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CLIMATE CHANGE AND THE DYNAMICS OF DANGEROUS PHENOMENA IN UDMURTIA

Specialization 25.00.30 – meteorology,
climatology, agrometeorology

REPORT
of Philosophy Doctor Thesis
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The work was carried out at Department of Meteorology, Climatology and Atmospheric Environment of Institute of Environmental Sciences of Kazan Federal University

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The PhD thesis manuscript can be found in Kazan Federal University Library. The electronic version of the author's abstract is available on the official website of Kazan Federal University (http://kpfu.ru/).

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The report was distributed on 24th October 2017

Scientific secretary of the PhD Council,

PhD, assistant professor Nadezhda A. Vazhnova

GENERAL CHARACTERISTICS

Relevance of the research topic

The amount of dangerous weather events has significantly increased in the conditions of the past decades climate change. According to the assessment report of Roshydromet (2014), climate change can have numerous and potentially serious consequences for natural complexes, economy and health of the population in Russia. Russia signed the Paris Agreements, aimed at climate protection. Therefore, it is important to have an objective view of the spatiotemporal changes and dynamics of the main climatic indices taking place against the background of global warming and influencing the life activity of a person in a particular region. A correct assessment of observed climate changes and the dynamics of dangerous phenomena allows to organize the livelihoods of the population of the region most rationally and economically, adapt to climate change.

The relevance of this work is determined by insufficient knowledge of regional climate change and severe weather (SW) events in today's global warming, the need to obtain reliable and timely information about the changing climatic conditions of the Udmurtia for practical purposes.

The goal of the work is to research modern climate changes and the dynamics of dangerous phenomena in Udmurtia.

To solve the set goal, the following tasks were set:

– analysis of the spatial-temporal distribution and interannual changes in the main meteorological characteristics in the territory of the Udmurt Republic;
– assessment of the contribution of large-scale factors of changing air temperature in Udmurtia;
– study of the influence of atmospheric circulation on weather and climatic parameters;
– study of the frequency and dynamics dangerous meteorological phenomena observed in the cold and heat waves, detection synoptic causes of their occurrence;
– assessment of economic damage and risks posed by hazardous weather phenomena;
– study of natural climatic resources, affecting the region's economy.

Object of study is the climate and dangerous weather phenomena in Udmurt Republic.

The subject of the study are:

– spatio-temporal distribution of climatic characteristics;
– time trends and long-term fluctuations in the ranks of meteorological values in the territory of the Udmurt Republic;
– the connection of weather and climate events with the atmospheric circulation and physico-geographical factors;
– relationship between meteorological quantities;
– climatic resources in Udmurtia.

Methods of research

Approved statistical methods are used. Assessments of regional climate changes in the territory of the Udmurt Republic are obtained against the background of changes in the global climate using statistical methods, correlation and trend analysis. Visualization of the spatial fields of meteorological quantities was carried out using GIS-technologies. Reliability of the results was assessed using the Student's test.

The methodological basis was the works of famous Russian and foreign scientists developed the scientific foundations of meteorology, fundamental and applied climatology, the basis for studying modern climate changes under the influence of natural and anthropogenic factors; assessment reports of the IPCC and Roshydromet.

The information base of the research was surface and high altitude synoptic maps (1933-2014), monthly data of surface meteorological observations on the territory of the Udmurt Republic at 8 meteorological stations (1961-2014); daily data of air temperature and atmospheric precipitation at the station Izhevsk from the archive of the Udmurt State Central Hydrometeorological Service (1933 - 2014); data of urgent observations at meteorological stations Izhevsk and Glazov (2005-2015); indices of atmospheric circulation NAO, AO, SCAND, EA (1961-2014); Climate Research Unit of the University of East Anglia (CRU) data on the average monthly air temperature at the nodes of the regular grid (1900-2014).

Scientific novelty of results:

For the first time for the Udmurt Republic on the basis of modern data:

– shows the dynamics of meteorological characteristics and dangerous weather phenomena during the period 1933-2014;

– the estimation of the century history of changes in air temperature in Udmurtia is given, the relationship between the increase in air temperature in the region and global warming is shown;

– classification of synoptic conditions of occurrence of dangerous weather phenomena on the basis of joint analysis of surface and high altitude maps is carried out;

– the catalog of abnormally cold and warm winters in Udmurtia was compiled;

– the economic damage and risks associated with dangerous weather phenomena were assessed;

– the state of climatic resources is estimated.

Scientific and practical value of the work:

The results obtained by the author were used:

– in the operational practice of the Short-Term Forecasts Department of the Udmurt Center for Hydrometeorology and Environmental Monitoring (UCGMS), with a forecast of the SW with a view to increasing the lead time and increasing the accuracy of forecasts;

– in the form of recommendations for the recording of meteorological values and their differences in the electric power industry and in medical care;

– in the educational process at the Department of Meteorology, Climatology and Atmospheric Environment of the KFU reading lectures on the course "Natural and socio-economic consequences of climate change";

– in the educational process of the Institute of Natural Sciences of UdSU reading the course "Meteorology and Climatology";

– can be used in the form of climate certificates for organizations involved in the fields of agriculture and forestry, housing, government and the Ministry of Emergency Situations;

– can be used to adapt various sectors of the economy and social sphere to changes in the regional climate;

– used in the preparation of a scientific report on the RFBR grant No. 15-05- 06349

"Construction of a regional model for diagnosing and forecasting current climate changes and their social and environmental consequences (for example, the Volga Federal District)."

The following provisions are put on defense:

1. Climatic changes occurring in the territory of the Udmurt Republic are associated with the process of modern global warming;
2. Regional climate changes, most pronounced in cold half of the year, affect the time dynamics of various SW in different ways;
3. Classification of synoptic situations favorable for the emergence of SW in the territory of the Udmurt Republic;
4. The tendency to increase the climate risks revealed in recent decades in the territory of Udmurtia;
5. Assessment of climatic resources and their dynamics as indicators of the natural potential of the region.

The validity and reliability of the results and conclusions is confirmed:

– using of a large array of primary meteorological information;
– using statistical criteria to assess the reliability of the findings;
– using approaches based on modern scientific positions and quantitative methods;
– the correspondence of the results to the main provisions of climatology and synoptic meteorology.

Personal contribution of the applicant. Applicant together with the scientific advisor determined the purpose and objectives of the study. Analysis of the aero synoptic material, the results of statistical processing of meteorological data was carried out by the author personally. All the main results of the defense, their interpretation were obtained by the author.

Approbation of work:

The main and intermediate results were reported by the author at the International Scientific and Practical Conference "Geography and the Region" (Perm, 2015); All-Russian scientific-practical conference "Geographical space: balanced development of nature and society" (Chelyabinsk, 2015); III All-Russian scientific conference "Ecology and Space" (St. Petersburg, 2017); III international scientific conference "Environment and sustainable development of regions: environmental challenges of the XXI century" (Kazan, 2017); II All-Russian Scientific and Practical Conference with international participation "Problems of regional ecology and geography" (Izhevsk, 2017), final scientific conferences and seminars of the Department of Meteorology, Climatology and Atmospheric Environment of KFU (2013-2017).

Publications.

7 scientific works were published on the topic of dissertation, including 5 works published in journals recommended by the Higher Attestation Commission for candidate and doctoral dissertations; a number of research results is used in the "Atlas of the Udmurt Republic", published in 2016.

Structure and scope of the manuscript

The work consists of an introduction, five chapters, a conclusion and a bibliography. The total amount of work is 173 pages, including 43 figures, 46 tables and 13 applications. Bibliography cited totals 154 sources.

CONTENTS

In introduction, the relevance of the chosen topic is substantiated, the purpose and objectives of the research are stated. The estimation of scientific novelty and practical significance of the results of work is given. The main provisions put forward for defense are given.

In the first chapter, the physico-geographical conditions of the Udmurt Republic (UR) located in the eastern part of the Russian Plain in a significant distance from the oceans are considered, which determines the features of its climate (Fig. 1).

Fig. 1. Physical map of Udmurtia with the location of 8 weather stations

Radiation and circulation factors, the formation of regional climatic features are described, a brief climatic description of the region is given. The role of the influence of the Atlantic and external air masses on fluctuations in weather and climate conditions is highlighted.

