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Spatiotemporal Dynamics of the Urals' Climate in the Second Half of the 20th Century

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Abstract—Dynamics of the surface air temperature and amount of precipitation in the Polar, Northern, and Southern Urals in the 20th century is analyzed. Charts of the temperature distribution in the Urals for the period from 1961 to 2000, taking into account the relief, are plotted in the geographical informational system on the basis of data of instrumental measurements at meteorological stations with the use of the multiple regression analysis and raster modeling. The northeastern direction of the warming gradient and increase of falling precipitations in the period under review is established. Time series of anomalies of the average annual air temperature and amount of precipitation in the 20th century at three meteorological stations, situated in the Polar, Northern, and Southern Urals, are analyzed. The tendency of the growth of anomalies of the average annual temperature and total amount of precipitation is revealed.

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INTRODUCTION

The problem of the climate change estimation is in the spotlight of the scientific community. Numerous investigations enabled to establish changes in the climatic system of the Earth on the global [1, 7, 18, 24] and regional [3, 4, 9, 11, 15] levels. The typical peculiarity of the warming and increase in humidity is the unidirectional change in both positive and negative anomalous deviations for concrete areas. It aggravates possible consequences of climatic fluctuations in the case of arid or excessively moistened climate [18]. In the period from 1906 to 2005 the change of the average global air temperature was 0.74°C [24]. The growth of the amount of continental precipitation by 5–10% in the 20th century is established [7].

The tendency of modern growth of the global temperature has been observed since the end of the 19th– the beginning of the 20th century till now. The insignificant diminution of temperature took place from 1946 to 1975 [4]. According to recent estimations [24], the most intensive warming has been observed during last 12 years (1995–2006), 11 of which are referred to the warmest 12 years of the whole period of instrumental observations.

The speed of warming in the Northern Hemisphere in 1856–2005 is estimated at 0.46°C/100 years. In most regions related to high and middle latitudes of the Northern Hemisphere the growth of the amount of precipitation in the 20th century is 0.5–1% for a decade [17]. In Russia, the temperature rise in the 20th century during all seasons exceeded corresponding estimations for the globe and the Northern Hemisphere as a whole, and in 1886–2004 it amounted to 1.0°C/100 years [19]. As well, the tendency of small increase in precipitation amount was observed in the last century (1901–2000) on the European territory of Russia, unlike eastern and southern regions of the country [17, 19].

The estimation of climate changing of the Urals according to data of instrumental observations is represented in papers [9, 15, 21]. The analysis of climate of the Ural region is also carried out by means of paleontological reconstruction on the basis of dendrochronological [2] and geothermal data [5]. These studies are well coordinated with each other as well as with data of instrumental observations at meteorological stations for recent century and a half.

Using results of investigations described above, it is possible to talk about the largest temperature rise in southern regions of the Central Siberia and in the utmost northeast of Russia [19]. In Western Siberia the temperature increased by 1°C for the period of 1901–1996 [9]. Maximal positive anomalies of air temperature are registered in winter and spring seasons [4, 6, 9, 17, 19], that, in turn, caused the increase in duration of the vegetation period [1]. Due to the insufficient study of precipitation climatology as compared with

