RESEARCH PAPER

# MAPPING TEMPERATURE AND PRECIPITATION EXTREMES UNDER CHANGING CLIMATE (ON THE EXAMPLE OF THE URAL REGION, RUSSIA)

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ABSTRACT. The paper presents a series of maps of extreme climatic characteristics for the Ural region and their changes under climate warming observed in last decades. We calculate threshold, absolute and percentile-based indices with the use of daily temperature and precipitation dataset of 99 weather stations of Roshydromet. Extreme climatic characteristics were averaged by moving 30-year periods from 1951 to 2010 for temperature and from 1966 to 2015 for precipitation. The regression-based interpolation was used for mapping climatic extremes taking into consideration the influence of topography. Elevation and general curvature of the terrain are considered as independent variables. In addition, the changes of extreme characteristics between the 30-year periods were estimated. As a result, a series of maps of temperature and precipitation extremes for the Ural region has been created. The maps present not only spatial distribution of the climatic extremes, but also regional features of their changes under climate warming. In general, the revealed changes in extremes in the Ural region correspond to the trends observed on the most of the territory of Russia. There is a substantial decrease of the number of extremely cold days in winter, and the minimum winter temperature has a strong positive trend (up to 1-5°C/30 years). The maximum temperature in summer has a positive trend in most of the territory, but the increase rate does not exceed 2°C between 1951–1980 and 1981–2010. The precipitation extremes also increased up to 0.5-1.5 mm when comparing 1966–1995 and 1985–2015 periods.

KEY WORDS: climatic extremes, extreme temperature and precipitation indices, mapping, regression-based interpolation, Ural regio

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## INTRODUCTION

Global warming leads to a change in both the mean and extreme values of climate variables. For decades, most analyses of long–term global climate change using observational data have focused on trends in mean values (Alexander et al. 2006). However, a change in extreme climatic characteristics may induce more substantial consequences, than in average. Last years, many studies examine the influence of global warming on the increase of climatic extremes and hazardous weather events (Frich et al. 2002; Groisman et al. 2005; Alexander et al. 2006; Bulygina et al. 2007; Zolina and Bulygina 2016; Mokhov and Semenov 2016). Changes in the frequency of occurrence of climatic extremes are under attention of the scientific community because the risks associated with them exceed the risks due to the changes in average values. In addition, the rate of increase of extremes can significantly exceed the same of the average values, which amplify the corresponding risks (Bardin and Platova 2013).

Expert Team on Climate Change Detection and Indices (ETCCDI) developed and recommended 27 indices of climate extremes, which can be derived from daily maximum and minimum temperature and daily precipitation. 16 of the 27 indices are temperature related and 11 are precipitation related (Alexander et al. 2006; Kiktev et al. 2009; Donat et al. 2013 a,b). The indices are used to estimate an intensity, frequency and duration of extreme temperature and precipitation events, and can be divided into five different categories.

*Percentile–based indices of temperature and precipitation extremes*. The temperature percentile-based indices show the coldest and warmest deciles for both maximum and minimum temperatures (TN10p, TN90p, TX10p and TX90p). The precipitation indices in this category represent the amount of precipitation falling above the 95th (R95p) and 99th (R99p) percentiles. Sometimes other percentiles are used, e.g. 95p or 99p for temperature extremes. The advantage of these indices is the possibility of their use for large areas with various climatic conditions. However, the calculated threshold values of extremes are often not associated with hazardous weather and climate-related risks (Bardin and Platova 2013; Zolina and Bulygina 2016).

*Absolute indices* represent maximum or minimum values within a season or year. They include maximum daily maximum temperature (TXx), maximum daily minimum temperature (TNx), minimum daily maximum temperature (TXn), minimum daily minimum temperature (TNn), maximum 1-day precipitation amount (RX1day) and maximum 5-day precipitation amount (RX5day) (Alexander et al. 2006; Kiktev et al. 2009).

*Threshold indices*, which are defined as the number of days on which a temperature or precipitation value falls above or below a fixed threshold, such as number of frost days or number of days with very heavy precipitation (> 30 mm). The threshold values of the indices can coincide with the accepted criteria of hazardous or adverse weather events. However, threshold criteria are not suitable for large areas with various climatic conditions (Alexander et al. 2006; Kiktev et al. 2009).

*Duration indices*, which define periods of excessive warmth, cold, wetness or dryness or in the case of growing season length, periods of mildness. Growing season length, consecutive dry days and heat wave duration index are the most frequently used indices of this category.

Other indices, which do not fall into any of the above categories, characterized the diurnal temperature range, extreme temperature range, contribution from very wet days to annual precipitation etc. (Alexander et al. 2006; Kiktev et al. 2009).

Two global land gridded datasets of temperature and precipitation extremes have been developed for climate change monitoring purposes. The first was HadEX dataset which cover the period 1951–2003. It is not updated and most of the data is not publicly available (Donat et al. 2013a). A new dataset termed GHCNDEX is an operationally updated and based on daily observations of maximum and minimum temperatures as well as daily precipitation amounts from 29.000 weather stations (Donat et al. 2013b). The dataset is publicly available at https://www.climdex.org. It contains 26 of the indices recommended by the ETCCDI and updated until 2013 for the territory of Russia. However, the data has a substantial number of omissions.

The indices recommended by ETCCDI and their modifications are widely used to study observed changes in extreme climate events in Russia. Bulygina et al. (2007) used percentile-based indices to estimate the changes in annual and seasonal extreme characteristics of temperature and precipitation for 1951–2005, according to 857 weather stations of Roshydromet. A decrease in the number of extremely cold days, an increase in the number of extremely warm days and the number of extreme precipitation events have been found for most of the territory of Russia. Bardin and Platova (2013) compared long-term changes of temperature and precipitation extremes by seasons of a year, calculated from percentile-based indices, with changes of the mean values (for 1976–2009). They found substantial distinctions between the changes in means and extreme temperature (especially in winter season).

Last years, several studies have considered the changes of extreme precipitations in Russia. Zolina and Bulygina (2016) calculated the absolute and relative indices of precipitation extremes, and also the number of consecutive dry days (CDD) and consecutive wet days (CWD) indices for 1966–2012. They showed that the frequency and intensity of extreme precipitation increases in most regions of Russia. Also, the rise in duration both dry and wet periods was found for many regions, which indicated a significant clustering of precipitation over time and an increase of probability of both floods and droughts events. Titkova et al. (2018) compared the frequency of extreme climatic events in winter season for 1970–2000 and 2001–2015. A significant decrease of very cold days, increase of very warm days and extreme precipitation events has been confirmed for most of Russia, especially for the European part of the country (ER). Zolotokrylin and Cherenkova (2017) analyzed the probable damaging effects of the observed increase of precipitation extremes on the environment and human activities for Russian regions with high population density.

So, the changes of temperature and precipitation extremes over entire Russia, observed during last decades, are relatively well-studied. At the same time, no such studies were performed at the regional scale level, which require an analysis of the geographical location of each weather station and consideration of the underlying surface influence on the spatial distribution of climate extremes. Some experience of climatic extremes mapping at the regional scale level is presented in the Atlas of hazardous hydro-meteorological events of the Perm region (Pyankov et al. 2017). However, the similar studies for other regions of Russia have not been conducted.

Worldwide, most of regional investigations of the climatic extremes examine the characteristics of extreme precipitation. A number of extreme rainfall characteristics are considered, such as probable maximum precipitation (PMP), intensity-duration frequency curve, probable maximum of precipitation for the period of 10 or 100 year, expected return interval of extreme precipitation events, e.g. 100 mm/day et al. (Beguería and Vicente-Serrano 2005). In some studies, not only daily precipitation extremes, but also extreme events lasting several days are considered (Beguería et al. 2009).

Mapping of other climatic extremes (e g. temperature, wind speed extremes) at a regional scale level is considered in few publications. Blennow and Persson (1998) developed a GIS-based linear regression model for local-scale temperature interpolation and frosts probability. The model takes into account four independent variables – sky view factor, elevation, relative relief and presence of peat soil. Li and Zha (2018) proposed a method for mapping climate variables (including extreme temperature) based on random forest regression models.

The purpose of this study is to develop a series of maps of temperature and precipitation extremes and their changes under observed climate warming for the Urals region. Earlier, the maps of the mean annual and monthly values of temperature and precipitation and their changes for 1951–2015 have been created for the same territory (Abdullin and Shikhov 2019). Therefore, the second purpose of the study is to compare the trends in average and extreme characteristics.

## DATA AND METHODS

### Initial data

We used daily temperature and precipitation dataset (http://aisori.meteo.ru/ClimateR), compiled by All-Russian Research Institute of Hydro-Meteorological Information – World Data Center (RIHMI-WDC) as input data for mapping temperature and precipitation extremes. We selected the data from 99 weather station of Roshydromet, located within the studied region and near it (Fig. 1). Temperature dataset was analyzed for 1951–2015 and precipitation – for 1966–2015, because precipitation data is not homogeneous before 1966 (Bulygina et al. 2007). A digital elevation model (DEM) with 1 km resolution, obtained on the basis of the GMTED-2010 DEM (Danielson and Gesch 2011), was used to find the relationships between extreme climatic characteristics and terrain properties (elevation, slope, aspect and curvature).