In the same chapter, the initial data and the method of investigation are considered. To achieve this goal, spatio-temporal, correlation and trend analyzes were used, the low-frequency digital Potter filter was used to isolate the low-frequency component (LFC) of air temperature changes. To create maps of the spatial distribution of meteorological quantities, the software package ArcGis 10.3 was applied.

In the second chapter, the regularities of the space-time variation of atmospheric pressure (*P*) and wind speed in the territory of Udmurtia are considered. Distribution maps are constructed and trends in climatic characteristics are analyzed.

The patterns of atmospheric pressure distribution in UR reflect the continental type of climate with a large influence of atmospheric circulation on the variability and spatial heterogeneity of the *P* value in the cold half of the year. In the northern regions of Udmurtia cyclonic activity is more pronounced, which leads to greater variability in air pressure.

According to trend analysis, there is a tendency for *P* to fall in the winter and spring months, a statistically significant trend is observed in March at Glazov station (-1,4 hPa/10 years). In July, at a half of the examined stations, there is a statistically significant increase in pressure with time, the highest growth rate was observed at

Debesy station: 0,8 hPa/10 years. The linear trend of annual values of P is not statistically significant.

The predominant wind direction in winter and for the year as a whole is southern (11,7%); in the summer is north-east and north. The average annual wind speed for the period 1961-2014 in Udmurtia is 3,2 m/s. The highest averaged rates for the year are observed with southern and western winds (3,6-3,7 m/s). The frequency of wind speeds more than 15 m/s is maximum in May (77 % of the total number of years); is minimal in August (35 % of the total number of years). The maximum repeatability of the number of calm is found in July (13,9 %); The calm is observed most rarely in November – 5,2 %.

The average annual wind speed is weakening with time at a rate of -0,2 m/s/10 years. The most significant contribution is made by November and December, at which the rate of decline is -0,3 m/s /10 years. From the 1980s to the 2000s, a decline in the number of calm was observed predominantly in all the months of the year; in the periods from January to March and from May to September from the beginning of the 21st century, there is a noticeable growth. In November from the beginning of the 2000s, the number of calm decreases.

The third chapter series discusses the characteristics of temperature and humidity, cloud cover and precipitation of Udmurtia. Investigation of the conditions of moisture and dryness is carried out using a known index proposed by D. Ped. The influence of atmospheric circulation on the weather and climate of the region is considered.

Due to the high correlation between the detected data on CRU and air temperature data of Udmurtia ground stations during the years 1961-2014, secular change history the average annual temperature (AAT) in Udmurtia is estimated. The relationship of AAT in the territory of Udmurtia with the temperature trend in the temperate zone of the Northern Hemisphere as a whole and its northern and southern parts shown.

Analysis of the low-frequency component of air temperature, obtained as a whole for the temperate latitudinal zone, its northern and southern parts, and also for the node with coordinates 57.5 °N and 52.5 °E, which characterizes the thermal regime of UR shows that prior to the 1970s the process was heterogeneous. Current warming well coordinated in time both in latitudinal zones of the joint venture, and in UR (Fig. 2). The air temperature for the period 1900-2014 increased by almost 2 °C, the main contribution was made between 1968 and 2011, for which it has grown to 1,65 °C.

At the beginning of 21st century the average growth rate and winter temperature has decreased and the end of the study period had fallen practically to zero, with the temperature rise in summer lasts until the end of the test period.

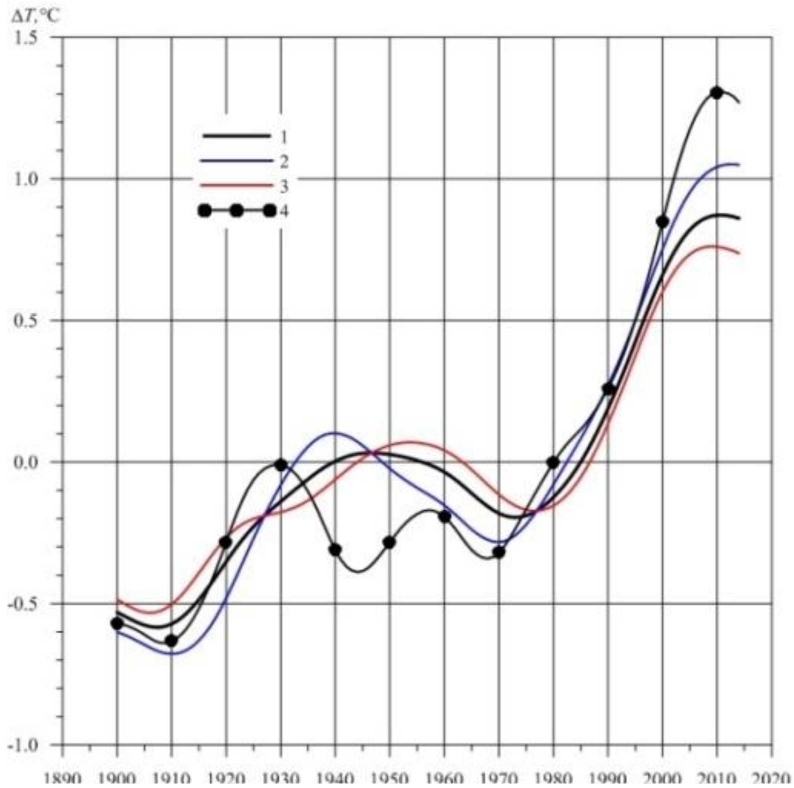


Fig. 2. Proceedings AAT low frequency component with a period of over 20 years. 1 - moderate NH zone, 2 - the northern part of the temperate zone, 3 - the southern part of the temperate zone, 4 - node with coordinates 57.5°N and 52.5°E

Throughout the territory of Udmurtia, there are a positive AAT whose values range from 1,9-2,2 °C in the north to 3,0-3,2 °C in the south.

Monthly temperature distribution anomalies in January and July averaged over UR (Fig. 3) is reviewed. Within $\overline{t} \pm 2\sigma$ fit about 95 % of total air temperature in January in the range -5,5 ÷ -21,9 °C, in July – 14,8 ÷ 22,4 °C. Here $\overline{t}$ – the average temperature, σ – standard deviation.

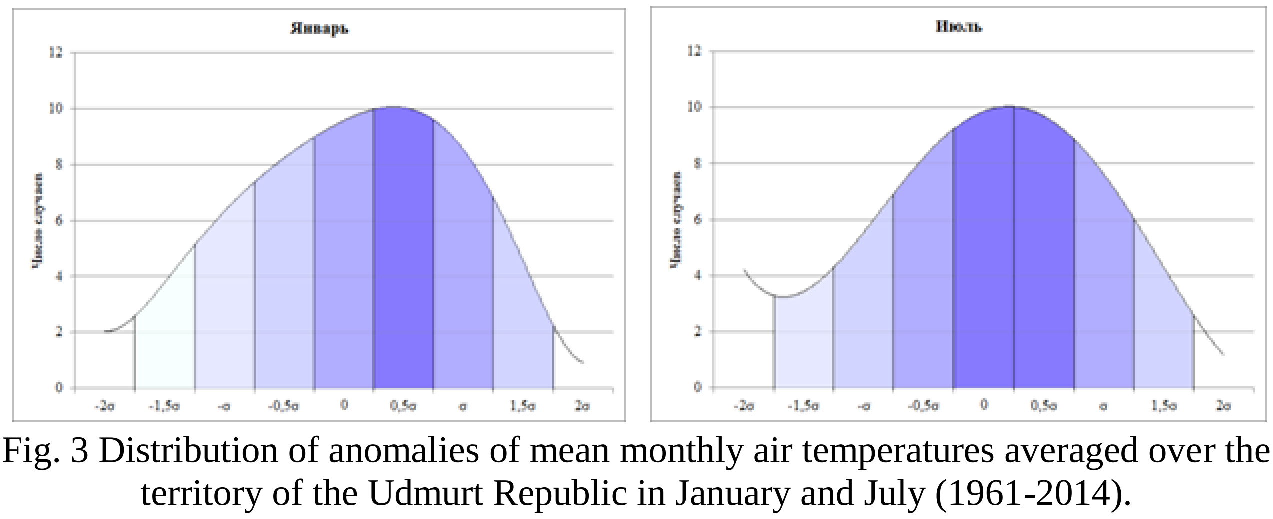


Fig. 3 Distribution of anomalies of mean monthly air temperatures averaged over the territory of the Udmurt Republic in January and July (1961-2014).