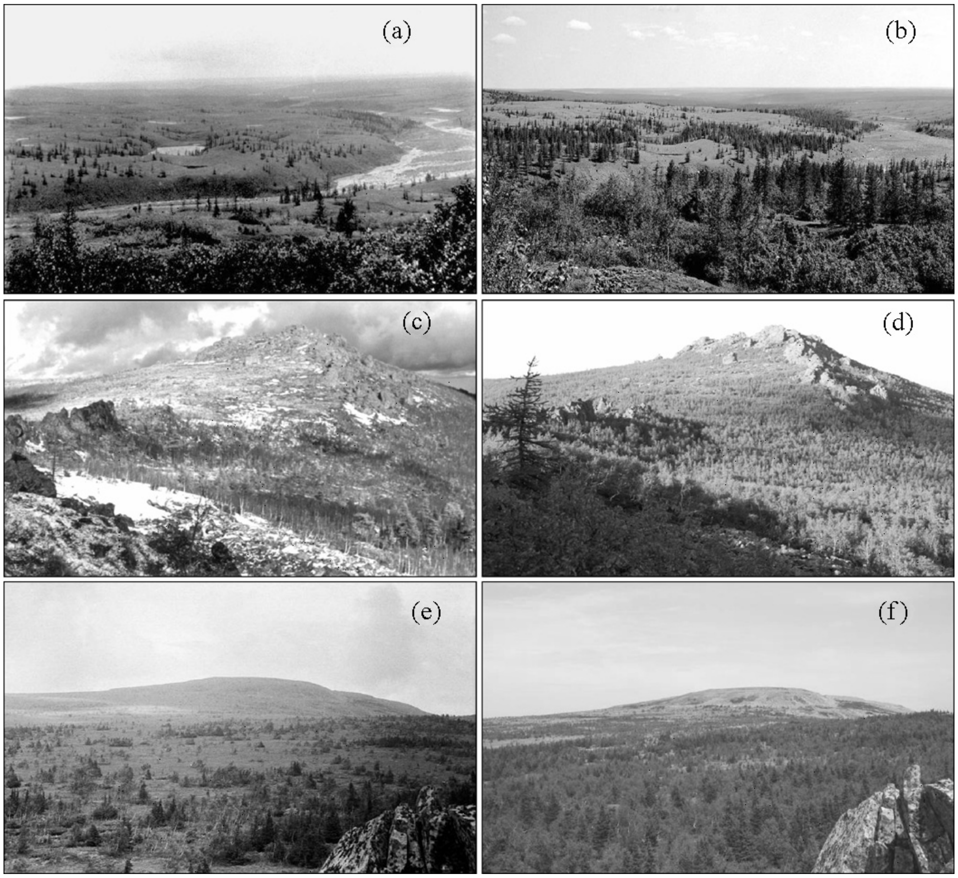

Fig. 1. Landscape photographs. (a, b) The Ray-Iz Massif, the Polar Ural (S.G. Shiyatov, (a) 1965; (b) 2005); (c, d) Konzhakovskiy Kamen', the Northern Ural ((c) S.G. Shiyatov, 1956; (d) P.A. Moiseev, 2006); (e, f) Malyi Iremel, the Southern Ural ((e) S.G. Shiyatov, 1973; (f) V.V. Fomin, 2006).

temperature climatology, one can tell only about the general tendency of the growth of precipitation amount in the Urals in recent years owing to the increase in heavy precipitation recurrence [9, 11].

In this work the results of analysis of spatiotemporal dynamics of the Urals' climate in the second half of the 20th century are given. This analysis is carried out on the base of data of instrumental observations at the meteorological stations and is very important for problems, associated with the estimation of the response of terrestrial ecosystems to the climate changing [10, 22, 23, 25].

In the 20th century, the second lifting of forest upper bound of Urals massifs during recent millennium was registered. The previous one was observed in the Middle Ages (1100–1200) [5, 10, 22, 25]. It is stated that the significant increase in the crown density and productivity of the stand in the upper tree-line ecotone has occurred throughout the last century, as well as the growth of forest-covered areas (Fig. 1). The expansion of arboreal vegetation to the mountain tundra is seemingly caused by the air temperature rise in summer and, especially, in winter [14], as well as by the increase in the duration of vegetation period, because the factors are limiting for stands of trees, growing on the upper bound of their area of distribution [23].

Considering the practical importance of the warming going on and increase in the humidity and their effect on the biological productivity of massifs' vegetation, which, in turn, influence the climate, it seems necessary to investigate changes of the air temperature and precipitation falling on the territory of the Urals in the 20th century.

The aim of the study is the analysis of spatiotemporal dynamics of the surface air temperature and amount of precipitation falling on the territory of the Urals in the second half of the 20th century, caused by the necessity of correction of global models of climate change on a regional scale taking into account the complex partitioned relief.

OBJECTS AND METHODS OF STUDY

The Urals is the unique region for climate study because of the significant meridional extent and location in northern latitudes with prevailing continental type of climate, which are the most sensitive to the influence of global air temperature rise [6]. It enables to estimate in more detail consequences of the warming and growth of precipitation amount in mountain regions.

