Atmospheric droughts in Southern Siberia in the late 20th and early 21st centuries

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Abstract. The modern warming that began in the 70s of the 20th century is characterized by an increase in the frequency of extreme natural phenomena. Some characteristics of droughts (repeatability, intensity, etc.) for individual years are calculated on the basis of a drought index for Southern Siberia from 1979 to 2017. Specialized computational algorithms are developed to calculate these characteristics. All these algorithms are integrated into a previously created web-GIS called “CLIMATE”. It has been found that in recent years the duration of dry periods during the growing season increased. At the same time, the trends of the drought index in the summer months are different and, on average, there has been no significant change in the hydrothermal conditions over the past 40 years. However, in recent years there is an increase in the frequency of extreme events, both drought and excessive moistening ones.

1. Introduction

The increase in the global air temperature which started in the 1970s and the recent fires and floods make the scientific community more careful and detailed about the causes of extreme hydrothermal phenomena [1-3]. Drought is a complex natural phenomenon with the strongest regional anomalies of temperature and humidity (precipitation, soil moisture) [4]. In general, a drought means a temporary decrease in the humidity of the environment in relation to its average state. A large number of scientific papers are devoted to assessing the frequency, intensity, and area of droughts [5-8]. We study atmospheric, soil, and atmospheric-soil droughts. A drought occurs if the amount of precipitation decreases over a certain period in relation to the average value. It refers to a period when the balance between the precipitation and evapotranspiration in a territory becomes less than the water available for life than the quantity marked as the norm. The significance of a drought can be judged by its consequences, which are often complicated by the expanding human activity, which requires local and regional water and other natural resources to be increased locally. The history of droughts shows that the population and economy in all regions of the world remain vulnerable to them. The agriculture is essentially affected. Unfavorable agroclimatic conditions significantly reduce the agricultural potential of the climate. At atmospheric drought there is a process of active heating and relative air desiccation in the absence of precipitation and a large radiation influx of heat. According to [9], an atmospheric-soil drought often occurs due to a prolonged atmospheric drought and is intensified by a soil drought. There were years when a soil drought was intensified by an atmospheric drought, and an atmospheric-soil drought is characterized by a combination of soil and atmospheric droughts. Global warming is accompanied by a change in the general circulation of the atmosphere, which leads to a
redistribution of heat and moisture and to the manifestation of regional features of climatic changes [10].

Extensive droughts are associated with large-scale stationary anticyclones. In the early 1980s, the concept of atmospheric blocking formations (blockings) was developed, explaining the correlation of blocking and droughts in the middle latitudes, in particular, in the Russia’s grain belt [11]. The concept stressed that an adequate study of the genesis of droughts is impossible without an understanding of the conditions for the formation and evolution of atmospheric blockings. A statistical study of the connection between blocking formations and the main modes of large-scale circulation (teleconnection indices) shows that the contribution of these phenomena to the variability of aridity in many regions of the globe is very significant [12]. The influence of the North Atlantic oscillation on the occurrence of large anomalies in Europe is mostly observed in winter [13]. Papers [14, 15] established the influence of the elementary circulation mechanisms of the Northern Hemisphere, according to the typifications of Dzerdzeevsky and Wangenheim-Girs, on the formation of droughts of varying intensity in the 20th century and the beginning of the 21st century.

A clear periodicity of droughts or a certain unidirectional trend in the frequency and intensity of droughts in Russia in the 20th century were not revealed. The tendency to increase the frequency of droughts has only manifested itself in some regions [2].

2. Objects, data, and methods
Various hydrothermal coefficients are used to quantify the droughts, which in most cases are a combination of air temperature and precipitation characteristics. This work is a continuation of the series of works [16-18] on studying the humidification conditions in the territory of Southern Siberia (50-65 N, 60-120 E) during the period of the most intense global warming. To assess the hydrothermal conditions in different landscape conditions, the drought index suggested by D A Ped’ (Si) is used [19]. The index is the normalized indicator of the relationship between the air temperature and the sum of atmospheric precipitation:

$$S_i = \frac{\Delta T_i}{\sigma_T} - \frac{\Delta P_i}{\sigma_P}$$  \hspace{1cm} (1)

where $i$ is the number of a certain period, $\Delta T_i = T_i - T_{\text{norm}}$ is the temperature anomaly in the $i$-th period, $T_{\text{norm}}$ is the long-term average air temperature, and $\sigma_T$ is the standard deviation of the temperature. For precipitation ($P$) the notations are similar.