Extreme climatic characteristics are calculated for 30-year periods (1951–1990, 1971–2000, 1981–2010 for temperature extremes and 1966–1995, 1976–2005, 1986–2015 for precipitation extremes), since World Meteorological Organization (WMO) recommended the use of 30-year periods for climatological studies. The first 30-year interval (1951–1980) indicates the state of the climate before the start of contemporary rapid warming in the Northern Eurasia (Groisman and Soja 2009).

Four categories of indices, recommended by ETCCDI (Alexander et al. 2006) are calculated for temperature and precipitation extremes. Among threshold indices, number of days with minimum temperature ≤ –30°, maximum temperature ≥ 30°C and heavy precipitation ≥ 30 mm (over above-mentioned 30-year periods) are calculated. The selected threshold values coincide with the criteria of adverse weather events, accepted in the most of studied regions. Annual minimum and maximum of temperature and annual maximum of daily precipitation, averaged over 30-year periods, are used as absolute indices. We also calculated percentile–based indices for temperature and precipitation extremes. Extreme temperature events are determined as the days with maximum temperature exceeding 99% percentile (99p), and with minimum temperature of less than 1% percentile (1p) of empirical distribution function for maximum and minimum daily temperatures respectively. Extreme precipitation events are determined similarly, as daily precipitation exceeding 99% percentile of empirical distribution function, which was calculated from the entire studied period (1951–2015 for temperature, and 1966–2015 for precipitation).

Among the duration indices, we calculated only the average annual number of CDD for summer months. Its values may be related to the frequency and intensity of summer droughts and wildfire outbreaks, which occur every few years in different parts of the Ural region (Shikhov et al. 2019).

*Programs and programming languages that were used in the study*

The climatic data were processed with Python program language (Pandas library). The maps were constructed with ArcGIS 10.4.

*Overview of the interpolation methods appropriate for climate mapping*

Spatial distribution of both mean and extreme climatic characteristics is determined by both the geographical location (latitude, longitude) and characteristics of the underlying surface, especially in areas with rugged terrain. Various statistical methods have been developed to predict (interpolate) climatic variables in regions with sparse observation network and rugged terrain (Ninyerola et al. 2000; Weisse and Bois 2002; Vicente-Serrano et al. 2003). They can be subdivided into global and local methods.

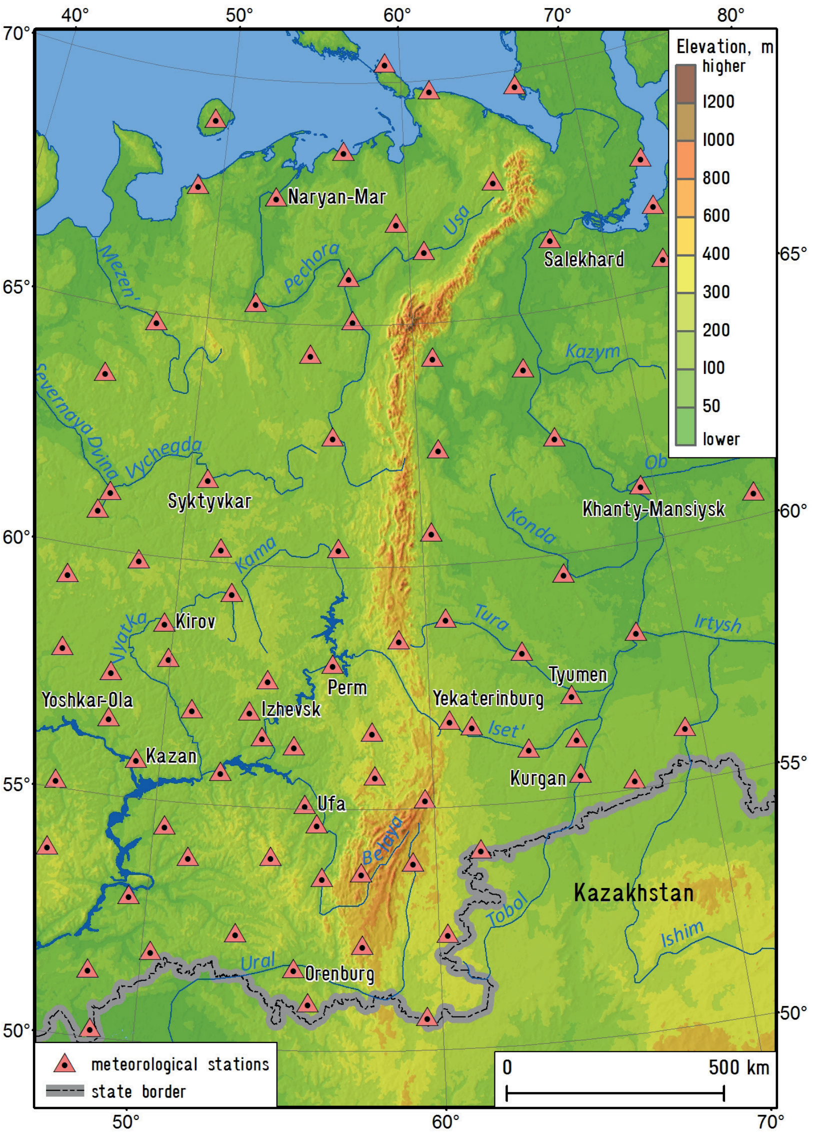


**Fig. 1. Study area and location of the weather stations whose observations were used**

A general practice of the use of global methods presume estimation of the relationships between climatic data and independent variables (predictors) such as latitude and longitude of the weather stations, topographic (e.g. elevation, aspect, slope, etc.) and/or geographic (e.g. distance to water bodies) variables. These relationships are used to produce climatic maps by means of empirical simple- or multiple-regression models. Such global regression-based estimate is inexact since the predicted values do not coincide with the measured values at weather stations (Goodale et al. 1998; Vicente-Serrano et al. 2003).

Among local methods, the most widely used for the climate mapping are various geostatistical techniques (Goovaerts 2000; Vicente-Serrano et al. 2003). Some of them based only on the climatic data recorded at the weather stations (e.g. simple kriging, ordinary kriging), while others use topographic/geographic information (e.g. cokriging or universal kriging).

Also, a group of 'mixed' methods combines global, local and geostatistical techniques (Ninyerola et al. 2000, Brown & Comrie 2002). These methods take into account both the physical relationships between climatic data and geographic/topographic variables, and the spatial correlation between weather stations data. Vicente-Serrano et al. (2003) showed that regression-based interpolation and geostatistical methods are most appropriate for temperature and precipitation mapping in the areas with rugged terrain.

*Mapping of the climatic extremes with threshold indices*

In this study, we used a 'mixed' interpolation technique which was firstly proposed to predict the spatial distribution of snow water equivalent (Shutov 1998). It combines spline interpolation with simple linear regression model. Earlier, we successfully used this technique for mapping of the frequency of hazardous weather events in the Perm region (Abdullin and Shikhov 2017). We could not use the multiple regression model based on several geographical and topographic variables, since the determination coefficients were not high enough (less than 0.85), except for the minimum daily temperature in winter.

The maps of threshold indices, as well as on absolute indices of climatic extremes were created based on the technique including five consecutive stages.

1. Fitting a linear regression between the calculated indices of climatic extremes (dependent variables) and terrain properties such as elevation, aspect, general curvature (independent variables), estimated for the location of each weather station;
2. Assessment of the regression significance at a threshold p-value of 0.05. The examples of a statistically significant regression are shown at Fig. 2;
3. Calculating of the values of indices under the assumption of a zero value of independent variables for each weather station according to the formula:

$$y_0 = y - ax_{st} \tag{1}$$

Where $y_0$ is the value of dependent variable under the assumption of a zero value of independent variable, *y* signifies the initial values of dependent variable, $x_{st}$ is the value of independent variable in the location of each weather station and *a* is the coefficient in the linear regression equation (e.g. elevation-dependent gradient of temperature or precipitation);
4. Interpolation of the indices values from weather stations, calculated under the assumption of a zero value of the independent variable, using the method spline with tension. Spline interpolation method was selected due to its successful application in a number of climatic studies (Fick and Hijmans 2017; Chernokulsky et al. 2018);
5. Correction of interpolation results based on estimated regression between indices and independent variables with map algebra tool, according to the following formula:

$$y_0 = y + ax_f \tag{2}$$

where $x_f$ signifies the values of independent variable (for example, elevation) in each grid cell. Then, the resulting grid was smoothed with mean filter.

So, large-scale variability of the indices, related to latitude and longitude of location, was taken into account with spline interpolation of the weather stations data, and mesoscale variability (related to underlying surface properties) was considered using regression models.

The resulting values in grid cells, corresponding to the location of the weather stations are equal to the observed values. The exception is only if the elevation was a single independent variable. In this case, initial values of elevation of the weather station, obtained from (http://meteo.ru/), may differ from the elevation values in the corresponding cells of the DEM. Consequently, the resulted value of the indices at the cell of weather station may differ from the observed value. In other cases, the initial values of independent variables were extracted from DEM.

Surface elevation is the main variable determining the spatial distribution of extremely high temperature (number of days with a maximum temperature ≥ 30°C) and heavy precipitations (≥ 30 mm/day). Large water bodies and urban heat islands have also some influence on the spatial distribution of a maximum temperature, but it is low-pronounced at a scale of 1:10 000 000. The linear regression between the number of days with temperatures ≥30°C and elevation was estimated on the data from 36 weather stations located between 56 and 60° N. Thus, the influence of the large-scale (zonal) temperature gradient was reduced.