The Urals' climate mainly forms under the influence of Atlantic air masses from the west and Arctic air masses from the north, and the most part of precipitation falls on the western slopes of the Urals.

The analysis of spatiotemporal dynamics of climate is made on the base of average monthly data of instrumental observations, published in meteorological monthly magazines [12] and international data banks. In this study, the data from meteorological stations, situated on the territory of the Urals and adjacent territories of the East European Plain and West Siberian Lowland from 55° E to 68° E, are used. Research of time series change in the air temperature and precipitation in the Polar, Northern, and Southern Urals were carried out at three stations: Salekhard, Biser, and Zlatoust. Stations chosen have the longest and the fullest series of data of meteorological parameters. The altitudes of these stations are: Salekhard, 16 m; Biser, 463 m; Zlatoust, 468 m. Available data on the average monthly air temperature are related to the period from 1883 to 2004, on precipitation, from 1891 to 2004. For the analysis of temperature and precipitation series, following time periods are chosen for these meteorological stations: a year, spring (March–May), summer (June–August), autumnal (September–November), winter (December–February), vegetative (May–August) and cold (November–March) periods.

An average air temperature for above-mentioned time periods as the ratio of the sum of products of the average monthly temperature and number of days in a month (according to a number of months in the period under review) to a number of days in the period under review was preliminarily computed. Precipitation data are represented as summed up values of precipitation fallen in each month of the period under review. An inhomogeneity of long time series of precipitation at three stations was removed by the means of introduction of conversion factors from readings of the raingauge with Nipher shield to readings of the Tret'yakov precipitation gauge (till the beginning of 1950s) and by the exclusion of the moistening correction (since 1966), published in Handbook on the Climate of the USSR [20], according to recommendations of the homogenization of data on atmospheric precipitation, described in [13, 19]. Anomalies of the average air temperature and total amount of precipitation for every year were calculated as the difference between a current value and an average one for the base period (1961–1990).

A quantitative estimation of climatic conditions and degree of the dryness is obtained with the use of the pluviothermal coefficient, which is the relative measure of the provision of plants with moisture. This coefficient is the ratio of the amount of precipitation fallen (mm) to the sum of average monthly temperature during the same time gap [16]. Calculations are carried out for three meteorological stations taking into account a shift of the start and duration of vegetation period depending on the latitude. Thus, a pluviothermal coefficient is calculated for June and for July–August for Salekhard, and for Biser and Zlatoust the start and the end of the vegetation period is May–June and July–August, respectively.

The study of the spatiotemporal dynamics of the climate of the whole Urals is based on the data for the period from 1961 to 2000, characterizing the present-day climate. Besides above mentioned periods (year, seasons of the year, vegetative and cold periods), data for every ten and twenty years are considered.

To analyze air temperature changes 132 meteorological stations, 111 of which are located in the mountain terrain, were selected. One of the problems the scientists, who treat the series of meteorological data, are dealing with is the missed values in certain time gaps. Absent values were recovered with the use of statistical laws for meteorological stations, having statistically significant linear dependences on neighboring stations with similar location height. Coefficients of determination R^2 of almost all linear models were more than 90.4%. Only ten stations were exceptional. For three of them the value of R^2 was more than 60.3%, and for remaining, more than 75.0%.

After the recovering procedure an array of meteorological data was divided into testing and learning samples which numbered 30% and 70% of total amount of meteorological stations, respectively. Multiple linear regression models were formed on the basis of learning sample data and can be written as

$$T_i = a_0 + a_1 \mathrm{long}_j + a_2 \mathrm{lat}_j + a_3 \mathrm{elev}_j,$$

where T_i is the average temperature for the period, °C; a_0 is the absolute term; a_1, a_2, a_3 are variable-held constants; long_j is the longitude, grad E; lat_j is the latitude, grad N; elev_j is the height above sea level, m (values of longitude and latitude are reduced to one decimal digit); i is the index of the period under review; j is the index of the meteorological station.

