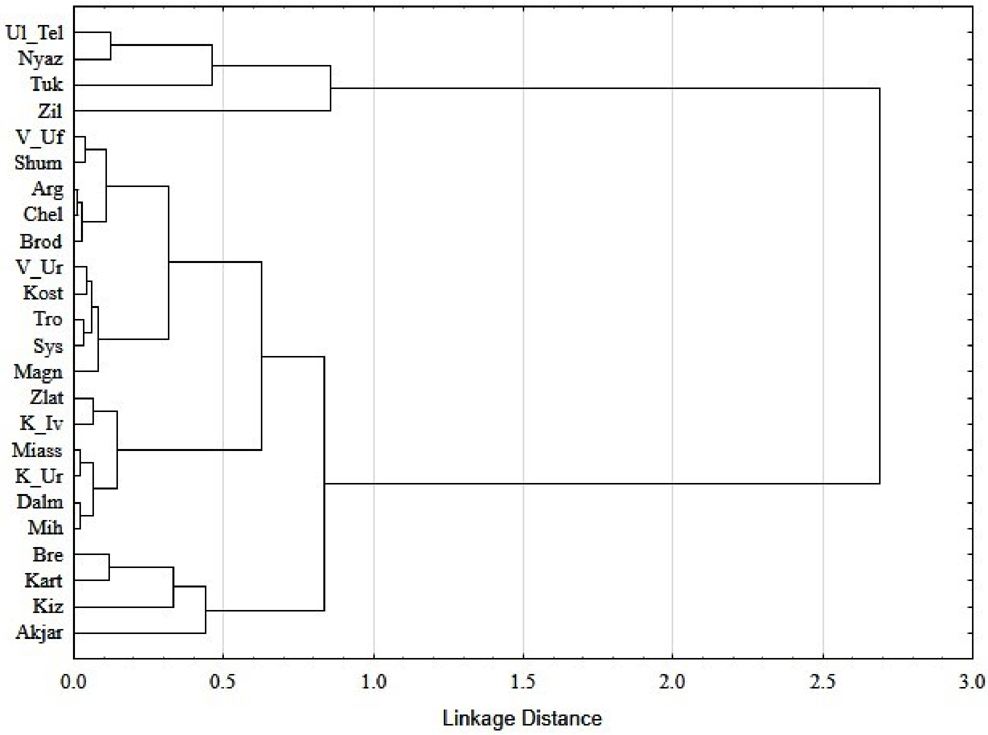

Fig. 2. Clustering of precipitation monitoring by meteorological stations in the Southern Urals and adjacent territories.

The nature of the spatial distribution of precipitation in the Southern Urals is similar to that of temperature and it is also characterised by meridional extention.

Firstly, a meridional southern steppe zone (1) is defined. This zone coincides with the highest temperature zone and the southern and central part of the southern temperature cluster and it is characterized by the least amount of precipitation in late spring-early summer (May-June) and in late summer and autumn (August-November). This zone is also characterized by the lowest average values of precipitation per calendar year and calendar spring-summer-autumn. The reason for the decrease in precipitation is the weakening of the cyclonic circulation in winter. At this time, the area is under the influence of a higher pressure area from the more southerly regions.

Table 3.

Average precipitation values (mm) for selected moisture availability zones of the Southern Urals

Zone	month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	22.4	26.5	30.1	34.4	33.9	43.2	47.4	33.4	26.3	32.8	22.1	26.4
2	24.3	22.2	38.1	41.3	64.8	78.8	78.7	60.9	56.8	46.2	43.4	27.0
3	23.4	22.5	32.6	36.8	47.4	54.9	85.3	66.0	35.9	33.4	29.3	26.2
4	22.0	18.6	29.9	30.4	52.0	66.3	89.0	49.8	37.0	36.6	32.8	22.0
5	25.1	27.1	40.0	40.5	35.5	48.3	38.5	47.6	46.0	52.5	44.9	34.6

Fig. 3. Zoning of the Southern Urals by average monthly precipitation per calendar year (zone numbers correspond to cluster numbers-see text).