The number of days with heavy precipitation (≥ 30 mm/day), also correlate with surface elevation, but correlation coefficient is non-significant at 0.05 P-value. We used two-step approach with the introduction of additional variable, namely annual average maximum of daily precipitation. It has a statistically significant correlation with elevation at a 0.05 P-value (Fig. 3b), and also it has a strong correlation ($R^2$ = 0,82) with the number of heavy precipitation events (Fig. 2a). We supposed, that spatial distribution of the number of days with heavy precipitation is similar with average annual maximum of daily precipitation. So, we initially interpolate the annual average maximum of daily precipitation with elevation-dependent regression (Fig. 3b). Then, the corresponding values of the number of days with heavy precipitation were estimated for each pixel, using the linear regression (Fig. 2a).

The spatial distribution of the minimum daily temperature in winter is determined not by elevation, but by general curvature of the terrain (Fig. 2b). Indeed, the minimum temperature is much lower in landforms with negative curvature, than over elevated landforms, especially under anti-cyclonic weather conditions. Consequently, the frequency of extremely low temperatures should increase in the negative landforms. The relationship between the frequency of extremely low temperatures and general curvature was previously used for the Perm Region (Abdullin and Shikhov 2017). However, it is impossible to use it for the entire Ural region, since the frequency of the days with a minimum temperature ≤ –30° strongly increases from south-west to north-east. Therefore, we applied a multiple linear regression which is based on three independent variables such as latitude, longitude and general curvature of the terrain, extracted from a smoothed DEM. The value of the multiple $R^2$ is 0.85.

*Mapping of the climatic extremes with absolute indices and duration indices*

To create the maps of the average annual maximum and minimum of temperature, as well as the average annual maximum of precipitation, we used the same relationships with the terrain properties, as for the corresponding absolute indices. The workflow of the creation of the maps includes the above-described five steps. The examples of the relationships between absolute indices of climatic extremes and terrain properties are shown at Fig. 3.

The number of CDD in summer has statistically significant inverse relationship with elevation of the weather station (at a 0.05 P-value). So, we interpolate CDD with elevation-dependent regression and obtained a reliable estimate of its spatial distribution.

*Mapping of climatic extremes with percentile-based indices*

Percentile-based indices of climatic extremes can be divided into two types, such as threshold values of temperature (1% and 99% percentiles) or precipitation (99% percentile) (type 1), and number of days with extreme temperatures or precipitations (type 2). Threshold values of extreme characteristics, calculated by percentile-based indices, have the same patterns of the spatial distribution, that corresponding absolute indices. So, we used interpolation with elevation-dependent regression to create the maps of 99p daily precipitation (calculated over the entire year and for cold season only), and for 99p maximum temperature in summer (Fig. 3a). The 1p minimum temperature in winter has statistically significant relationship with general curvature of terrain (Fig. 4b).

In turn, the spatial distribution of the number of days with extreme temperatures or precipitations (calculated by percentile-based threshold values) weakly correlated with underlying surface properties. Therefore, simple interpolation methods without considering any regressions are sufficient for mapping them.

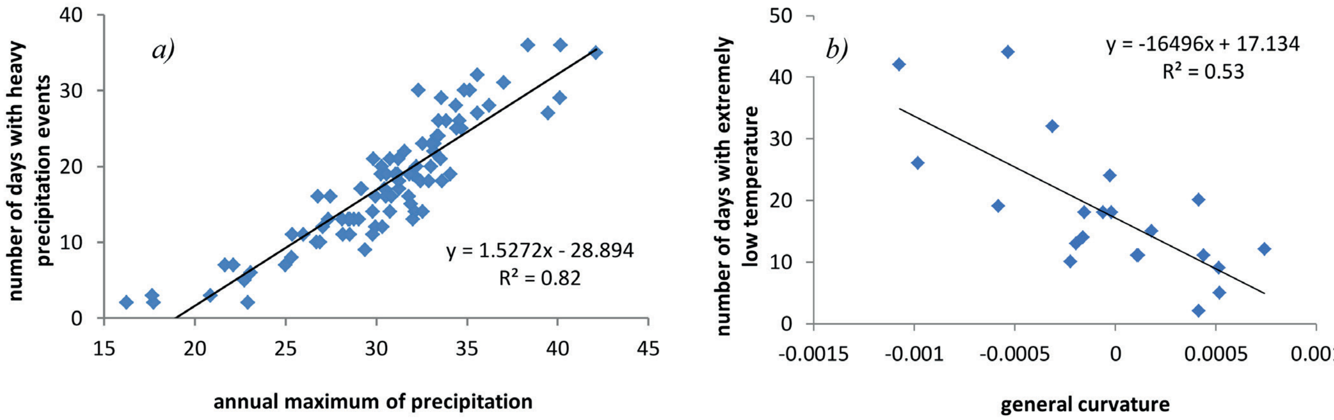


**Fig. 2. Relationships between number of days with heavy precipitation and annual maximum of daily precipitation (a), and between number of days with minimum temperature ≤ –30°C and general curvature (b)**

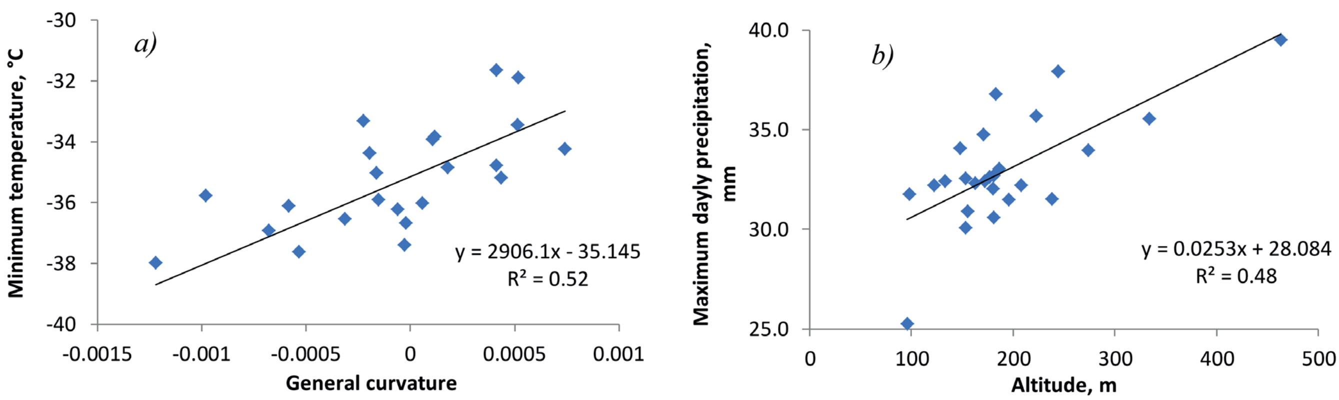


**Fig. 3. Relationships of average annual minimum of temperature with general curvature (a), and average annual maximum of daily precipitation with elevation (b)**

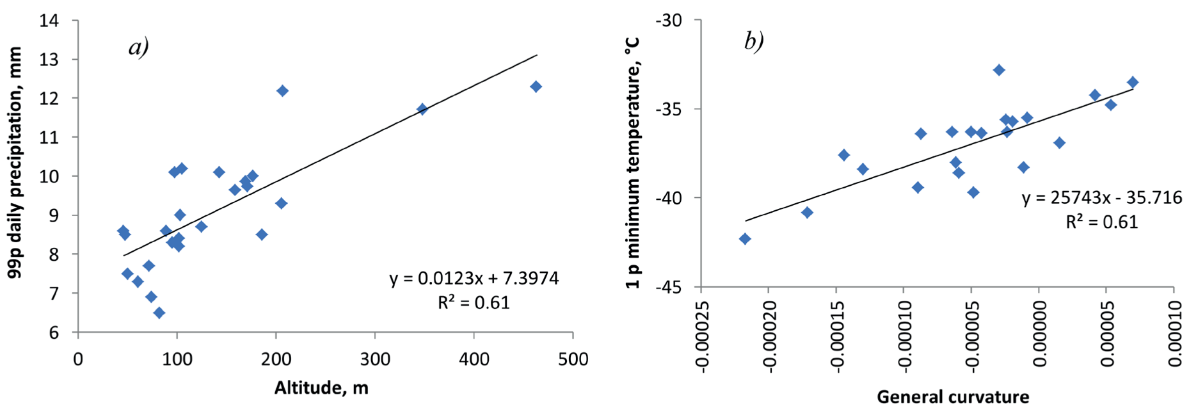


**Fig. 4. Relationships of 99p daily precipitation in cold season with elevation (a), and 1p minimum temperature in winter with general curvature of the terrain (b)**

## RESULTS AND DISCUSSION

The created maps of the spatial distribution of temperature and precipitation extremes are shown at Fig. 5-11. We compared the climatic extremes indices for the first and last studied 30-year periods (1951–1980 and 1981–2010 for temperature extremes, 1966–1995 and 1986–2015 for precipitation extremes) and also calculated the difference between them to indicate the changes that have been occurred in the last decades. The difference maps (Fig. 5-11c) are more smoothed than initial maps of climatic extreme indices, since the above-described relationships of the indices with terrain properties (elevation, curvature) does not changes with time. Therefore, the difference maps indicate only large-scale variability of the indices, related to latitude and longitude of location, without substantial influence of the terrain.