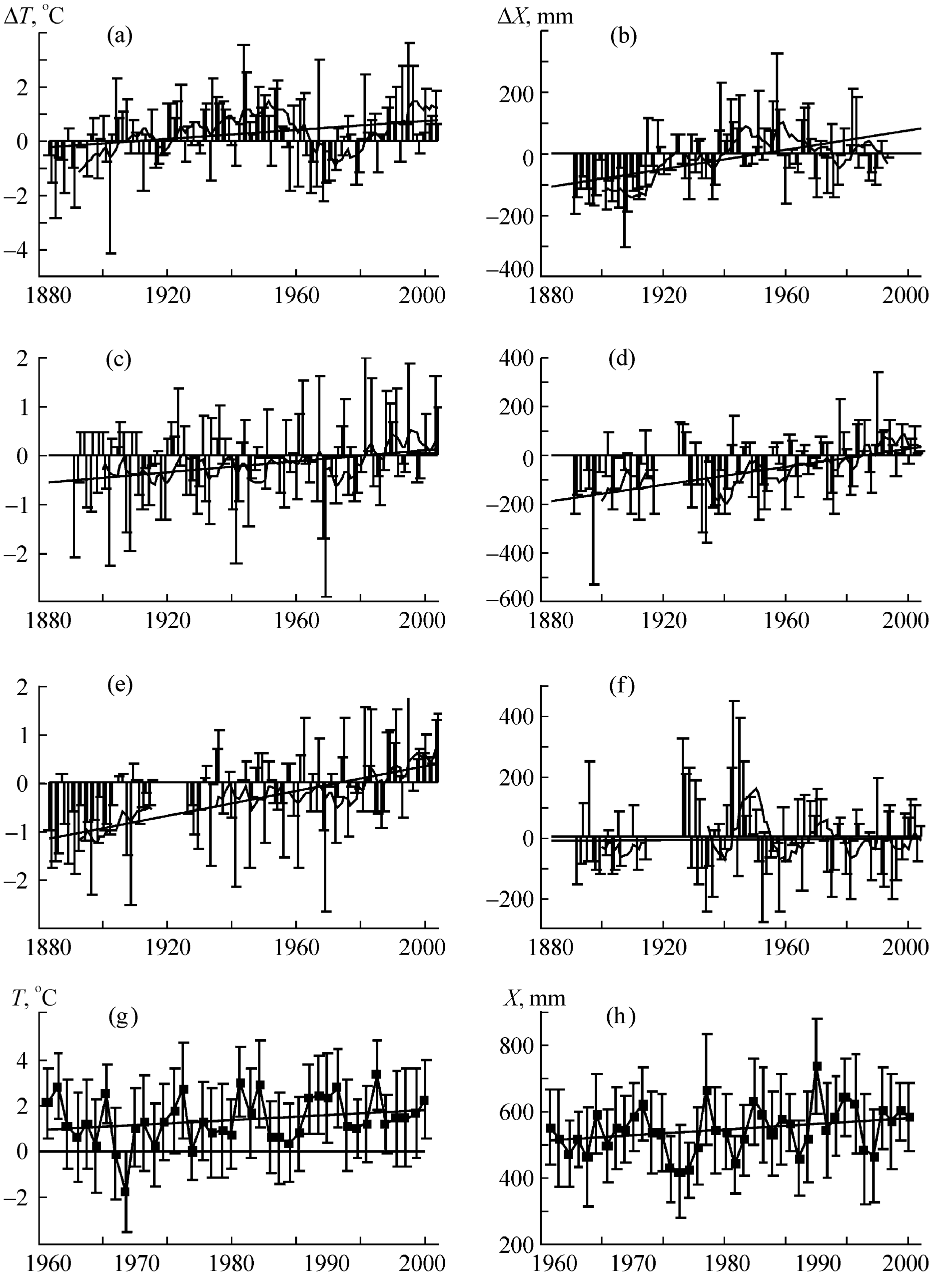

Fig. 2. Time series of anomalies of the average annual (a, c, e) surface air temperature Δ*T* and (b, d, f) annual precipitation totals Δ*X* for meteorological stations (a, b) Salekhard, (c, d) Biser, (e, f) Zlatoust, and time series of spatially averaged mean annual air temperature (g) and mean annual sums of precipitation (h) in the Ural region with the root-mean-square deviation. The period 1960–1990 is taken as standard. The heavy line indicates the linear trend, heavy curves show the moving average with ten-year period of smoothing.