A transition zone of the northern part of the steppe Southern Urals(3) with a latitudinal extension is formed to the north. The zone is characterized by average for the Southern Urals monthly precipitation averages for calendar months and "peak" precipitation in July-August.

The central (forest-steppe) part of the Southern Urals is occupied by the moisture availability zone (4), which is characterised by a meridional extension in its northern and central part. This zone is also characterized by "average" for the Southern Urals monthly precipitation averages for the growing season and subsequent autumn period, with a precipitation peak in July.

The mountain and foothill moisture availability zones (2), windward northern and southern slopes, and leeward northern parts are distinguished separately.

The zone is characterized by the highest values of average annual precipitation and the highest amount of precipitation during the calendar spring-summer-autumn period. Moreover, the mountainous area (meteorological stations Zlatoust-Katav-Ivanovsk) coincides with the high-mountain low temperature cluster of the Southern Urals and it is characterized by the highest level of precipitation in the region during the calendar spring-autumn period.

The Predoral cluster (5) has a meridional strike character in the area of the western macro-slope of the Southern Urals and Ural-Tau. The cluster shows a combination with temperature indices and it is characterized by the highest average precipitation amount in winter and early spring (March-April). For the territory of Russia the most significant increase in seasonal precipitation amounts is observed in spring, and this is particularly represented for the territory of Western Siberia. Thus, it can be assumed that the formation of the zone is due to air masses coming in during this period from the Arctic along the western ridges of the Ural Mountains, and a change in baric fields over European Russia, and in particular over the open spaces of Western Siberia.

Four discriminant functions are distinguished in the presented model. The first function is determined by a decrease in precipitation during the calendar spring (March to May). The second one is determined by high precipitation during the summer and the calendar spring. The third function is determined only by high precipitation during the calendar spring and the last by low precipitation during the calendar winter (especially December and February) and the dry month of July.

Thus, all monthly precipitations determined to a greater or lesser extent the specifics of moisture availability clusters.It should be noted that the time interval available for analysis includes the 10-year period of growth of spring precipitation in the European territory of Russia, in the Urals and Western Siberia. This undoubtedly influences the overall analysis, as each of the functions is an aggregate of the overall trend.

Of particular interest is the integrated assessment of heat and moisture availability regimes and differentiation by values of average annual temperatures and precipitation. The cluster analysis (fig. 4) revealed five clusters and, respectively, five areas of heat and moisture availability (fig. 5).