Table 1 summarizes the average, minimum and maximum values of such differences over the Ural region.

In average for the Ural region, there was a substantial decrease of the frequency of extremely cold days in winter. In turn, the frequency of extremely warm days and extreme precipitation has increased. In accordance with this, the average annual maximum and minimum of temperature have also increased (especially the annual minimum of temperature) like the average annual maximum of precipitation.

The similar changes in temperature and precipitation extremes have been observed during last decades in the most of Northern Eurasia (Bulygina et al. 2007; Zolotokrylin and Cherenkova 2017; Titkova et al. 2018). However, the notable regional variations in climatic extremes changes are found within the Ural region, which may be related to both changes in the atmospheric circulation and geographical features of the location of weather stations. These regional variations are analyzed in more detail.

*The average annual minimum of temperature* ranges from –44…–47°C east of the Polar Ural to –31…–34°C west of the Southern Ural and also near the Yekaterinburg city (Fig. 5). It has increased by 1-5°C between 1951–1980 and 1981–2010. The highest increase rate (up to 4-5°C per 30 years) is observed in the south-east of the Ural (Sverdlovsk, Kurgan and Tyumen' regions), and the lowest rate is only 1°C per 30 years near the Polar Ural. The 1p minimum daily temperature in winter has also increased by 1-5°C per 30 years (Fig. 6). The spatial distribution of the increase rate is similar to that of the average annual minimum of temperature. The number of extremely cold days in winter has been also significantly reduced (from 20-25 days/10 years in 1951–1980 to 4-8 days/10 year in 1981–2010) in the south-east of the Ural.

In general, the positive trend of minimum winter temperature corresponds to the observed decrease of temperature variance in high and middle latitudes of the Northern Hemisphere (Screen, 2014; Titkova et al. 2018). However, the regional variations are related to other factors. For instance, extremely cold winter seasons have been occurred in the south-east of the Urals in the 60s and 70s of 20th century (e.g. 1968–1969), when seasonal minimum of temperature ranged from –40° to –50°C. After 1984, such extreme cold days were not observed it this area, although long-term, but less severe frosts happened, in 2005–2006 and 2009–2010 winter seasons.

A relatively weak positive trend in the minimum winter temperature observed west of the Polar Ural may be related to the increase of the frequency of arctic air mass advection during cold season. The observed anticyclonic anomaly of 500hPa geopotential height and sea level pressure over the Barents and Kara Seas may contribute to this process (Titkova et al. 2018).

In addition to the changes of atmospheric circulation, the features of geographical location of the weather stations also affect the increase rate of the minimum winter temperature. For example, the weather stations located in the depressions or in the deep valleys such as Krasnoufimsk and Verkhneural'sk., reported an increase in the minimum winter temperature of only 1-2°C/30 years, whereas at neighboring stations the increase was much stronger (up to 3-3.5°C/30 years). Before the start of the contemporary climate warming extremely cold days observed more often on the entire territory (regardless of the topography features). Currently, severe frosts are mainly observed in depressions and in deep valleys of rivers. This pattern can be also related to theincrease of temperatures of the air masses spreading from the Arctic to the Ural region (Kim et al. 2019).

*The average annual maximum of temperature* ranges from +26°C in the Polar Ural to +35°C west of the Southern Ural (Fig. 7). When comparing the periods 1951–1980 and 1981–2010, it has increased from 0.1-0.2°C in the southeast of Ural to 0.6-0.7°C in the north-west. The values of 99p maximum daily temperature in summer have increased by 0.5-1°C in the most of the territory (Fig. 8). The highest increase rate (up to 2°C per 30 year) is observed to the west of the Ural ridge, in the Kirov region and Udmurt republic, which were most affected by the extreme heat wave of summer 2010. In the same time, the 99p maximum daily temperature decreased by 0.5-1°C in the southeast of Ural (Kurgan and Tyumen' regions). This indicates the amplification of summer heat waves in the ER, with simultaneous reduction in Western Siberia. An increase of the maximum temperature in summer west of the Ural

**Table 1. Average, maximum and minimum values of the difference of climatic extreme indices between two compared periods**

| Variable | Compared periods | Average difference | Minimum difference | Maximum difference |
|---|---|---|---|---|
| Average annual minimum of temperature, °C | 1951–1980 and 1981–2010 | 2.8 | 0.1 | 5.8 |
| 1p minimum daily temperature in winter, °C | 1951–1980 and 1981–2010 | 2.4 | 0.1 | 5.6 |
| Average annual maximum of temperature, °C | 1951–1980 and 1981–2010 | 0.4 | –0.1 | 1.0 |
| 1p maximum daily temperature in summer, °C | 1951–1980 and 1981–2010 | 0.6 | –2.2 | 2.4 |
| 99p daily precipitation, mm | 1966–1985 and 1986–2015 | 0.3 | –3.1 | 2.1 |
| Number of days with daily precipitation ≥ 30 mm | 1966–1985 and 1986–2015 | 0.5 | –4.1 | 4.3 |
| Consecutive dry days in summer | 1966–1985 and 1986–2015 | 0.4 | –2.4 | 3.0 |

ridge is related to the rise in the frequency and intensity of blocking anticyclones in the Atlantic-European region (Cherenkova 2017). The decrease in extreme summer temperatures in the southeast Ural is also due to the same process, since arctic air masses spread to the Western Siberia along the eastern periphery of these blockings.

The number of extremely hot days in summer also amplified most strongly (by 7 days/10 years) in the Kirov region and Udmurt republic, and also west of the Polar Ural. On the contrary, it decreased by 1-3 days/10 years in the southeastern Ural (Kurgan and Tyumen' regions).

*Average annual maximum of precipitation* ranges from 15 mm on the Yamal peninsula to 35-40 mm along the Ural ridge and near Tyumen' city. The second local maximum near Tyumen' city is most likely due to the fact that southern cyclones which induced heavy precipitation are often moving through this area. Between 1965–1995 and 1985–2015, average annual maximum of precipitation has increased to 1-5 mm on the most part of the territory. The most substantial increase was observed in the Middle Ural and adjacent plains.

*The threshold values of 99p daily precipitation* ranges from 11 mm on the Yamal Peninsula to 20-22 mm along the Ural mountains. When comparing the 1965–1995 and 1985–2015 periods, it has increased by 0.5-1.5 mm in the most part of the Ural region (Fig. 9). Some weather stations in different parts of the Ural reported a decrease of 99p daily precipitation to 0.5-1 mm per 30 year, and up to 1.5 mm on the Yamal Peninsula. The observed increase of 99p daily precipitation is in concordance with positive trends in precipitation extremes changes which were previously found for the most part of Russia (Zolina and Bulygina 2016; Zolotokrylin and Cherenkova 2017).

The number of days with daily precipitation exceeding 30 mm ranges from 2 days/10 year on the Yamal Peninsula to 12 days/10 year on the Northern and Middle Ural ridge, with the observed maximum at the Biser weather station (58.51°N, 58.85°E). It has also increased to 1-3 days/10 year when comparing 1965–1995 and 1985–2015 (Fig. 10). The negative trend is observed at some weather stations located in different parts of the region, mainly east of the Northern and Polar Ural, and also in the Orenburg region.

Comparing the changes of precipitation extremes between 1966–1985 and 1986–2015, it is important to consider that the highest precipitation amount and many extreme precipitation events in the Ural have been observed in 1989–1990 and 1992–1994 (Perevedentsev et al. 2013). These years already fall into the period 1966–1995. Therefore, the observed increase in precipitation extremes is relatively weak.

The distribution of the number of CDD in summer months ranges from 5-6 days in the northern part of the Ural ridge to 14-15 days in Orenburg region, where summer droughts are most frequent. The number of CDD had no significant changes between 1966–1995 and 1986–2015 on the most part of the Ural region. The most substantial increase (up to 2 days) occurred in the Kurgan region (Fig. 11). Strong droughts in southern part of the Ural region have been observed regularly, every 10-15 years (e.g. in summer of 1975, 1989, 1998 and 2010). However, a substantial increase in their frequency is not observed.

### Comparison of the changes in average and extreme climatic characteristics

We compared the maps of the changes of temperature and precipitation extremes (1p and 99p threshold values) with the previously created maps of the changes in average annual and monthly temperature and precipitation for the same 30-year periods (Abdullin and Shikhov 2019). The Pearson correlation coefficients between the raster of changes (difference) in average and extreme values were calculated to estimate the similarity of their spatial distribution (Table 2).