Model data enable to reconstruct the spatial distribution of the air temperature in the region under study according to time intervals.

Coefficients of determination of the multiregression model vary from 90.3% to 93.4% for average values of air temperature in the periods of ten and twenty years, represented in this paper. The mean shift fluctuates from 0.14 to 0.20°C, reaching 0.32°C in the last decade. The root-mean-square error (RMSE) varies from 0.57 to 0.60°C.

Rasters, which consist of cells containing air temperature values, were computed in the geographic information system (GIS) with the use of equations derived. A digital model of the Urals' relief and rasters with cells, containing values of latitude and longitude, are used as the input parameters of the model. Climatic charts, computed in GIS as a difference between temperature rasters of two adjoining ten- or twenty-year periods, were created for the estimation of a spatial temperature change during ten- or twenty-year periods, respectively.

Analysis of the precipitation distribution on the territory of the Urals was carried out with the use of data of 31 meteorological stations, situated in its central part, in the Northern and Middle Urals. Only these stations have complete series of data. The recovery of missed values on other stations wasn't carried out as data on the amount of precipitation on neighboring stations are slightly correlated, as a rule. Data processing consists in an averaging of the total annual amount of precipitation according to periods of ten and twenty years being considered in this study. A distribution of precipitation on the Urals' territory is also expressed in schematic maps, which contain conventional signs showing the difference of average total values in the specified period.

For stations, for which data on temperature and precipitation were obtained, the spatially averaged mean annual anomalies of these parameters with the root-mean-square deviation are calculated. Spatial analysis was carried out with the aid of geographic information system ARC/INFO (ESRI Inc., USA). The mathematical-statistical processing was made with the use of the statistical package R (R core team, www.r-project.org).

RESULTS AND DISCUSSIONS

The variety of the Urals' climate is determined by the temporal and spatial change in fundamental climatic parameters, in the first place, the air temperature and amount of precipitation fallen. Basing on obtained data a local change in the air temperature and precipitation amount, corroborating a tendency of the warming and humidity growth in the Urals in the second half of the 20th century, was analyzed.

Time series of mean annual anomalies, given in Figs. 2a–2e, indicate the dynamics of the air temperature and precipitation amount at meteorological stations Salekhard (the Polar Urals), Biser (the Northern Urals); and Zlatoust (the Southern Urals). Trends of linear dependence and the moving average with ten-year period of smoothing for the visualization in tendencies of temporal changes in temperature values and precipitation amount are also represented.

Anomalies of the mean annual temperature show the increase in deflection from the reference period for three linear trends of stations: Salekhard, 0.8°C/100 years; Biser, 0.6°C/100 years; Zlatoust, 1.3°C/100 years. Maximal positive temperature anomalies were observed in 1995 in Salekhard and Zlatoust, and in Biser anomalies of this year are among the biggest ones. The analysis of data of meteorological stations for other periods showed that in winter months the most significant warming, which decreased gradually when approaching summer months (with taking into account the actual time of seasons' passage), took place.

The change in total annual precipitation anomalies for the period under review is 152.5 mm/100 years in Salekhard and 188.3 mm/100 years in Biser. In Zlatoust, the reliable tendency according to linear trend is not revealed (Figs. 2b, 2d, and 2f). The correlation of heat and moisture, being determined by the pluviothermal coefficient, exceeds the normal one for most years, that makes it possible to talk about overwetting of the Urals' climate. Anomalies of the pluviothermal coefficient especially increase at meteorological stations Zlatoust and Biser. The largest values of positive anomalies are registered in Biser, of negative ones, in Zlatoust.

Time series of the spatially averaged data at all meteorological under study stations of the Urals indicate the positive trends of mean annual air temperature and mean annual sums of precipitation (Figs. 2g and 2h). Maximal temperature for the period from 1961 to 2000 was observed in 1995, the minimal one, in 1969. The largest and the least summarized precipitation amount fell in 1990 and 1975, respectively.

At the majority of stations of the Northern and Middle Urals values of the pluviothermal coefficient correspond to the overwetting of air. Maximal anomalies of this coefficient (4.6) were obtained in 1969 for the beginning of vegetation period, and minimal ones, for the end of vegetation period. On the whole, the dynamics of the pluviothermal coefficient values shows a tendency of the increase in anomalies in the end of vegetation period and the reduction of fluctuations dispersion in the end of the vegetation period, especially in the recent decade.