The lifespan of positive and negative anomalies Δt is calculated. In half the cases the average monthly air temperature anomalies are not more than one month. Duration of anomalies equal to 2 months occurs in 22-27 % of cases, three – at 14-17 %. Repeatability of duration of anomalies equal to four months or more is low. Maximum of lifespan of anomalies is 9 months.

The highest rate of temperature increase was observed in winter and autumn: in January it increased at a rate of 0,67-0,8 °C/10 years, in October at a rate of 0,4-0,5 °C/10 years. The rate of growth of annual values of minimum temperatures is slightly higher than the growth rate of maximum air temperatures.

To estimate the moisture regime the partial pressure (pressure WV) (*e*) and relative humidity (*f*) are investigated. Pressure WV *e* changes during the year from 2,2 in January and February to 15,0 hPa in July. In the summer the distribution of *e* primarily influenced by local geography. During the cold period the distribution of *e* acquires latitude orientation with a maximum in the south-west and a minimum in the northeast region.

Annual value of *e* grows over time, the most pronounced growth is in the north-east of the region (0,2 hPa/10 years), the least intensive growth is observed in the south-west (0,1 hPa/10 years). Absolute humidity is increasing mainly due to its growth in the fall.

Maximum of the annual *f* detected in November (86 %), minimum – in May (61 %). Most of the year in the northern regions of the Udmurtia the values of *f* is higher than in the south. The maximum number of dry days is observed in May, humid days are most common in November and December. In the south-west of the UR a decrease of average annual values of *f* is observed over time, with an average rate of -0,37 %/10 years, in the north-east and east – on the contrary increase at a rate of 0,6 %/10 years.

The spatial-temporal distribution of the lower and the total cloud cover, the frequency of the different forms of clouds is also considered, the analysis of the number of clear and cloudy days is given.

The most cloudy month is November (8,4 points), the least cloudy is July (6,1 points). The coefficient of variation of the total cloudiness (C_v = 14 %) indicates an average variation of the characteristics, the lower cloud cover varies significantly (C_v = 30 %). Most often, with an annual repeatability of 24 %, there are a middle layer clouds form. Cumulus clouds are least common – 5,5 %. The annual course of frequency of different forms of clouds is shown in Fig. 4.

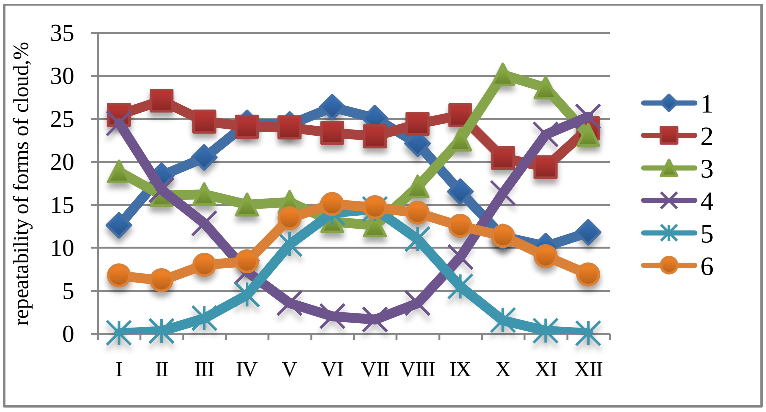


Fig. 4. Annual variations repeatability cloudiness forms, averaged over Udmurtia: 1 – top, 2 – medium, 3 – stratus and stratocumulus, 4 – nimbostratus and pannus, 5 – cumulus, 6 – cumulonimbus

Total cloud cover is increasing in most of the year in the north of the region. The highest rate of increase is observed in August: 0,3 points/10 years. The number of lower cloud in winter increased from 1970s to the end of 1990s, after which the number falls. The same pattern is observed in the spring. During the summer, the trend is not statistically significant, in the autumn the number of lower clouds from the beginning of the 21st century is increasing.

Repeatability of the upper cloud increased at an average rate of 2 %/10 years, the dynamics is most pronounced during the winter months. Linear trend of repeatability middle cloud has a positive sign in the spring. Stratus cloud tends to increase during the cold half of the year, especially in the fall – 4 %/10 years. Nimbostratus over the past 30 years recorded less, especially in winter. Repeatability of cumulus clouds over the past decade is reduced.

In the mode of precipitation, the distribution of annual and monthly precipitation amounts, the number of days with precipitation, the repeatability of the number of days with a daily precipitation amount of 5 mm and more were investigated. The long-term annual precipitation on the territory of Udmurtia is 568 mm. In the annual course, a maximum is detected in July (69,2 mm) and a minimum in February (25,9 mm). The spatial distribution of precipitation amounts is not homogenous, the most moisture-rich are the south-western regions of the republic (Fig. 5).

a) *b)* *c)*

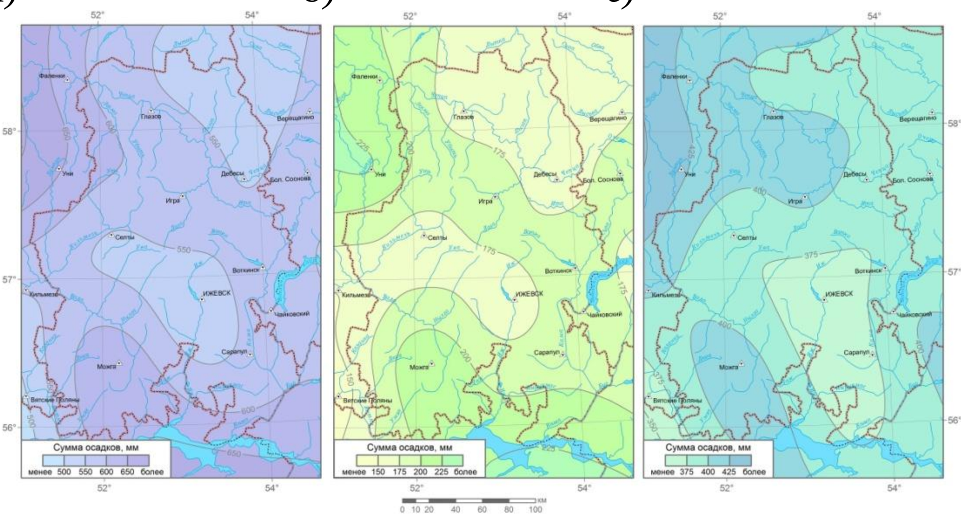


Fig. 5. Average annual (*a*), the average amount of precipitation for cold (*b*) and warm (*c*) periods, mm

In February averaged over the Udmurtia σ of precipitation is 13 mm, in July it reaches up to 37 mm which is nearly half of the value of the average amount of rainfall in the month. The coefficient of variation of precipitation for the year is higher than 40 %, which shows a significant variability of precipitation.

Precipitations in UR are observed most of the year – 218 days. Most often, they fall in the south-west of the region (230 days). The number of days with precipitation of more than 20 mm in winter, referring to SW – very rare with an average repeatability of less than 1 day per month. The daily amount of precipitation over 50 mm is extremely rare and it only occurs in the period from May to September.

Annual amount of precipitation in UR in the period 1961-2014 is growing at a rate of 1,36 mm/10 years. Polynomial trend reflects a complex and heterogeneous structure of the value changes from month to month. The annual amount of days with precipitation increases over time at an average rate of 1 day per 20 years, mainly due to the increase of the characteristics in the cold season. An increase of the daily totals precipitation averaged over the year in the northern and central regions of UR is observed with an average speed of 0,4 mm/10 years, which is mainly due to the warm period.