The air temperature and precipitation totals from the ERA Interim reanalysis of the European Center for Medium-Range Weather Forecasts (ECMWF) [20] at grid nodes with a step of 0.75 × 0.75° and data of weather stations [21] for 1979-2017 (Figure 1) were used in the analysis.

For a detailed analysis of droughts in Siberia, the following characteristics were calculated based on the Si drought index:

- maximum index values,
- minimum index values,
- variability range of the index (the difference between the maximum and minimum values),
- the frequency of droughts of different intensity for the study period,
- the duration and beginning of the dry period (when $S_i > 1$).

New computational algorithms have been developed that allow calculating maximum and minimum values of the index, as well as its variability, for each month of the growing season (May-September) for each year of the period under study. Additional software algorithms were also developed to calculate the frequency of occurrence of droughts of different intensity, duration and beginning of the dry period. The repeatability of droughts is calculated based on the classification presented in Table 1.
As a result of the algorithm application, the percentage of dry years from the total study period (39 years) for each month from May to September was calculated. The algorithm for calculating the duration of a drought determines it as the number of consecutive months in the vegetation period when $S_i > 1$, this algorithm also allows one to calculate the beginning of the dry period. As a result of using the algorithm, we get the month number when the drought started and its duration for each year of the study period.

**Table 1.** Classification of droughts based on the Ped’ drought index.

| Intensity of drought | Ped’ drought index ($S_i$) |
|----------------------|-----------------------------|
| Weak                 | $1 \leq S_i < 2$            |
| Medium               | $2 \leq S_i < 3$            |
| Severe               | $3 \leq S_i < 4$            |
| Extreme              | $S_i \geq 4$                |

All developed computational algorithms were integrated into the previously created web-GIS "CLIMATE" [22, 23] as additional modules to the main computational module for calculating the Ped’ drought index created earlier for the system [18]. The "CLIMATE" system, built on the basis of web and GIS technologies, is a part of the hardware and software complex for "cloud" analysis of climate data, including various sets of climate and meteorological data, as well as special interactive tools for their search, sampling, processing, and visualization. Using this system greatly facilitates and accelerates work with large volumes of geospatial climatic data, allowing a user who is not an expert
in information technologies to remotely perform their statistical analysis using any modern desktop PC connected to the Internet.

As the main results of the modules and the system, archives of the calculated characteristics were obtained, as well as a set of cartographic layers on the basis of which further analysis of the hydrothermal conditions in the territory of Siberia was carried out. Previously, the precipitation reanalysis data were corrected using the observation data according to the previously proposed approach [17].

3. Results and discussion

During the year, the latitudinal distribution of the mean monthly air temperature is observed in the study area. In Eastern Siberia, the orographic factor contributes a certain violation to this pattern. Trends of the monthly temperature for 1979-2017 were analyzed. The spatial distribution of the trends varies during the growing season. In May, the temperature in most of Siberia increases at a rate of 0.3-0.7°C / 10 years. In June and July, a decrease in the air temperature is observed in Western Siberia and an increase in the air temperature in Eastern Siberia. The maximum contrast in the distribution of trends is observed in July in the southern part of the territory. The trend coefficients vary from -0.65°C / 10 years in the south-west to 1.2 in the south-east of Siberia. At the same time, in the north of the territory, the air temperature trends are minimal in modulus. In August and September, the air temperature trends with values of 0.4-0.8°C / 10 years were observed in the west and south-east of Siberia, and for the rest of the territory there are not statistically significant trends. During all summer months, the same regularities are observed in the distribution of long-term average amounts of precipitation over the study area. The maximum in the monthly precipitation (up to 125 mm) is recorded in the mountains (Altai, Western and Eastern Sayan, Khamar-Daban, Stanovoye Highlands), and a minimum (less than 10 mm) is observed in the south-west of the territory. At the same time, the greatest humidification is observed in the whole territory in July, and the smallest one in May. The trends in the amount of atmospheric precipitation during the warm period are multidirectional. In most cases the trends are negative. Changes in the hydrothermal conditions within the territory, according to the results of the analysis of the $S_i$ index, are characterized as follows. In May, aridity increases in most of the territory, only in the mountainous regions of the Transbaikalie there is a slight decrease in $S_i$. In June, humidification grows in the central regions of Western Siberia, while the south of Eastern Siberia becomes more arid. In July the contrasts increase: the $S_i$ trends in the territory vary from -1.0 to +1.4 units / 10 years. In August and September there is a latitudinal distribution of trends: from positive ones in the south to negative ones in the north of Siberia [18].