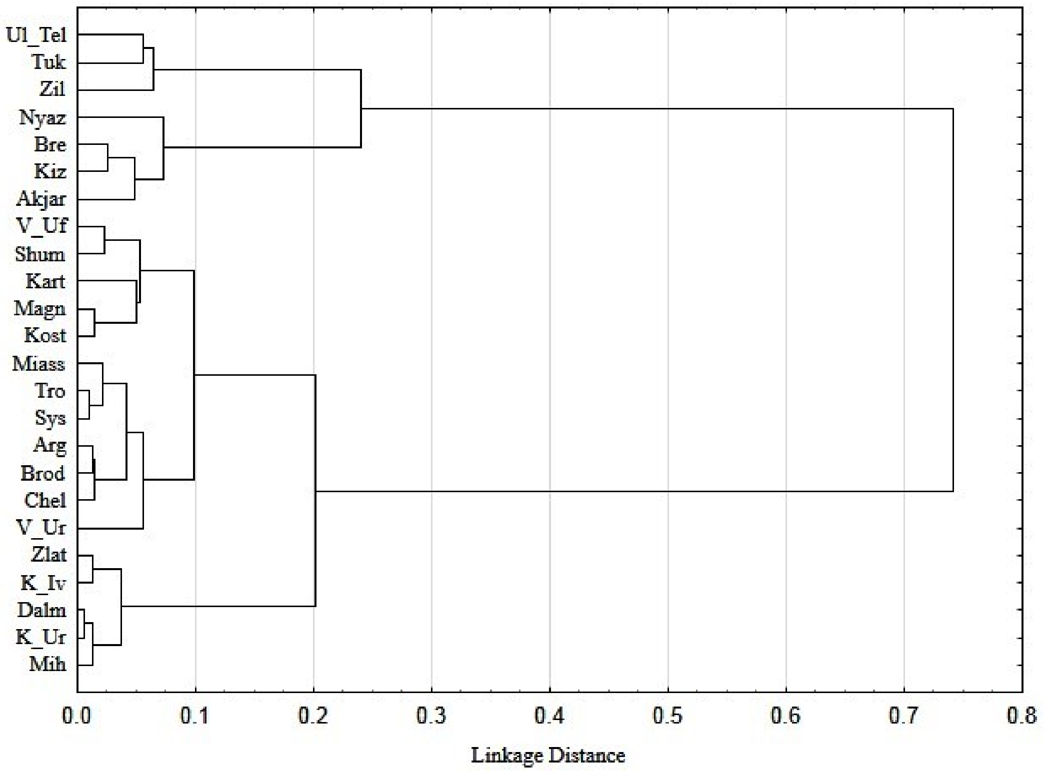

Fig. 4. Classification of temperature and precipitation monitoring by meteorological stations in the Southern Urals and adjacent areas.

First of all, it should be noted that most of the identified areas (fig. 5) largely coincide not with temperature zones, but with zones identified by precipitation monitoring data (fig. 3). This points to the importance of differentiating the territory of the Southern Urals according to climatic parameters by focusing on the distribution of precipitation regime, as well as taking into account the thirty-year and ten-year periods of moisture for a more detailed inter-period analysis.

Firstly, a meridional area is identified that practically coincides with the Pre-Ural precipitation cluster (except for the northern part), determined by data from Ulu-Telyak-Tukan-Zilair meteorological stations(1).

Secondly, the mountain and foothill zone (5) stands out, which almost completely coincides with the zone of high moisture content. Coincidence concerns both mountainous part of Southern Urals (meteorological stations Zlatoust-Katav-Ivanovsk) and Mikhailovsky and meteorological stations Kamensk-Uralsky and Sysert. There come into effect both the vertical zonality in the mountainous part and the predominance in the western part of low relief forms not providing favourable conditions for upward movements and precipitation.