The analysis of spatial distribution of climatic factors' values in the Urals reveals a number of peculiarities, connected with altitude and geographical location. In particular, a tendency of the shift of borders of temperature zones to the north of the Eastern Siberia is clearly seen, when comparing temperature charts for 1961–1980 and 1981–2000 (Figs. 3a and 3b), that comes to agreement with results of other investigations [9, 17]. This fact is also confirmed by a chart of climatic distribution of temperature differences between

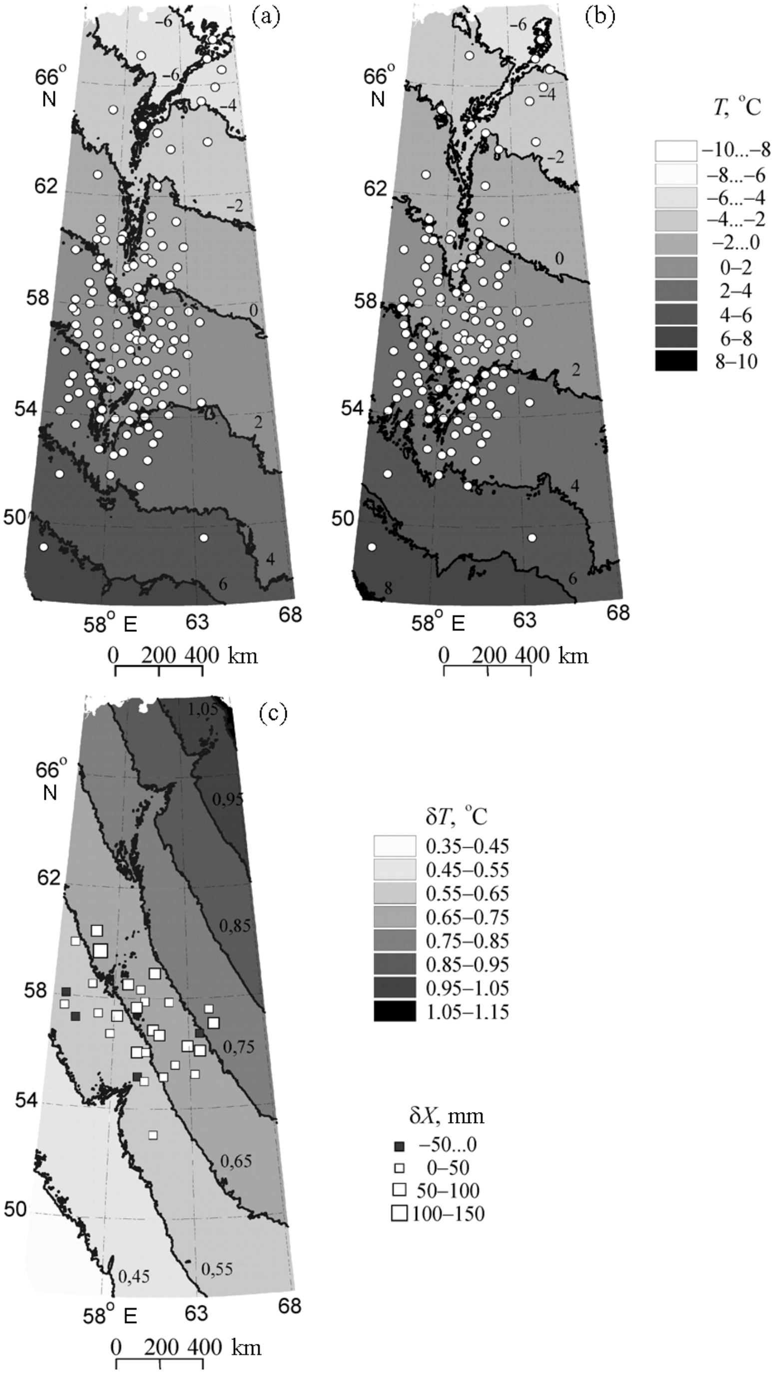

Fig. 3. The distribution of the mean annual air temperature on the Ural territory in twenty-year periods of (a) 1961–1980 and (b) 1981–2000 and the difference of mean annual temperature δT and (c) precipitation amount δX between these twenty-year periods. Solid lines are isotherms.

twenty-year periods, on which the northeastern direction of the warming gradient is clearly seen (Fig. 3c). On average, the temperature difference between twenty-year periods is 0.7°C, reaching the maximal value 1.1°C in the Polar Urals. In mountain regions, the increase in warming with the increase in height was less intensive.