It can be noted, that two of three correlation coefficients are statistically significant at a 0.05 P-value. . Indeed, both the average January temperature and 1p minimum winter

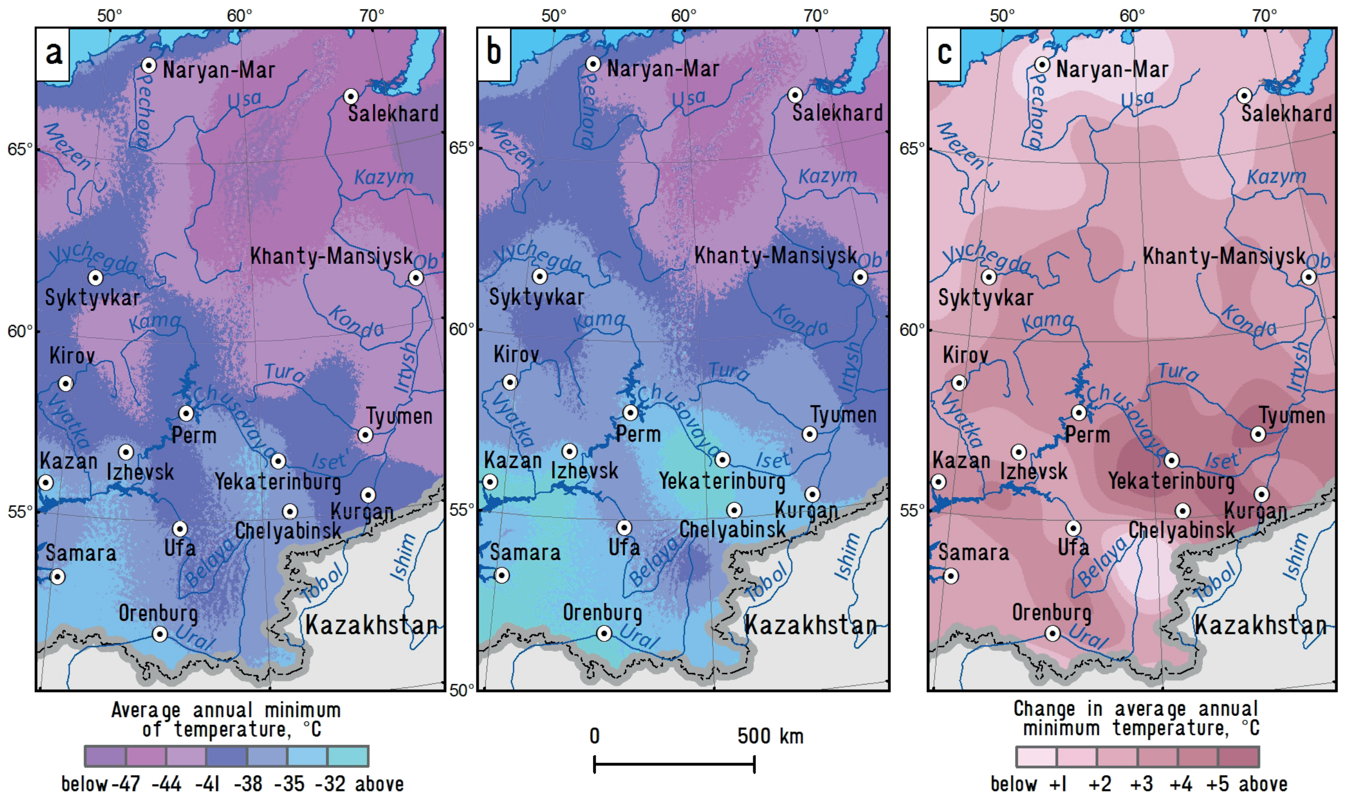


**Fig. 5. Average annual minimum of temperature for 1951–1980 (a), 1981–2010 (b) and the difference between them (c)**

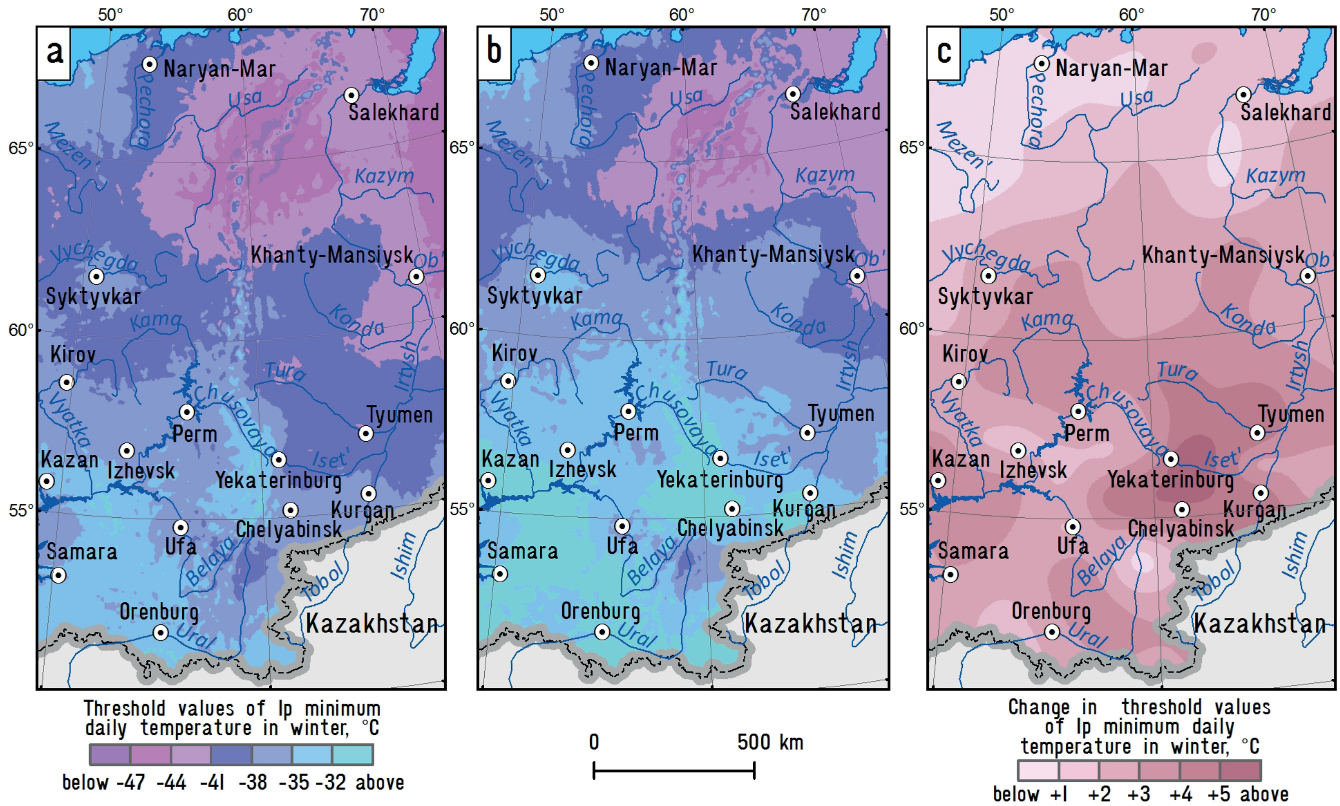


**Fig. 6. Threshold values of 1p minimum daily temperature in winter for 1951–1980 (a), 1981–2010 (b) and the difference between them (c)**