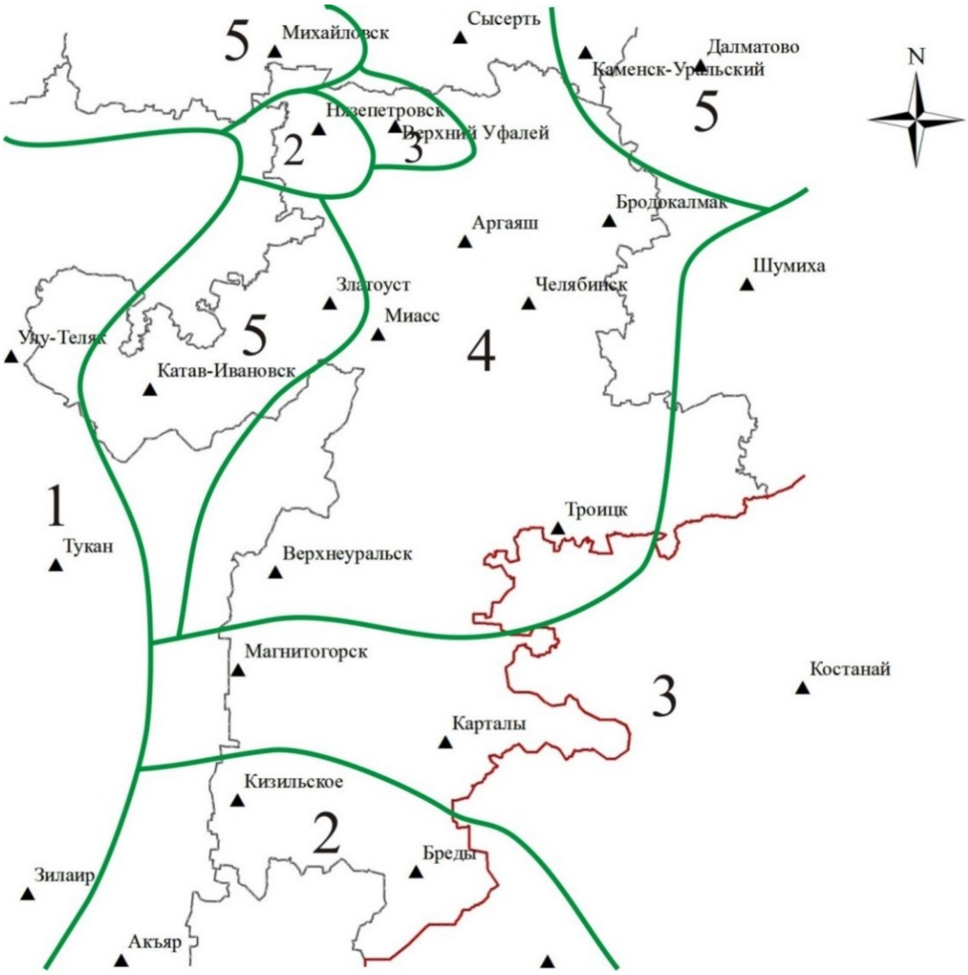

Fig. 5. Zoning of the Southern Urals by heat and moisture availability regimes (area numbers conform to cluster numbers-see text).

There is a southern steppe zone (2), which coincides (except for the north-eastern part in the area of Kartaly meteorological station) with the corresponding precipitation zone. However, the northern transition zone of the eastern slope (3) and the central zone (4) differ from the respective zones highlighted by precipitation levels. Thus, the transition zone includes the northeastern part in the area of Shumikha meteorological station, and the central zone includes the northern part of the area of Sysert meteorological station. Thereby, the last two zones of heat and moisture supply have a stronger meridional character of stretching.

Districts of Nyazepetrovsk (2) and Verkhny Ufaley (3) meteorological stations form separate clusters of heat and moisture supply, gravitating to the more southern dry zones according to the amount of precipitation. They are located on slopes of different exposition. River valleys here are stretched submeridionally. In intermountain basins and on river watersheds there is a downward movement of air, which reduces the amount of precipitation. This confirms the thesis that precipitation regime is a determinant for climatic zoning of the Southern Urals.

Ordination of monthly temperature and precipitation values by non-metric multidimensional scaling methods allowed identifying two leading factors in the complex distribution of these resources in the Southern Urals (fig. 6).

The first geographic and eco-climatic vector determines the nature of the latitudinal change in the temperature and precipitation gradient from the very southern steppe heat and moisture zone (2) to the central zone of the Southern Urals (4). The second vector is latitudinal, that is associated with the direction of movement of air masses from the Ural Mountains in the eastern direction. The character of inclination of these geographic vectors is determined by the peculiarities of meridional transfer of warm and humid air. Climatic conditions of the Pre-Ural region determine a separate temperature cluster (1) that is associated with the movement of air masses westward from the Urals. Finally, mountain and foothill areas form a separate cluster (5).