Summer and winter index Pedya calculated in the following formulas:

$$S_S = \frac{\Delta T}{\sigma_{\text{т}}} - \frac{\Delta R}{\sigma_R},\ S_W = \frac{\Delta T}{\sigma_{\text{т}}} + \frac{\Delta R}{\sigma_R}, \qquad (1)$$

Where S_S - summer index Pedya, S_W - winter index Pedya, $\Delta T$and ΔP – monthly air temperature and precipitation anomalies; σ_m and σ_R – their standard deviations.

If the $S_S > 2$, drought is observed; $1 < S_S \leq 2$ – drought conditions; $-1 \leq S_S <1$ – normal moisture conditions; $-2 \leq S_S <-1$ – wet conditions; with $S_S <-2$ – excess moisture. If the index value is more than 3 – there is a strong drought; if $S_S \leq -3$, there is a strong excess moisture. Winter conditions: at $S_W > 2$ winter is considered warm and snowy, while $S_W <-2$ – winter is cold and snowy.

According to the analysis of the results of calculating index, in half of the cases examined, normal moistening conditions (Table 1).

Table 1

Repeatability of humidification conditions for warm and cold periods in the Udmurt Republic for 1961-2014

	Number of years	*%*	*Number of years*	*%*	*Number of years*	*%*	*Number of years*	*%*	*Number of years*	*%*
Summer	***Drought***		***Drough tconditions***		***Normal conditions***		***Wet conditions***		***Excess moisture***	
May	5	9	11	20	25	46	6	11	7	13
June	7	13	7	13	25	46	11	20	4	7
July	3	6	10	19	25	46	11	20	5	9
August	6	11	6	11	30	56	8	15	4	7
September	6	11	8	15	25	46	10	19	5	9
Winter	***Warm and snowy***		***Snow conditions***		***Normal conditions***		***Snowy conditions***		***Cold and little snow***	
November	5	9	8	15	29	54	9	17	3	6
December	5	9	11	20	24	44	9	17	5	9
January	6	11	9	17	25	46	7	13	7	13
February	7	13	4	7	31	57	5	9	7	13
March	4	7	9	17	26	48	9	17	6	11

Most often, cases of drought observed in the southwest of region, excess moisture encountered most often in the east. In the cold season frequency of extreme index Pedya more on the north of the region, less often they are recorded in the central and south-eastern regions.

In the 21st century in the vegetative period there is a tendency to increase dryness (Fig. 6). Winters become softer and snowy – linear trend for period for November to March is 0,16/10 years. The highest rate of growth of the index noted in March: 0,28/10 years.

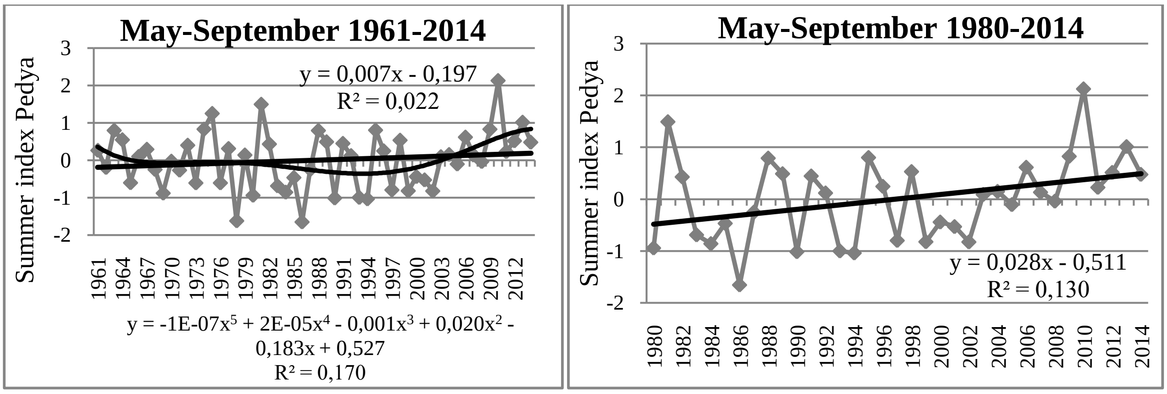


Fig. 6. Long-term changes summer index Pedya, linear and polynomial trend for the years 1961-2014 and 1980-2014

The paper analyzes the influence of atmospheric circulation on the weather and climate of the region. The most informative indices are SCA and EA-WR. If SCA Scandinavian fluctuation affects the weather of the region only in the cold season, the East Atlantic Oscillation - West Russia EA-WR affects the P and T for the entire year. Arctic Oscillation AO associated with P and T in January and December. Precipitation has a connection in the winter and transitional months with the Scandinavian swing.

In the fourth chapter dangerous phenomena associated with waves of heat and cold, its repeatability and dynamics are considered, synoptic conditions of their occur is studied. A catalog of cold and warm winters in Udmurtia is compiled. An attempt to assess climatic and weather risks in the territory of the republic was undertaken.

Frosty period with the probability of lowering temperatures below -20 °C lasts in Izhevsk 153 days with an average frequency of 8-11 days in a season; air temperatures -30 °C or lower – 114 days. Extreme cold -35 °C recorded very rarely and only in the winter months.

Extreme cold air with a minimum temperature below -35 °C in 80 % of cases occurs in Izhevsk at ultrapolar intrusions. Effect of these synoptic conditions within a few days contributes most strongly reduced of temperature up to -40 °C and below. Directions of the air mass flow at a pressure level AT_{500} more than half are northern. Lowering the temperature to the most extreme values observed in the center of high altitude cyclones.

The increase in the frequency of extreme frosts in the middle of the last century and its decline after the 1970s is traced (Fig. 7). The last 30 years the duration of the cold wave with extreme frosts reduced. Since 1961, the number of frost days decreased at a rate of -1 day/10 years.

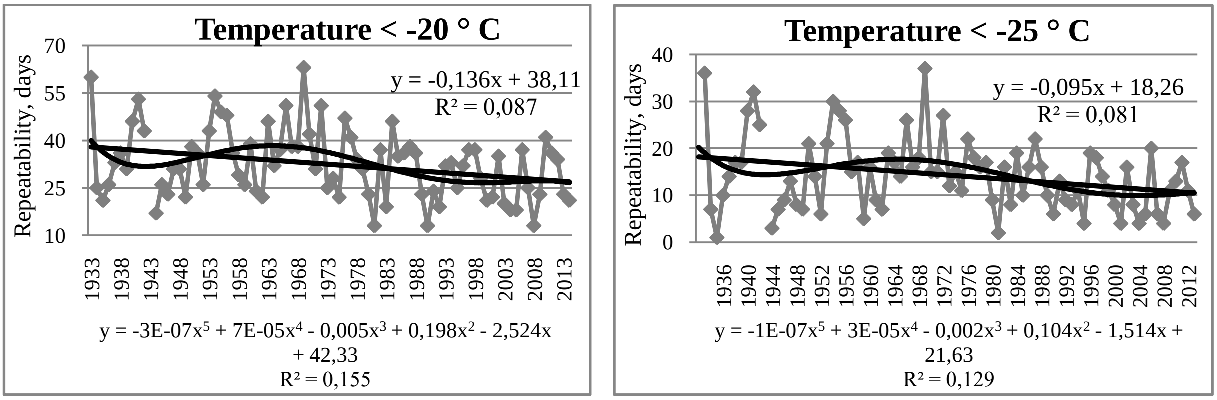


Fig. 7. The interannual change, linear and polynomial trends of repeatability (in days) the minimum air temperature below -20,-25 °C

A catalog of abnormal winters in the Udmurt Republic is made based on an index the severity of the winters, which is proposed by A.V. Mescherskaya (2015):

$$\alpha = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{2}\left(\frac{\Delta t_i}{\sigma_i}+\frac{\Delta t_j}{\sigma_j}\right), \qquad (2)$$

where α – integral evaluation of the degree of anomaly of winter air temperature, N – number of meteorological stations, $\frac{\Delta t_i}{\sigma_i}$ and $\frac{\Delta t_j}{\sigma_j}$ – normalized temperature anomalies in stations for January and February. To improve the sustainability of the results the coldest and most stable during the winter January and February data used. During the period from 1961 to 2014 in Udmurt Republic 29 cold and 25 warm winters noted.