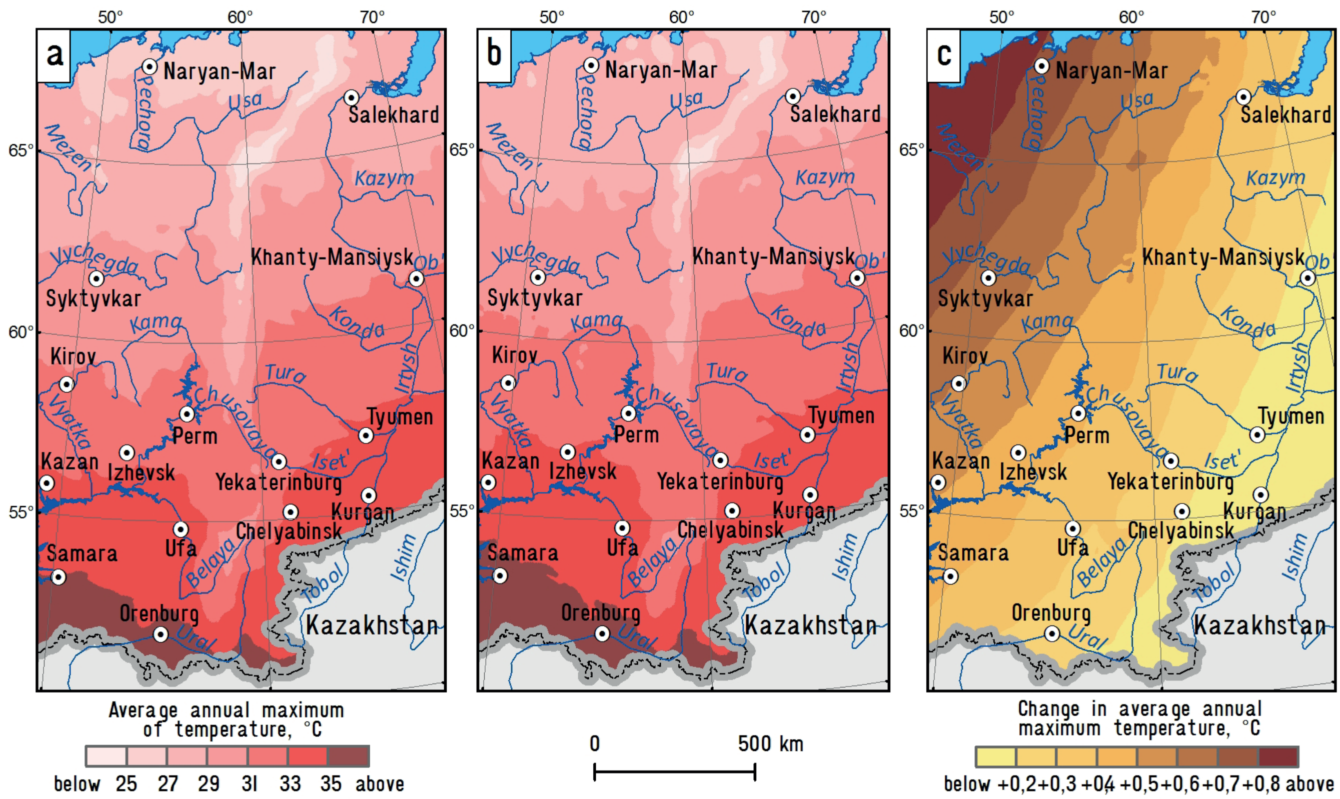


**Fig. 7. Average annual maximum of temperature for 1951–1980 (a), 1981–2010 (b) and the difference between them (c)**

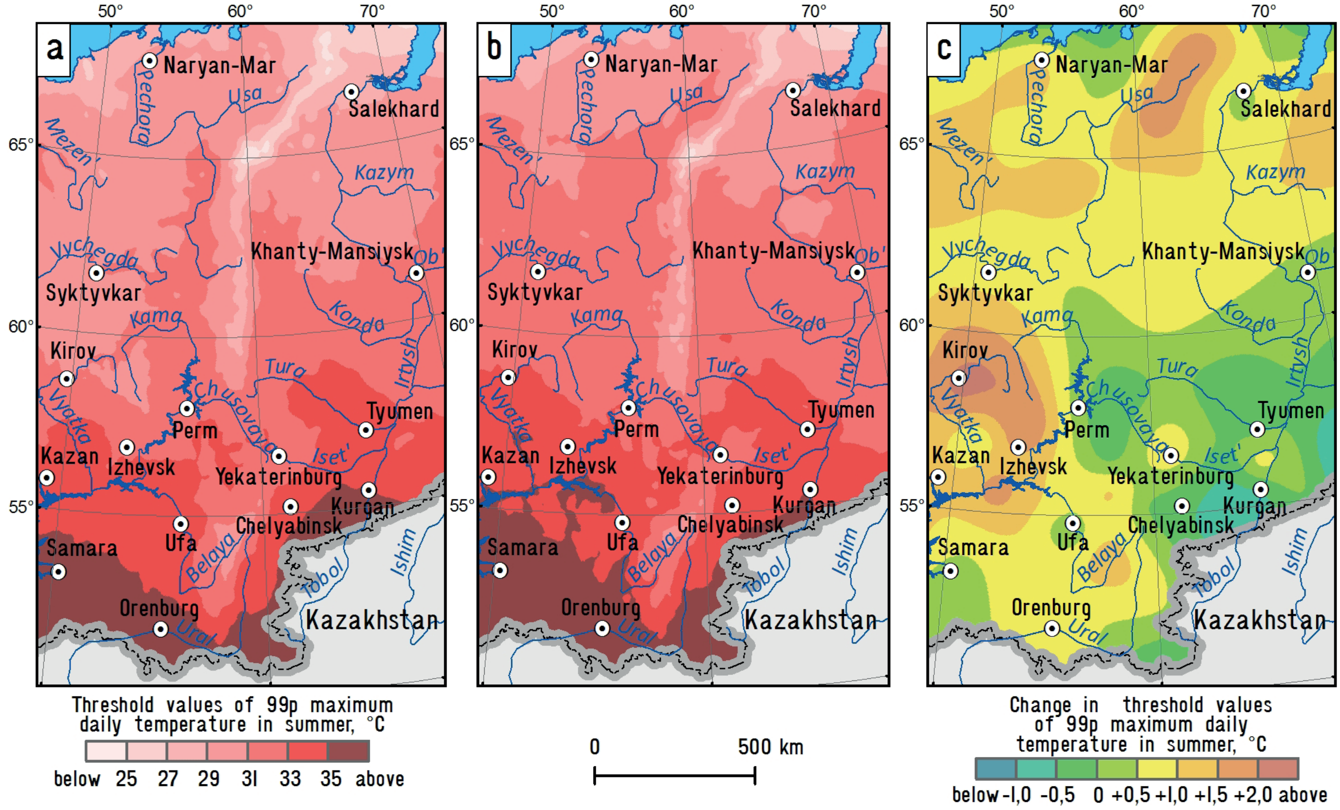


**Fig. 8. Threshold values of 99p maximum daily temperature in summer for 1951–1980 (a), 1981–2010 (b) and the difference between them (c)**

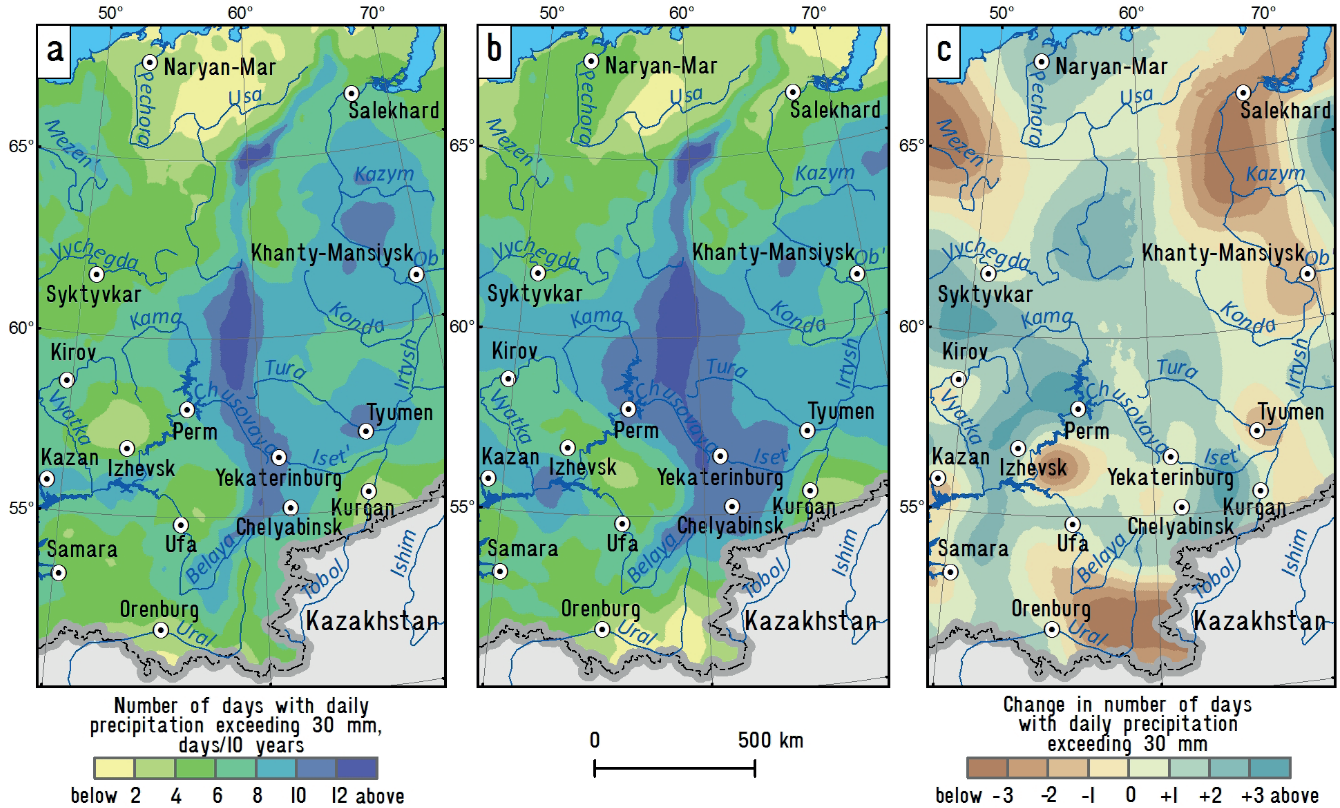


**Fig. 9. Threshold values of 99p daily precipitation for 1966–1995 (a), 1986–2015 (b) and the difference between them (c)**