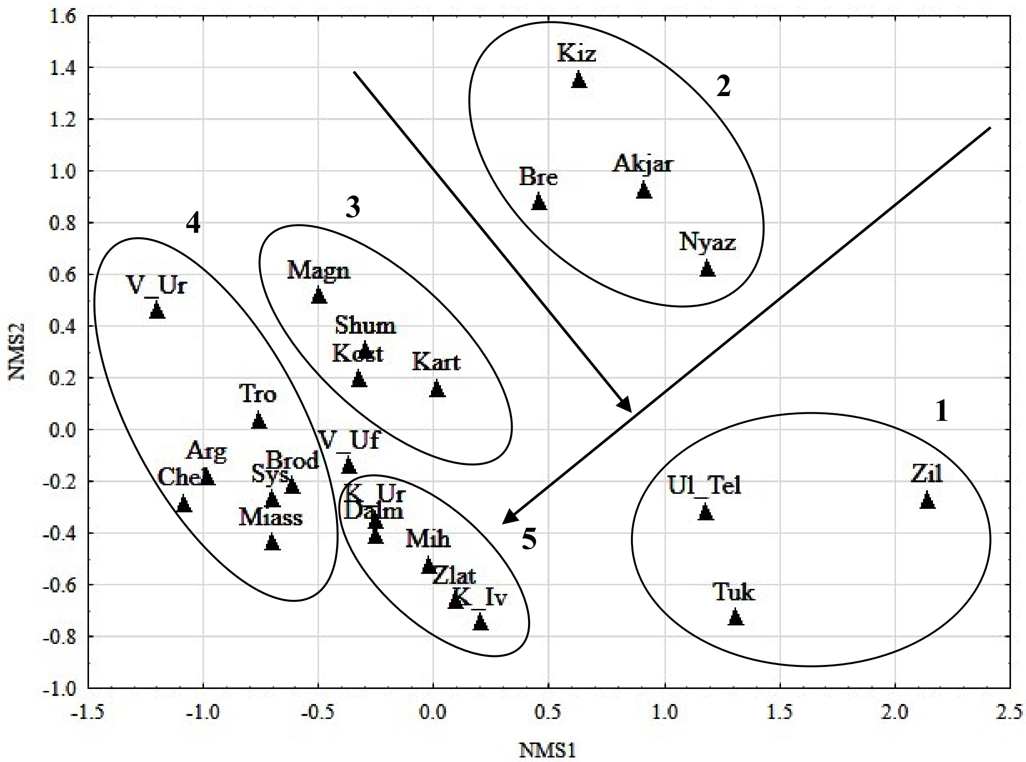

Fig. 6. The ordination of temperature and precipitation monitoring in the non-metric multidimensional scaling axes (there are shown clusters and vectors of the leading climatic factors).

Interpretation of the multidimensional scaling axes (tab. 4) allows determining the following leading eco-climatic parameters. They determine the zoning of the Southern Urals territory according to heat and moisture resources.

Table 4.

Interpretation of non-metric multidimensional scaling axes by seasonal temperature and precipitation dynamics data*

Axis	Factor	Months											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
NMS1	temperature	0.20	-0.07	-0.27	-0.15	-0.01	-0.05	-0.04	0.06	-0.07	-0.20	-0.07	0.06
	Precipitation	0.18	0.28	0.23	0.20	-0.24	-0.22	-0.64	-0.25	0.12	0.24	0.21	0.40
NMS2	temperature	-0.2	-0.2	-0.2	0.4	0.4	0.4	0.5	0.4	0.4	0.3	0.3	-0.1
	Precipitation	-0.2	-0.1	-0.4	-0.4	-0.5	-0.6	-0.2	-0.4	-0.7	-0.4	-0.6	-0.1

* — statistically significant Tau-Kendall values are in bold.

The leading eco-climatic factors that determine the zoning of the territory of the Southern Urals in terms of heat and moisture resources are: arid summer conditions (low precipitation in July), the distribution of precipitation in the mountainous area will be influenced by altitude, and lower relative humidity, active precipitation in winter (in December), the influence of the extension of mountain ranges that determine the transport of the western air masses.

The second factor is complex and is defined as an increase in temperatures from February to November, and a decrease in precipitation from March to June and from August to November.

CONCLUSION

Thus, the temperature changes over the study period can be characterized by an increase in average annual temperature values and an increase in climate complexity and contrast in terms of average annual temperatures (an increase in the number of defined heat availability zones and temperature amplitude) for the Chelyabinsk region. The meridional character of the spatial distribution of temperature zones, which were previously observed significantly transform by warming periods.