The most extreme cold winters, usually associated with high-rise blocking anticyclones. In the cold winters rank first place belongs to 1969 (α = -2,229). The warmest winter in the reporting period was in 2002 with a value of α = 1,635. The period of growth of the index from the beginning of the 1970s to the mid-1990s is noted, in the 21st century its values decrease due to an increase in the temperature repeatability below -20 °C in the conditions of blocking anticyclones in January and February.

In the warm season maximum temperature > 30 °C are found in Izhevsk almost annually with an average repeatability of 8 days per season in the period from 9 May to 9 September (124 days). A strong heat of 35 °C was recorded for the history of observations during the period from June 4 to August 27; it record duration of 11 days per season was observed in 2010.

Unlike extreme frosts that depend not only on the thermal and humidity properties of the air mass, but also on the vertical air temperature profile, extreme heat is primarily due to temperature properties and is observed at temperatures on AT_{850} from 18 to 24 °C. The heat is noted mainly in the south and south-west directions of flows on the AT_{500}, south flow direction observed in more than half of the cases (57 %) (Fig. 8a). Most often it occurs in the anticyclone (Fig. 8b).

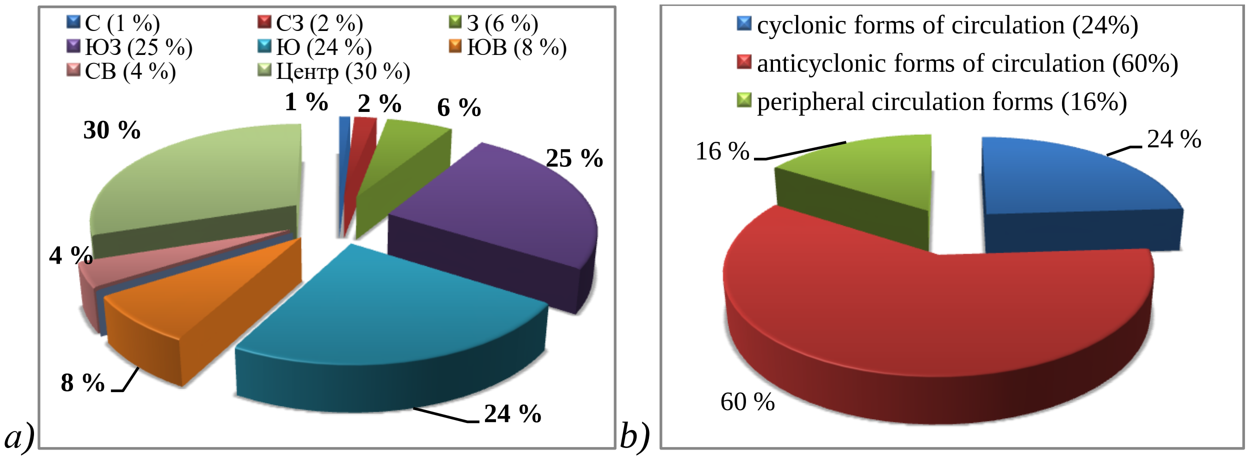


Fig. 8. Repeatability of the direction of the leading flow on the isobaric surface of AT_{500} (*a*) and the form of circulation at strong heat (*b*)

2 peak frequency of occurrence of hot weather obtained – at 80s of 20th century and at the end of the first decade of 21st century, and the period of increase of the frequency of heat since the early 1990s. Repeatability of heat waves has increased compared to the period 1933-1992 in the last 20 years 2-3 times.

During winter period in Izhevsk there is 29 days with thaws, most of them are in November and March; in winter thaws repeatability is 1-3 days per month.

From 1933 to 2014 number of days with thaws during the cold period in Izhevsk increased by an average of 12 days. Increase is largely due to the transitional seasons. The intensity of thaws decreased until the 1990s and has grown in recent decades. The duration of the heat waves, during the thaw observed which also increases.

The work analyzes thaws of various types: radiation, advection and radiation advection. Their repeatability is presented in Table 2.

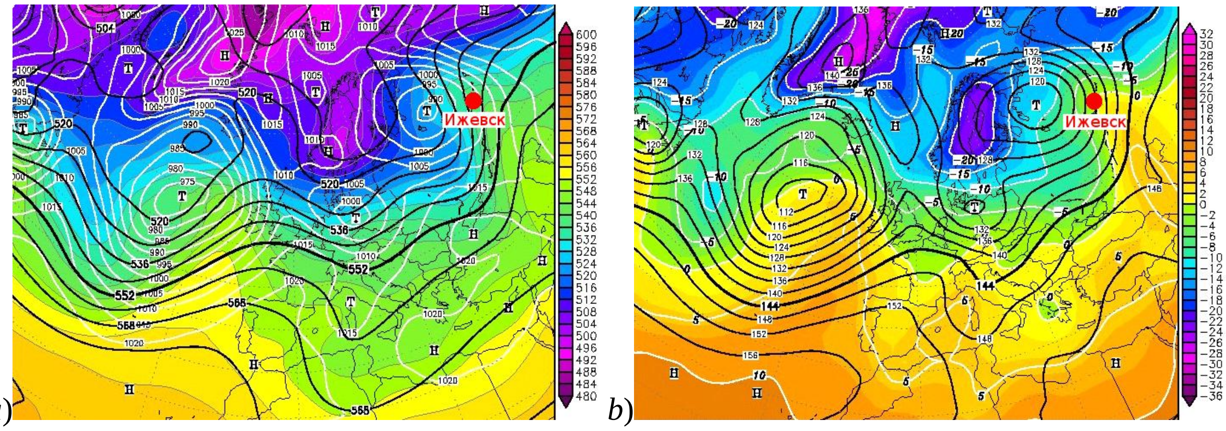
Table 2

Repeatability (%) of different types of thaws

Type of thaw	*November*	*December*	*January*	*February*	*March*	*Year*
Advection type	79	69	64	59	43	61
Radiation type	4	13	18	21	26	16
Mixed	17	18	18	20	31	23

Analysis of synoptic conditions showed that thaws most often occur in warm sector of the vast cyclone (43 %). Repeatability of thaws is also significant at exit of southern cyclones. At high altitude maps during thaws there is mainly a heat ridge. The phenomenon ends, as a rule, with a weakening of the altitude heat ridge and the spread of the cold valley from west to east.

Fig. 9 as an example shows the synoptic conditions thaw at January 10, 1948, when it was established the absolute maximum for the coldest months January: +5,4 °C.



a) *b*)

Fig. 9.The pressure field on AT_{500} (white contours, color box), the air pressure at sea level (hPa) (black contour) (*a*); temperature (°C) AT_{850} (white contours, color box) (*b*) 10 January 1948 12h UTC

Frosts in the surface air layer are most often observed in Izhevsk in early May and at the end of September, on average, during the growing season, there are 6 days with frosts. More than half the duration of the frost does not exceed one day. The duration of cold waves, at which freezing was observed 2 days or more, had a tendency to increase from the beginning of the 50s to the end of the 70s of 20th century, at the beginning of the 21st century it is reduced.

In May and for the warm season as a whole the number of frost decreases from 30s to the 60s of 20th century, after which it number grows to mid 90s. From this time, the frequency of frost decreases (Fig. 10). Dynamics of frost in September, has two peaks –

in the mid 1965s and in the early 2000s; in recent decades, frosts in September are also less frequent.