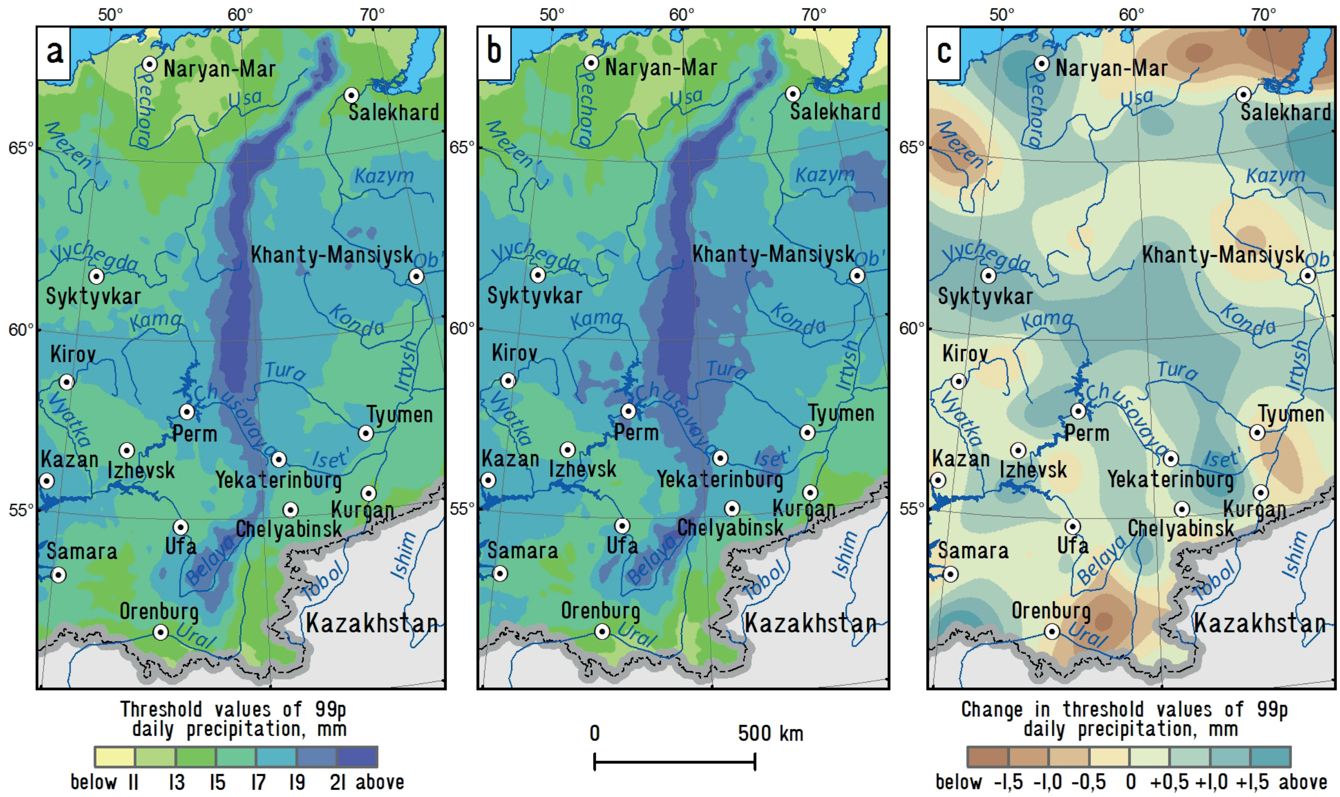


**Fig. 10. Number of days with daily precipitation exceeding 30 mm averaged over 1966–1985 (a), 1986–2015 (b) and the difference between them (c)**

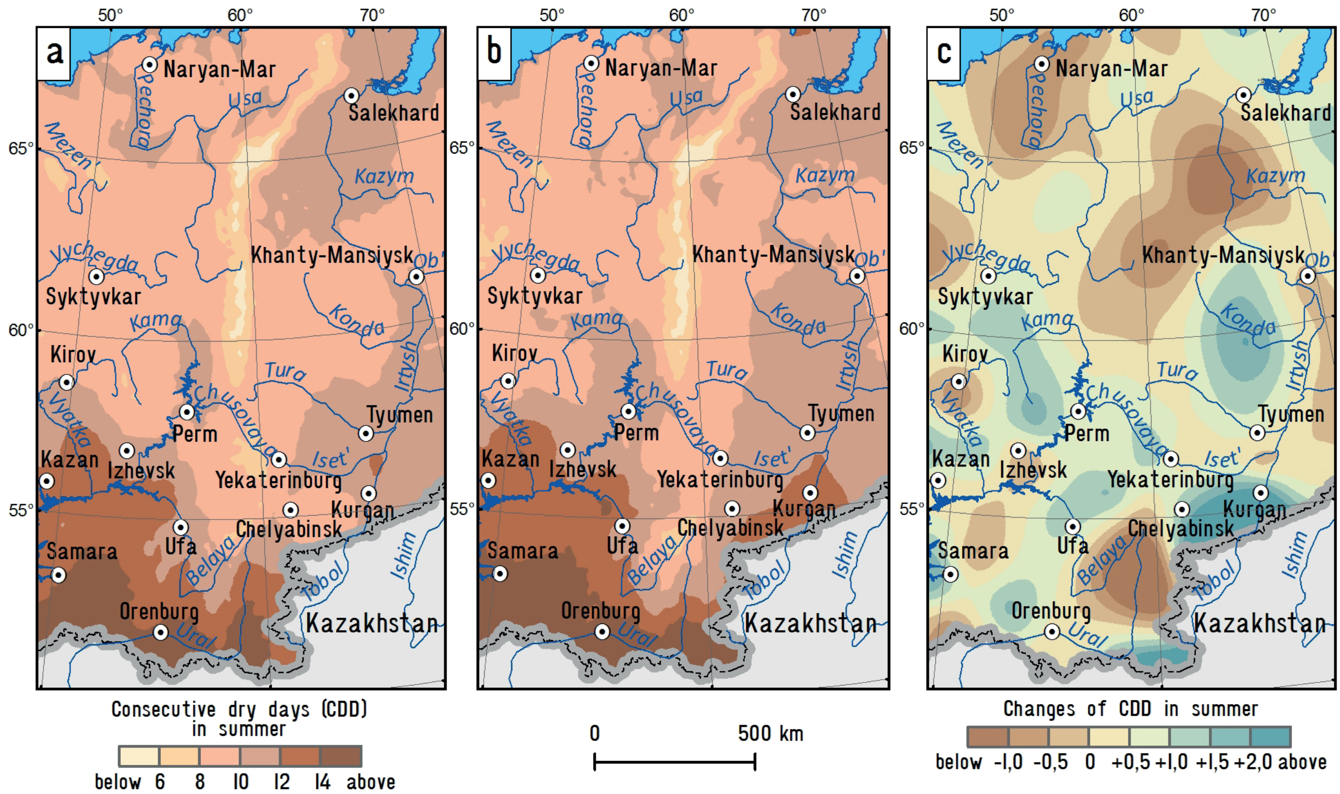


**Fig. 11. Number of CDD in summer months averaged over 1966–1985 (a), 1986–2015 (b) and the difference between them (c)**

**Table 2. Pearson correlation coefficient between the changes in average and extreme temperature and precipitation (statistically significant coefficients at 0.05 P-value are highlighted)**

| Average parameter (difference) | Extreme parameter (difference) | Pearson correlation coefficient |
|---|---|---|
| Average January temperature (1951–1980 and 1981–2010) | 1p minimum daily temperature in winter (1951–1980 and 1981–2010) | 0.58 |
| Average July temperature (1951–1980 and 1981–2010) | 99p maximum daily temperature in summer (1951–1980 and 1981–2010) | 0.11 |
| Average annual precipitation (1966–1995 and 1986–2015) | 99p daily precipitation (1966–1995 and 1986–2015) | 0.69 |

temperature increased in the south of the Ural more than in the north, when comparing 1951–1980 and 1981–2010. As for the changes of average and extreme precipitation, their spatial distribution is similar since the most substantial increase was observed in mid-latitudes (between 55° and 60° N). Moreover, the area with a strongest increase of the average annual precipitation (up to 45 mm/30 years) overlaps with the same of 99p daily precipitation.

The changes in average July temperature and 99p maximum daily temperature are correlated very weakly, since the areas with strongest changes of such variables do not overlap. The maximum increase of average temperature in July between 1951–2010 and 1981–2010 was observed in the Northern Ural and Yamal Peninsula, while the 99p maximum daily temperature increased more substantially in Kirov region (which is probably due to the extreme heat wave of summer 2010).

## CONCLUSION

The created maps not only show the spatial distribution of temperature and precipitation extremes in the Ural region, but also allow identify some regional features of its changes under observed climate warming. In general, the reported changes in extremes correspond to the trends observed on most of the territory of Russia in recent decades. There is a substantial decrease of the number of extremely cold days in winter. The 1p minimum temperature in winter also has a strong positive trend (up to 1-5°C/30 years). The 1p maximum temperature in summer has a positive trend in most of the territory, but the increase rate does not exceed 2°C between 1951–1980 and 1981–2010. The precipitation extremes also increased as for the entire year and in winter season. However, the maximum increase rate for 99p daily precipitation between 1966-1995 and 1985–2015 does not exceed 2.1 mm.

The observed changes of extreme temperatures and precipitation have substantial spatial variability, which is due both the changes of atmospheric circulation and the influence of topography. So, the 1p minimum winter temperature increased to 4-5°C in the southeast of the Ural and only to 1°C to the west of the Polar Ural. The 99p maximum temperature in summer most strongly increased in the Kirov region and Udmurt republic, which is due to the rise of the frequency of blocking anticyclones in summer. However, the same process lead to decrease of the maximum summer temperatures in the southeast of the Ural region. The 99p daily precipitation increased mainly in mid-latitude zone and reduced near the Arctic coast.

The maps of climatic extremes may be also useful to estimate the observed changes in the frequency and intensity of hazardous weather events. On the one hand, the number of extremely cold days is strongly reduced over entire Ural region, that is certainly favorable for people and economy. On the other hand, there is an increase in the frequency of summer heat waves as well as extreme precipitation events. This tendency is confirmed by the strong summer heat waves of 2010, 2012 and 2016, and also by several extreme precipitation events (exceeding 100 mm/day), which occurred in summer of 2013 and 2015 and caused substantial economic losses.