Comparative analysis of charts of mean temperature of ten-year time periods (illustrations are not given) revealed an inhomogeneity of the warming from decade to decade. So, a comparison of 1970s and 1960s revealed the insignificant warming (under 0.3°C) at the direction from the Ural massifs to the southwest. The process of temperature fall (under –0.3°C) was observed in the opposite northeast direction. Comparison of these periods has also revealed the less considerable warming for massifs, than for plains, under conditions of the increase of the difference between temperature values with height. The mentioned difference increases in the direction of northeast.

It is stated, that the 1980s were warmer than the previous decade by 0.6ºC on average for the whole territory of the Urals. The warming gradient is directed to the northeast with the maximal air temperature difference of 1.0°C. A comparison of these decades has also shown the less considerable warming in massifs with the increase in height.

A comparison of temperature charts of the 1980s and 1990s enables to talk about the warming in the direction to the northeast from the Middle Urals (under 0.5°C) and falling of temperature to the southwest (under –0.3°C). The typical peculiarity of the difference of mean values of air temperature is higher temperature along the massifs as compared to plains, especially in the Northern and Polar Urals.

The analysis of climatic data enables to confirm that a tendency of precipitation amount increase is observed in the Urals (Fig. 3c). The mean value of the difference of average annual sums of precipitation between two twenty-year periods is 39.2 mm. The analysis of schematic maps of precipitation distribution by decades (illustrations are not given) indicates the decrease in precipitation amount in the 1970s as compared with the 1960s at the majority of stations of the Middle Urals. Meteorological stations of the western flank of the Northern Urals are the exceptions due to the revealed tendency of the increase in falling precipitation amount. In the 1980s, the growth of the precipitation amount at all stations of the Northern and Middle Urals as compared with the preceding decade was observed. A comparison of the 1990s and 1980s enabled to reveal only essential distinctions of precipitation totals (up to 150.0 mm) at some stations of the Northern Urals.

CONCLUSION

It is established, that in the second half of the 20th century in mountain regions of the Urals the warming was less considerable with the increase in height. The increase in air temperature in the northeastern direction for the Urals and the growth of annual precipitation totals at the majority of stations of the Middle Urals were also observed. Results of the study carried out, including the consideration of relief, enable to concretize climatic factors and to detail the climatic map of the region.

The analysis of spatiotemporal dynamics of the Urals' climate will make it possible to estimate more precisely the correlations (as well as interactions) of climatic fluctuations and vegetation reaction, as well as to forecast the change of its state and spatial location. In particular, the results obtained are well coordinated with data on spatiotemporal dynamics of mountain plant associations of the Urals [8, 22, 23].

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REFERENCES

1. I. I. Borzenkova, "On Natural Indicators of Current Global Warming," Meteorol. Gidrol., No. 6 (1999) [Meteorol. Hydrol., No. 6 (1999)].
2. E. A. Vaganov and S. G. Shiyatov, "Dendroclimatic and Dendroecological Researches in Northern Eurasia," Lesovedenie, No. 4 (2005) [Russ. Forest Sci., No. 4 (2005)].
3. G. V. Gruza and E. Ya. Ran'kova, "Climate Oscillations and Changes over Russia," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 2, **39** (2003) [Izv., Atmos. Oceanic Phys., No. 2, **39** (2003)].
4. G. V. Gruza and E. Ya. Ran'kova, "Detection of Changes in Climate State, Climate Variability and Climate Extremity," Meteorol. Gidrol., No. 4 (2004) [Russ. Meteorol. Hydrol., No. 4 (2004)].
5. D. Yu. Demezhko, "Why Does the Climate Change?" Nauka Urala, No. 25 (2003) [Ural Sci., No. 25 (2003)].
6. N. A. Efimova, E. L. Zhil'tsova, N. A. Lemeshko, and L. A. Strokina, "Comparison of Climate Change in 1981–2000 with Paleoclimate Analogues of Global Warming," Meteorol. Gidrol., No. 8 (2004) [Russ. Meteorol. Hydrol., No. 8 (2004)].
7. *Climate Change 2001. Synthesis Report. Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Ed. by R. T. Watson (WMO–UNEP, Geneva, 2003).