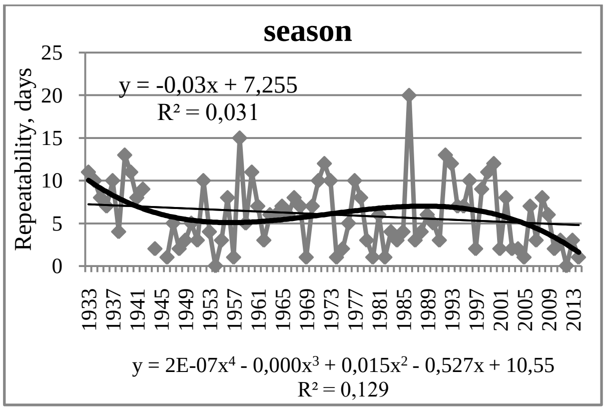


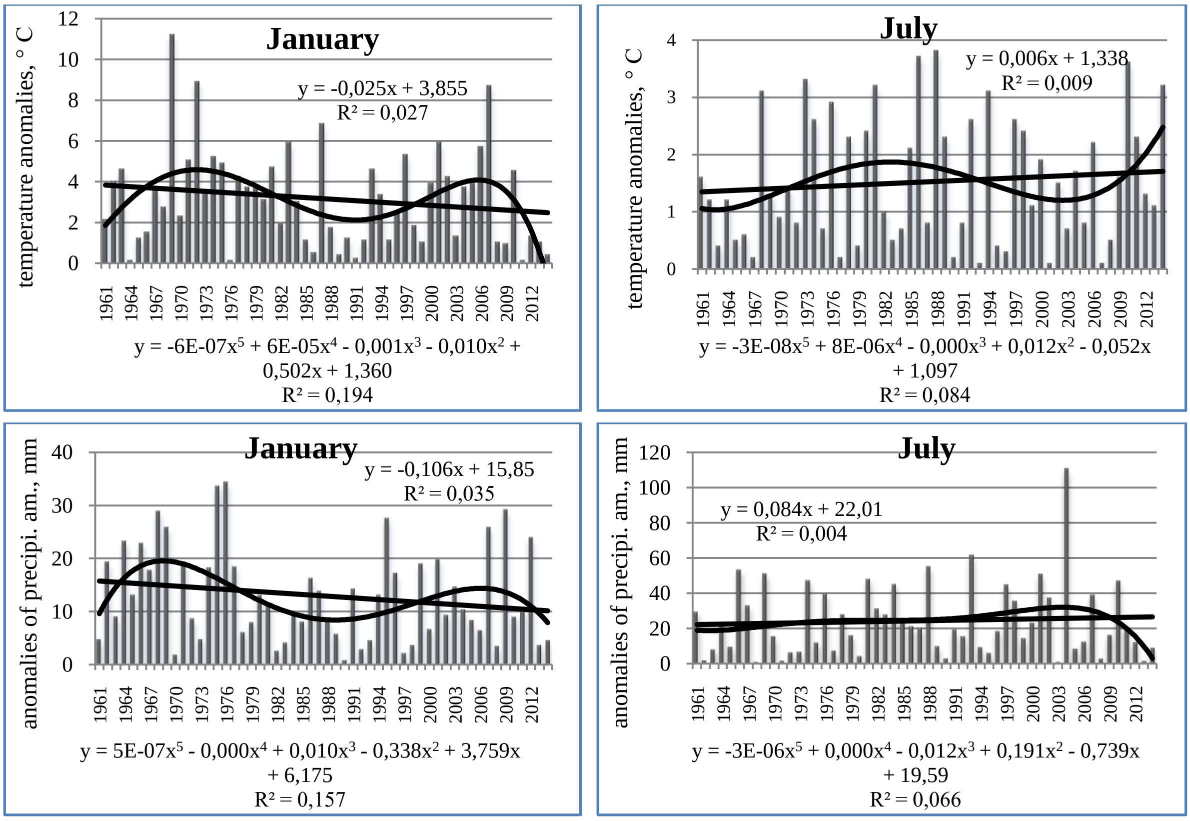
Fig. 10. Interannual changes, linear and polynomial trends of repeatability of frosts during the warm season

The most frequent frosts recorded in Izhevsk in the eastern periphery of the ridge. On the AT_{500} in 80 % of cases there is a cold trough, and in more than half the cases the flows of the northern and north-western directions. Long periods with frosts, as a rule, end when the altitudinal trough is replaced by a high altitude ridge, geopotential AT_{500} grows, and the direction of the leading flow changes from the north and north-west to the western and south-western.

At the end of the chapter, climatic risks are considered. The risks associated with the interannual variability of the seasonal values of climatic variables, in particular, affect agriculture, which largely depends on the thermal regime and moistening conditions.

Fig. 11 shows the temporal distribution of modular values anomalies precipitation and temperature in Izhevsk in January and July. In the long-term series of anomalies, a clear, statistically significant cyclicity of variations in the variation in air temperature and precipitation amounts is revealed. In January, it has been an increase in the absolute values of anomalies in a period of intense warming the end of the 20th-beginning of 21st century.

a)



b)

Fig. 11. The absolute temperature deviations (*a*) and precipitation (*b*) from the long-term average for January and July, linear and polynomial trends of the 5th degree

The economy is affected by risks not only with inter-annual, but also with intra-seasonal variability related to the weather factor. Anomalies of mean monthly temperatures and precipitation amounts the summer months relative to the average for the entire summer season are considered. The period of most active growth temperature, which is observed at the end of 20th-21st century beginning, there is an increase within variation of air temperature and amounts of precipitation.

The work assesses the risks and damages from SW in accordance with the methodology developed by N.V. Kobysheva (2014). The risk of occurrence of adverse consequences from the SW P estimated by the formula:

$$P = p_i \cdot \frac{s_i}{S}, \tag{3}$$

where p_i – SW frequency, s_i – the area covered by the i-th SW (km^2), S – the area of the whole territory (km^2).

For the recipient (economic object), this risk is:

$$P = p_i \cdot \frac{s_i}{S} \cdot \frac{s_{об}}{S}, \tag{4}$$

where s_{ob} – economic object area (km^2).

To determine the risk of causing social damage the next formula is used:

$$\mathrm{P}_{soc} = p_i \cdot \frac{s_i}{S} \cdot t \cdot l \cdot k, \tag{5}$$

where t – time of action SW (h), l – number of population (people), k – the aggressiveness factor.

For a particular recipient, this formula has the following form:

$$\mathrm{P}_{soc} = p_i \cdot \frac{s_i}{S} \cdot \frac{s_{об}}{S} \cdot t \cdot l \cdot k. \tag{6}$$

The values of the aggressiveness coefficient for various SW are presented in Table

Table 3

The values of the aggressiveness coefficient K

Strong wind	*Large hail*	*Shower*	*Heavy rain*	*Tornado*	*Squall*	*Blizzard*	*Strong ice*
1	3	0.03	0,002	6	1.4	0.8	2.5

The economic damage for the whole Udmurtia or individual recipient is given by:

$$P_э = P_{soc} \cdot A, \quad (7)$$

where *A* – factor of GDP share per one inhabitant of Udmurtia in 2014.

The results of calculations for UR, Izhevsk and conditional economic object with an area of 100 km^2 are shown in Table 4.

Table 4

The frequency of SW, the risk of SW, social risk P_{soc} and economic (mln.rub./year) risk P_e of SW for the Republic of Udmurtia, Izhevsk and economic object with an area of 100 km^2

Hazards	*Frequency RP pi*	*Udmurtia*			*Izhevsk*			*economic object*		
		P	*P_{soc}*	*P_e*	*P*	*P_{soc}*	*P_e*	*P*	*P_{soc}*	*P_e*
Very strong wind	0.2	$4.75 \cdot 10^{-2}$	9366.9	2317.6	$3.57 \cdot 10^{-4}$	70.4	17.4	$1.13 \cdot 10^{-4}$	22.3	5.5
Squall	0.36	$8.55 \cdot 10^{-3}$	127.1	377.4	$6.43 \cdot 10^{-5}$	0.96	2.8	$2.03 \cdot 10^{-5}$	0.3	0.90
Large hail	0.19	$2.26 \cdot 10^{-4}$	3.1	9.1	$1.70 \cdot 10^{-6}$	0.02	0.07	$5.36 \cdot 10^{-7}$	0.02	0.05
Very heavy rain	0.36	$8.55 \cdot 10^{-2}$	648.5	5.3	$6.43 \cdot 10^{-4}$	4.9	0.04	$2.03 \cdot 10^{-4}$	1.5	0.01
Heavy rain	0.12	$1.43 \cdot 10^{-3}$	1.4	0.34	$1.07 \cdot 10^{-5}$	0.01	0,003	$3.39 \cdot 10^{-6}$	0,003	0,001
Blizzard	0.02	$4.75 \cdot 10^{-3}$	1441.1	356.6	$3.57 \cdot 10^{-5}$	10.8	2.68	$1.13 \cdot 10^{-5}$	3.4	0.85

The risk of very strong winds and very heavy rain in the UR is unacceptable. The risks of the other SW are acceptable, lowest risk observed for large hail.