## REFERENCES


Abdullin R.K. and Shikhov A.N. (2017). GIS based modelling of spatial and temporal distribution of severe weather events. Geodesy and Cartography = Geodezija i kartografija, 78(2), 26-32 (in Russian with English summary), DOI: 10.22389/0016-7126-2017-920-2-26-32.

Abdullin R.K. and Shikhov A.N. (2019). Mapping of current climate changes in the Ural. Geodesy and Cartography = Geodezija i kartografija, 80(1), 3-12 (in Russian with English summary), DOI: 10.22389/0016-7126-2019-943-1-3-12.

Alexander L., Zhang X., Peterson T., Caesar J., Gleason B., Klein Tank A., Haylock M., Collins D., Trewin B., Rahimzadeh F., Tagipour A., Rupa Kumar K., Revadekar J., Griffiths G., Vincent L., Stephenson D., Burn J., Aguilar E., Brunet M., Taylor M., New M., Zhai P., Rusticucci M. and Vazquez-Aguirre J. (2006). Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research, 111, D05109, DOI: 10.1029/2005JD006290.

Bardin M.Yu. and Platova T.V. (2013). Changes in thresholds of extreme temperatures and precipitation on territory of Russia with global warming. Problemy ekologicheskogo monitoringa i modelirovaniya ekosistem, 2013, 25, 71-93 (in Russian with English summary).

Beguería S. and Vicente-Serrano S.M. (2005). Mapping the hazard of extreme rainfall by peaks over threshold extreme value analysis and spatial regression techniques. Journal of Applied Meteorology and Climatology, 45(1), 108-124, DOI: 10.1175/JAM2324.1.

Beguería S., Vicente-Serrano S.M., López-Moreno J.I. and García-Ruiz J.M. (2009). Annual and seasonal mapping of peak intensity, magnitude and duration of extreme precipitation events across a climatic gradient, northeast Spain. International Journal of Climatology, 29(12), 1759-1779, DOI: 10.1002/joc.1808.

Blennow K. and Persson P. (1998). Modelling local-scale frost variations using mobile temperature measurements with a GIS. Agricultural and Forest Meteorology, 89, 59-71, DOI: 10.1016/S0168-1923(97)00057-9.

Brown D.P. and Comrie A.C. (2002). Spatial modeling of winter temperature and precipitation in Arizona and New Mexico, USA. Climate Research, 22, 115-128, DOI: 10.3354/cr022115.

Bulygina O., Razuvaev V., Korshunova N. and Groisman P. (2007). Climate variations and changes in extreme climate events in Russia. Environmental Research Letters, 2(4), 045020, DOI: 10.1088/1748-9326/2/4/045020.

Cherenkova E.A. (2017). Dangerous atmospheric drought in European Russia under recent summer warming. Fundamental and Applied Climatology, 2, 130-143 (in Russian with English summary), DOI: 10.21513/2410-8758-2017-2-130-143.

Chernokulsky A.V., Kozlov F.A., Semenov V.A., Zolina O.G. and Bulygina O.N. (2018). Climatology of precipitation of different genesis in Northern Eurasia. Russian Meteorology and Hydrology, 43(7), 425-435, DOI: 10.3103/S1068373918070014.

Danielson J.J. and Gesch D.B. (2011). Global multi-resolution terrain elevation data 2010 (GMTED2010): U.S. Geological Survey Open-File Report 2011–1073, 26 p.

Donat M.G., Alexander L.V., Yang H., Durre I., Vose R., Dunn R.J.H., Willett K.M., Aguilar E., Brunet M., Caesar J., Hewitson B., Jack C., Klein Tank A.M.G., Kruger A.C., Marengo J., Peterson T.C., Renom M., Oria Rojas C., Rusticucci M., Salinger J., Elrayah A.S., Sekele S.S., Srivastava A.K., Trewin B., Villarroel C., Vincent L.A., Zhai P., Zhang X. and Kitching S. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research Atmospheres, 118(5), 2098-2118, DOI: 10.1002/jgrd.50150.

Donat M.G., Alexander L.V., Yang H., Durre I., Vose R. and Caesar J. (2013). Global land-based datasets for monitoring climatic extremes. Bulletin of American Meteorological Society, 94(7), 997-1006, DOI: 10.1175/BAMS-D-12-00109.1.

Fick S.E. and Hijmans R.J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37, 4302-4315, DOI: 10.1002/joc.5086.

Frich P., Alexander L., Della-Marta P., Gleason B., Haylock M., Klein Tank A. and Peterson T. (2002). Observed coherent changes in climatic extremes during the second half of the 20th century. Climate Research, 19, 193-212, DOI: 10.3354/cr019193.

Goodale C.L., Aber J.D. and Ollinger S.V. (1998). Mapping monthly precipitation, temperature and solar radiation from Ireland with polynomial regression and a digital elevation model. Climate Research, 10, 35-49, DOI: 10.3354/cr010035.

Goovaerts P (2000). Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. Journal of Hydrology, 228, 113-129, DOI: 10.1016/S0022-1694(00)00144-X.

Groisman P., Knight R., Easterling D., Karl T., Hegerl G. and Razuvaev V. (2005). Trends in intense precipitation in the climate record. Journal of Climate, 18, 1326-1350, DOI: 10.1175/JCLI3339.1.

Groisman P.Y. and Soja A.J. (2009). Ongoing climatic change in Northern Eurasia: justification for expedient research. Environmental Research Letters, 4, 045002, DOI: 10.1088/1748-9326/4/4/045002.

Kiktev D.B., Caesar J. and Alexander L. (2009). Temperature and precipitation extremes in the second half of the twentieth century from numerical modeling results and observational data. Izvestiya RAN. Fizika atmosfery i okeana, 45(3), 305-315 (in Russian with English summary), DOI: 10.1134/S0001433809030025.

Kim K.-Y., Kim J.-Y., Kim J., Yeo S., Na H., Hamlington B.D. and Leben R.R. (2019). Vertical Feedback Mechanism of Winter Arctic Amplification and Sea Ice Loss. Scientific Reports, 9(1), Art. no. 1184, DOI: 10.1038/s41598-018-38109-x.

Li L. and Zha Y. (2018). Mapping relative humidity, average and extreme temperature in hot summer over China. Science of the Total Environment, 615, 875-881, DOI: 10.1016/j.scitotenv.2017.10.022.

Mokhov I.I., Semenov V.A. (2016). Weather and Climate Anomalies in Russian Regions Related to Global Climate Change. Russian Meteorology and Hydrology, 41(2), 84-92, DOI: 10.3103/S1068373916020023.

Ninyerola M., Pons X. and Roure J.M. (2000). A methodological approach of climatological modelling of air temperature and precipitation through GIS techniques. International Journal of Climatology, 20, 1823-1841, DOI: 10.1002/1097-0088(20001130)20:14<1823.

Perevedentsev Yu.P., Sokolov V.V. and Naumov E.P. (2013). Climate and environment of the Privoljsky Federal District. Kazan, Kazan Federal University (in Russian).

Pyankov S.V., Shikhov A.N. and Abdullin R.K. (2017). Modern methods and technologies in thematic atlas mapping (on the example of the AIS «Hazardous hydro-meteorological events of the Ural Prikamye region»). Challenges in Geography = Voprosy Geografii, 144, 208-226 (in Russian with English summary).

Screen J.A. (2014). Arctic amplification decreases temperature variance in northern mid- to high-latitudes. Nature Climate Change, 4, 577-582, DOI: 10.1038/nclimate2268.

Shikhov A.N., Perminova E.S. and Perminov S.I. (2019). Satellite-based analysis of the spatial patterns of fire and storm-related forest disturbances in the Ural region, Russia, Natural Hazards, 97(1), 283-308, DOI: 10.1007/s11069-019-03642-z.

Shutov V.A. (1998). Investigations, analyses and modeling of different scaled spatial variability of snow storage. Izvestiya, Seriya Geograficheskaya, 1, 122-132 (in Russian with English summary).

Titkova T.B., Cherenkova E.A. and Semenov V.A. (2018). Regional features of changes in winter extreme temperatures and precipitation in Russia in 1970–2015. Led i Sneg, 58(4), 486-497 (In Russian with English summary), DOI: 10.15356/2076-6734-2018-4-486-497.

Vicente-Serrano S.M., Saz-Sánchez M.A. and Cuadrat J.M. (2003). Comparative analysis of interpolation methods in the middle Ebro Valley (Spain): Application to annual precipitation and temperature. Climate Research, 24(2), 161-180, DOI: 10.3354/cr024161.

Weisse A.K. and Bois P. (2002). A comparison of methods for mapping statistical characteristics of heavy rainfall in the French Alps: the use of daily information. Hydrological Sciences Journal, 47(5), 739-752, DOI: 10.1080/02626660209492977.

Zolina O. and Bulygina O. (2016). Current climatic variability of extreme precipitation in Russia. Fundamental and Applied Climatology, 1, 84-103 (in Russian with English summary), DOI:10.21513/2410-8758-2016-1-84-103.

Zolotokrylin A.N. and Cherenkova E.A. (2017). Seasonal changes in precipitation extremes in Russia for the last several decades and their impact on vital activities of the human population. Geography, Environment, Sustainability, 10(4), 69-82, DOI: 10.24057/2071-9388-2017-10-4-69-82.