8. D. S. Kapralov, *The Study of Spatiotemporal Dynamics of the Forest Upper Bound in the Northern and Southern Urals*, Extended Abstract of Candidate's Dissertation in Agriculture (Yekaterinburg, 2007) [in Russian].
9. A. I. Kuskov and S. G. Kataev, *The Sructure and Dynamics of Surface Temperature Field over the Asian Territory of Russia* (Izd. TGPU, Tomsk, 2006) [in Russian].
10. S. V. Mazepa and N. M. Devi, "Development of Multistemmed Life Forms of Siberian Larch as an Indicator of Climate Change in the Timberline Ecotone of the Polar Urals," Ekologiya, No. 6 (2007) [Ecology, No. 6 (2007)].
11. V. P. Meleshko, V. M. Kattsov, V. A. Govorkova, et al., "Anthropogenic Climate Changes in the Twenty-First Century in Northern Eurasia," Meteorol. Gidrol., No. 7 (2004) [Russ. Meteorol. Hydrol., No. 7 (2004)].
12. *Meteorological Monthly*, 1961–2000, Vols. 9, 17, Part 2, Nos. 1–13 [in Russian].
13. *Long-term Series of Monthly Sums of Average Regional Precipitation in the Cold Season for the Main Agricultural Zone of the USSR*, Ed. by A. V. Meshcherskaya and N. A. Boldyreva (Gidrometeoizdat, Leningrad, 1988) [in Russian].
14. P. A. Moiseev et al., "Effect of Climatic Changes on the Formation of Siberian Spruce Generations in Subglotsy Tree Stands of the Southern Urals," Ekologiya, No. 3 (2004) [Ecology, No. 3 (2004)].
15. A. S. Monin and D. M. Sonechkin, *Climate Fluctuations According to Observational Data: Triple Solar and Other Cycles* (Nauka, Moscow, 2005) [in Russian].
16. D. A. Ped', "On the Factor of Draught and Overwetting," Trudy Gidromettsentra SSSR, No. 156 (1975) [Trans. Hydrometeorological Res. Center of the USSR, No. 156 (1975)].
17. Yu. P. Perevedentsev et al., "Current Changes of Air Temperature Fields in the Northern Hemisphere," Problemy Analiza Riska, No. 1 (2007) [Issues of Risk Analysis, No. 1 (2007)].
18. *United Nations Framework Convention on Climate Change. The First Ten Years* (UNFCCC, Halesworth, 2004).
19. E. Ya. Ran'kova, *Climatic Changeability and Climate Changes for the Period of Instrumental Observations*, Extended Abstract of Candidate's Dissertation in Mathematics and Physics (Moscow, 2005) [in Russian].
20. *Handbook on Climate of the USSR* (Gidrometeoizdat, Leningrad, 1968), Part 4, Nos. 9, 17 [in Russian].
21. Yu. N. Shvareva, *Climate of the West Siberian Plain* (Nauka, Moscow, 1976) [in Russian].
22. S. G. Shiyatov and S. V. Mazepa, "Climatogenic Dynamics of the Forest-Tundra Vegetation in the Polar Urals," Lesovedenie, No. 6 (2007) [Russ. Forest Sci., No. 6 (2007)].
23. S. G. Shiyatov, M. M. Terent'ev, and V. V. Fomin, "Spatiotemporal Dynamics of Forest-Tundra Communities in the Polar Urals," Ekologiya, No. 2 (36) (2005) [Ecology, No. 2 (36) (2005)].
24. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report* (Valencia, 2007).
25. V. S. Mazepa, "Stand Density in the Last Millennium at the Upper Tree-line Ecotone in the Polar Ural Mountains," Can. J. Forest Res., No. 10, **35** (2005).