Economic risks are highest for very strong winds, reaching for the region 2317.6 million rubles/year.

The greatest material damage observed from squalls and strong winds.

In the fifth applied chapter, the estimation of the thermal resources of the vegetation and heating periods is carried out, the bioclimatic conditions developing in the territory of the UR in recent decades according to Izhevsk are characterized by.

As informative characteristics of agroclimatic heat resources for Izhevsk average dates of a stable transition of average daily temperatures (T_{av}) through 0, 5, 10 and 15 °C in the direction of increase in spring and decrease in autumn are calculated, the sums of active temperatures are obtained. Their dynamics is estimated.

The period with T_{av} > 0 °C increase over the past 80 years at a rate of 1,5 days/10 years, in the 1933-1950 this period was 205, in the XXI century – 218 days. Over the past 30 years, the trend has increased to 3,5 days in 10 years.

The transition date T_{av} at 5 °C in spring does not tend to shift; in autumn this indicator from the 70s of the 20th century deviates towards later dates at a rate of 4.1 days /10 years, due to which the time period with an average daily temperature of 5 °C increases.

Period with T_{av} > 10 °C increases with the average rate of 2 days/10 years; since the 1980s this rate increased up to 4,9 days/10 years; in the 1933-1950 the average duration of the period was 124 days, in 2000-2014 it amounted to 141 days.

In 1961-2014, the growth rate of the period with T_{av} > 15 °C was 3,4 days /10 years. The period increases due to a joint smooth earlier transition through 15 °C in early summer and late at the end of the summer period.

In recent decades, the amount of active temperatures (T_{av} >10 °C) is also increased – linear trend of the period 1980-2014 years is 77 °C/10 years (Fig. 12).

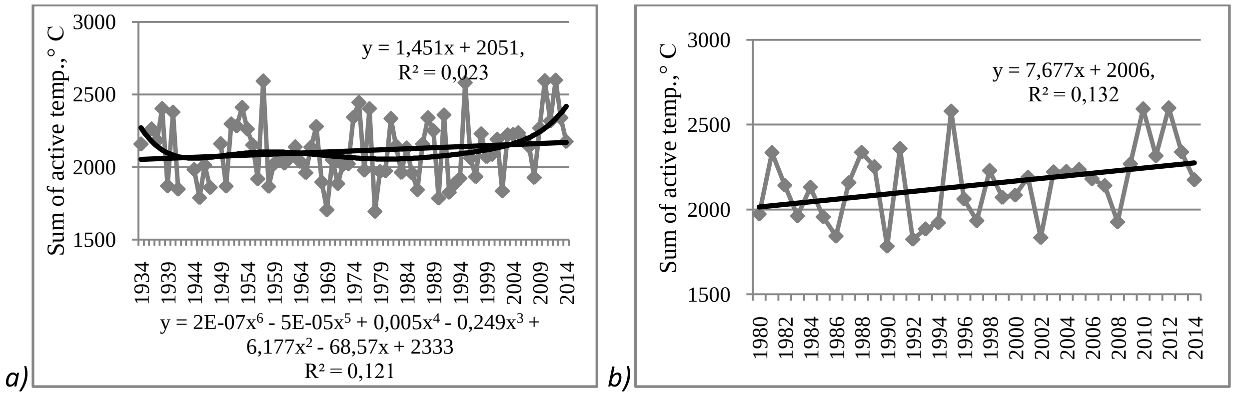


Fig. 12. The interannual change, linear and polynomial trends of the amounts of active temperatures in Izhevsk for the periods of 1933-2014 and 1980-2014

To assess the climatic characteristics of the heating period (*HP*) and their dynamics are calculated: start date *HP* in autumn (D_s), the date of the end in the spring (D_e), the duration of *HP* from the beginning of period to the end of December (L_1), the duration of the period from the beginning of January to the end date (L_2), the total duration of *HP L*, the average temperature *T* over the period *L*, the sum of the mean temperatures for *HP*, consumption index (*CI*) of fuel.

On average, *HP* begins in the third decade of September and ends in the third decade of April. The duration of L_1 is, on average, shorter than the duration of L_2. The average temperature of the L_1 period is lower than the average temperature of the L_2 period.

The characteristics of the duration of the *HP* change with time slightly, but the average temperature and the negative sum of the mean daily temperatures of *HP* increase (at a rate of 48 °C/10 years). Only in the last 20 years there has been a reduction in the duration of *HP*, mainly due to the autumn-winter period. Analysis of changes in the fuel consumption index made it possible to identify a tendency to reduce it at a rate of -69 °C/10 years. In the period 1960-2014, the rate of decrease reaches -91 °C/10 years.

The relationship between the characteristics of the *HP* and East Atlantic and Arctic oscillations is revealed.

As bioclimatic indicators, the following indices were calculated: the effective temperature *TE*, Stedman heat index ET_c, Missenard effective temperature *ET*, equivalent-effective temperature for Aizenshtat *EET*, radiation-equivalent effective temperature *REET*, Bodman’s weather severity index *S*, wind chill index for Siple-Passel *W*, reduced temperature for Adamenko-Khairullin t_{red}, and pathogenicity index *I* proposed by V.G. Bocsa. In addition to the period 1961-2014, the data for urgent observations in Izhevsk and Glazov during the period 2005-2015 were also used as initial data for calculations for 8 stations. Detailed results on the space-time distribution, the repeatability of the indices, their variability and dynamics are obtained.

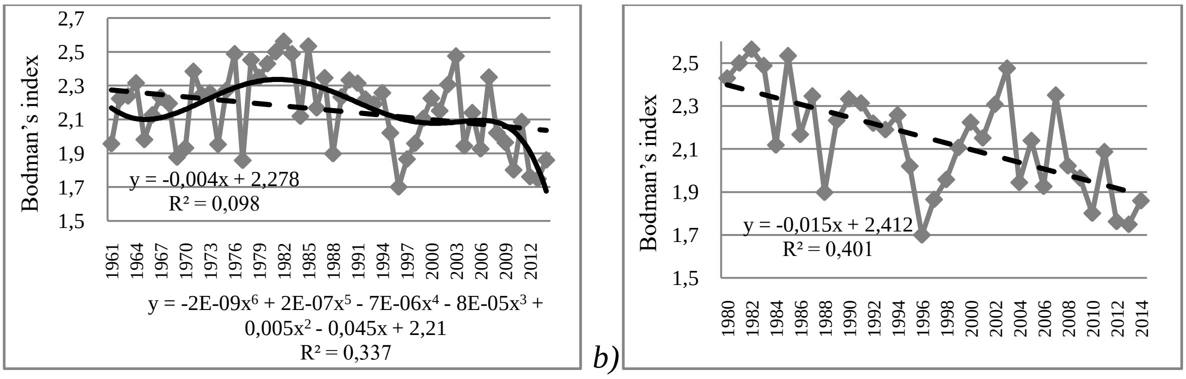
Bioclimatic indices, calculated for a warm half of the year, characterize this time for a person's warm sensation mainly as a comfortable one. All bioclimatic indicators used for the warm half of the year tend to grow[3], but the rate of their increase is low and most of the indicators remain in the comfort zone.

Index *ET* in the summer is growing almost twice slower than in winter: 0,56 °C/10 years, the lowest rate is observed in July: 0,43 °C/10 years. Only Stedman heat index ET_c indicates an increase in the risk of thermal danger due to a joint increase in temperature and humidity.

Moderate and heavy loads on humans prevail in winter in Udmurtia: most indices characterize the climate as cold and very cold. In the transitional months, the climate is moderately cold. Unlike the summer period, in winter hard conditions with strong loads on people are more often encountered. According to *ET* and t_{red}, in the period from December to February the most severe conditions with the threat of frostbite prevail.

All indices considered for the cold period change on a climatic scale, indicating a softening of conditions in the winter. Maximum rate of change is observed in January. The rate of change in the indices in winter is generally higher than summer, which is explained by a more intensive rise in air temperature and a decrease in the average wind speed on a climatic scale in winter.