The temperature increase varies for different areas of Chelyabinsk region. It is less represented in mountainous areas than in the plains. But the plain areas are of the greatest interest. Main part of the precipitations in the mountainous areas has an orographic origin. It is determined by circulation processes, that is why the changes within mountainous areas are more expressed.

5 areas of heat and moistureavailability are defined according to monthly dynamics of temperatures and precipitation for the Southern Urals. Their formation is connected with droughts in summer (June) and active precipitation in winter (December), and increasing of temperatures and decreasing precipitation levels during the growing season.

Under conditions of unstable fluctuations steppe areas with insufficient moisture require additional irrigation and changes in agricultural techniques and assortment of cultivated plants. It is clear that 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 plains-steppe areas of the Southern Urals.

For the Southern Urals the distribution of temperatures and precipitation is characterized by a predominantly meridional character of eco-climatic area formation. The areas identified according to modern monitoring data depart from those defined earlier. There are also differences in the zoning of the area based on monthly dynamics of temperatures and precipitation from the zoning by annual average parameters.

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АНАЛИЗ ТЕНДЕНЦИЙ ПРОСТРАНСТВЕННО-ВРЕМЕННОГО РАСПРЕДЕЛЕНИЯ ТЕМПЕРАТУРЫ И ОСАДКОВ ПО ТЕРРИТОРИИ ЧЕЛЯБИНСКОЙ ОБЛАСТИ И ФОРМИРОВАНИЕ ЗОН ТЕПЛО И ВЛАГООБЕСПЕЧЕННОСТИ

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В материалах рассматриваются тенденции пространственно-временного распределения показателей температуры воздуха и осадков на территории Челябинской области за период с 1936 по 2019 гг. Проанализированы среднегодовые температуры и осадки по 21 метеостанции Челябинской области. Полученные результаты позволили дифференцировать исследуемую территорию по условиям термического режима и режима увлажнения. Характер пространственного распределения осадков на территории Южного Урала сходен с распределением температур и характеризуются меридиональным простиранием. Для горно-лесной

зоны характерны наименьшие средние значения осадков за календарный год и календарные весну–лето–осень. В степной зоне отмечается стабильное уменьшение количества осадков, причиной является ослабление в зимний период циклонической циркуляции, в это время территория находится под влиянием области повышенного давления со стороны Казахстана. К северу формируется переходная зона, которая характеризуется «средними» для Южного Урала показателями среднемесячной суммы осадков за календарные месяцы и «пиком» выпадения осадков в июле — августе. Центральная часть изучаемой территории характеризуется «средними» для Южного Урала показателями среднемесячной суммы осадков за вегетационный и последующий осенний период с пиком осадков в июле. Выделяются горная и предгорная зоны влагообеспеченности, наветренных северных и южных склонов, и подветренных северных частей, здесь отмечаются наибольшие показатели среднегодовой суммы осадков и наибольшим количеством осадков в период календарных весны–лета–осени. Наибольшими средними сумами осадков в зимний и ранневесенний (март-апрель), характеризуется западный макросклон, что связано с приходящими в это период вдоль западных хребтов Уральских гор воздушными массами с Арктики, а также сменой барических полей над Европейской частью России, а в особенности над открытыми пространствами Западной Сибири. Выделены зоны роста температур, на территории Южного Урала, они носят меридиональный характер, связанный с влиянием южной части Уральских гор, меридиональным переносом холода в направлении хребтов и влиянием холодных воздушных масс, скатывающихся с хребтов. В районе горных хребтов в связи со сложной орографической обстановкой определяется своеобразное «ожерелье» меридиональных температурных зон, характеризующихся спецификой среднемесячных и среднегодовых значений температур. Определены границы зон увлажнения, играющие ведущую роль в развитии сельскохозяйственного производства Челябинской области.
Keywords: климат, температура воздуха, азональные факторы, экоклиматическое зонирование, методы многомерной статистики в климатических исследованиях.

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