As can be seen from Fig. 13, Bodman's weather severity index *S* is greatly reduced, while linear indices are statistically significant for both periods, and a smoothing curve represented by a polynomial of the 6th degree indicates a possible cyclicity in a row.



a)

Fig. 13. The interannual changes of Bodman's weather severity index in January in Udmurtia in the periods 1961-2014 (*a*) in the 1980-2014 (*b*)

Complex pathogenicity index *I* characterizes the weather conditions of UR primarily as sharp. Harsh weather conditions are formed mainly in the cold half of the year. The most extreme values are observed in the ultrapolar intrusion in the rear part of the cyclone with a sharp change in the main meteorological quantities (air temperature, pressure). Weather of the summer period in the UR is estimated as the most favorable. Comfortable weather occurs in more than half of the cases (50-60% repeatability).

An analysis of the partial pathogenicity indices calculated for individual meteorological values showed that in winter the main contribution to the integral index is made by the index of temperature pathogenicity and the index of day-to-day air temperature change, in summer the influence of the indices of the pathogenicity of cloudiness, humidity and diurnal temperature variation.

CONCLUSIONS

As a result of the completed comprehensive study, temporary climate changes in the territory of the Udmurt Republic, which contribute to the intensification of dangerous weather phenomena that damage the economy and public health are revealed. The following main results are obtained:

1. Using CRU data, the estimation of the age-old change in the average annual air temperature in Udmurtia is given. It is shown that the air temperature in the territory of Udmurtia in the period 1900-2014 increased by almost 2 °C, mainly due to the period from 1968 to 2011, for which it increased by 1,65 °C.
2. Climatic changes, which are most pronounced in winter and transitional periods, are manifested in the variability of meteorological quantities. Weak linear trends of pressure drop in the winter and spring months traced; the wind speed is weakening with the highest speed in November and December (coefficient of inclination of the linear trend = -0,3 m/s/10 years). Warming is formed due to winter and autumn months, in which the rate of temperature growth reaches 0,8 °C/10 years; absolute humidity increases mainly due to its growth in autumn. Cloudiness tends to increase in the north of the republic. The main contribution to the growth of the annual sums of precipitation in recent years is made by the months of March, April, October and December.
3. The classification of synoptic conditions for the occurrence of dangerous phenomena associated with heat and cold waves is fulfilled. Extreme frosts occur in 80 % of cases in the case of ultrapolar intrusions of air masses. The most extreme lowering of air temperature during frost is observed in the centers of high altitude cyclones. The determining factors for intense heat are the air temperature at AT_{850} and the presence of a heat ridge at the isobaric altitude AT_{500}. Most often, the heat (67 %) is noted in the anticyclonic field. In most cases, thaws (43 %) are determined by the warm sector of the vast cyclone. On the high altitude maps with thaws in the region, the ridge of heat is mainly formed. Frosts are most often recorded with advection of the cold arctic air mass and its further radiative cooling on the eastern periphery of the anticyclone. In 80 % of cases, frosts occur in the cold valley of the AT_{500}.
4. The duration of the cold waves in the period under consideration is decreasing, the tendency to decrease the occurrence of extreme frosts at a rate of -1 day/10 years is observed. The duration of heat waves at which a thaw is observed increases, and the frequency of thaws increases due to November and March. Index Pedya for the period November-March is 0,16/10 years, which indicates a tendency to mitigate the winters. According to the winter anomaly index α, the winters have softened since the early 1970s to the mid-1990s, and the value of the winter anomaly index decreases in the 21st century, which is due to an increase in the temperature repeatability below -20 °C under blocking anticyclones in January-February.
5. In summer, the frequency of strong heat over the past 20 years has increased by 2-3 times compared with the period of 1933-1992. Frosts in the growing season are less frequent, their duration is shortened.
6. In the context of global warming, inter-annual and intra-seasonal climate variability is increasing in the region, it leads to an increase in climatic risks - in the period of the most active temperature increase observed at the end of the 20th and beginning of the 21st century, in January, the absolute values of air temperature anomalies and precipitation, in July, an increase in the intra-seasonal variation in air temperature and the amount of precipitation is observed. The greatest economic and social risks from SW in Udmurtia are due to a very strong wind.
7. Agroclimatic resources in Izhevsk are improving: in the period 1980-2014, the growth rate of the growing season was 3,5 days/10 years, the growth rate of the sums of

active temperatures is 77 °C/10 years. At the same time, according to Pedya index, during the growing season, the trend towards an increase in aridity is observed, the Pedya summer index grows at a rate of 0,28/10 years.

8. The duration of the heating season in Udmurtia is reduced due to its later onset in the fall. During the period 1960-2014, the sum of the temperatures of the heating period increases at a rate of 61 °C /10 years, the fuel consumption index decreases at a rate of -91 °C/10 years, which is favorable for the housing and utilities sector.

9. Bioclimatic conditions on the territory of Udmurtia tend to improve, all biometeorological indices calculated for the cold period indicate a softening of weather conditions. In the period 1980-2014, the effective Missenard temperature increases at a rate of 1,4 °C/10 years, the Bodman index decreases at a rate of -0,2/10 years. In summer, the increase in effective temperature is not so significant and it persists in the comfort zone.

MAIN PUBLICATIONS OF THE INVITOR ON THE THEME OF DISSERTATION

Articles in journals recommended by the High Attestation Commission:

1. Perevedentsev, Yu. P. Changes of the climate in Privolzhsky Federal district in the recent decades and their relationship to geophysical factors / Yu.P. Perevedentsev, K.M. Shantalinsky, N.A. Vazhnova, E.P. Naumov, **A.V. Shumihina** // Bulletin of Udmurt University. Biology. Earth Sciences. – 2012. – no. 4. – pp.122-135.
2. **Shumikhina, A.V.** Extreme frosts in Izhevsk in XX-XXI centuries / **A.V. Shumikhina** // Bulletin of Udmurt University. Biology. Earth Sciences. – 2015. – T.25, no 1. – pp. 114-121.
3. **Shumikhina, A.V.** Repeatability and dynamics of thaws in Izhevsk / **A.V. Shumikhina** // Bulletin of Udmurt University. Biology. Earth Sciences. – 2015. – T.25, no 4. – pp. 129-135.
4. Perevedentsev Yu.P. The dynamics of the bioclimatic indices of environmental comfort in the Udmurt Republic, Russia. / Yu.P. Perevedentsev, **A.V. Shumikhina** // Uchenye Zapiski Kazanskogo Universiteta. Seriya Estestvennye Nauki. – 2016. – vol. 158, no. 4. – pp. 531–547.
5. **Shumikhina, A.V.** Precipitation pattern dynamics in the Udmurt Republic and its connection with atmospheric circulation index / **A.V. Shumikhina** // Geographicheskiy Vestnik. – 2017. – no. 1(40). – pp. 73-85.

Published in other editions:

1. **Shumikhina, A.V.** Frosts and thaws in Izhevsk in XX-XXI centuries / **A.V. Shumikhina** // Geography and region: materials of the international scientific-practical conference : in 6 t. – Perm, 2015. – T. IV: Hydrometeorology. Cartography and geoinformatics. – pp.180-185.
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4. Perevedentsev, Yu.P. Dynamics of bioclimatic indicators of natural environment comfort in the Udmurt Republic / Yu.P. Perevedentsev, **A.V. Shumikhina** // Ecology and space: international materials. sci. Conf. – St. Petersburg: VKA them. A.F. Mozhaiskogo, 2017. – pp. 234-239.
5. **Shumikhina, A.V.** Dynamics of dangerous phenomena and climatic risks in Izhevsk / **A.V. Shumikhina** // Environment and sustainable development of regions: environmental challenges of the 21st century: III international materials sci. Conf. – Kazan: Kazan. Univ., 2017. – pp. 272-282.
6. Perevedentsev, Yu.P. Long-term changes in air temperature in Udmurtia against the background of temperature changes in the temperate zone of the Northern Hemisphere / Yu.P. Perevedentsev, K.M. Shantalinsky, **A.V. Shumikhina** // Problems of regional ecology and geography: materials vseross. scientific-practical. Conf. with the international participants. – Izhevsk: Institute for Computer Research, 2017. – pp. 28-31.