According to the results of the analysis, the maximum values of the $S_i$ index (up to 4.6) and, therefore, the most intense droughts are observed in August. They are localized in the north-east of the territory and in the south of the West Siberian Plain. The north-west part of the territory is characterized by droughts with $S_i <3$ in all months. The minimum values of $S_i$ reach -5 and correspond to the state of waterlogging of the territory. In most cases they are -4 ... -3. The interannual variability of $S_i$, on average, does not exceed 6-7 units.

The repeatability of droughts of weak intensity in certain months during the study period reaches 38%, of moderate ones 23%, of strong ones 7%, and of extreme ones 2% (Figure 2). More than half of the cases of observed extreme events occur after 2000. For instance, Figure 3 shows the number of extreme and severe droughts in May for different periods.

Extreme droughts ($S_i \geq 4$) were observed only in August in a small area (in the north-east of the Central Siberian plateau and in Altai region). The repeatability of severe droughts ($3 \leq S_i <4$) is less than 5-7% and it has a local character. Severe droughts are observed in May in the territory adjacent to the Bratsk and Ust-Ilimsk reservoirs and the Stanovoy Range; in June in the Sayan Mountains, in July in the south of the West Siberian Plain; in August at the Sayan foothills and northern areas of the Central Siberian plateau. In September for the large part of the territory the frequency of severe droughts does not exceed 1-2%. Moderate droughts ($2 \leq S_i <3$) are observed in all months of the vegetation period, and their frequency in most of the territory is less than 10%, and they have lowest
values (4%) in May. The repeatability of weak droughts ($1 \leq S_i < 2$) is maximum in September in Western Siberia (20-35%). In Eastern Siberia weak droughts were observed twice less often. From May to August, the frequency of weak droughts does not exceed 10-20% throughout the study area.

| Month | Extreme | Severe | Medium | Weak |
|-------|---------|--------|--------|------|
| May   | ![Map]  | ![Map] | ![Map] | ![Map] |
| Jun   | ![Map]  | ![Map] | ![Map] | ![Map] |
| Jul   | ![Map]  | ![Map] | ![Map] | ![Map] |
| Aug   | ![Map]  | ![Map] | ![Map] | ![Map] |
| Sep   | ![Map]  | ![Map] | ![Map] | ![Map] |

**Figure 2.** Frequency of droughts, %.

**Figure 3.** Number of droughts in May.
In some years, continuous duration of a drought (for $S_i > 1$) in a significant part of the territory can reach 3-5 months. In Eastern Siberia, this situation was observed in 1986, 2001, 2002-2007; and in Western Siberia in 1988, 1998, and 2012 (Figure 4). After 2000, the frequency of droughts lasting more than 2 months increased throughout the region. In years when the duration of a drought does not exceed 2-3 months, the period with insufficient moisture in most cases begins in May-June.

**Figure 4.** Duration of drought periods ($S_i > 1$) in 2001, 2002, and 2012 in Southern Siberia.
4. Conclusions
The new computational algorithms developed for the web-GIS “CLIMATE” allowed us to calculate extreme characteristics of the drought index, estimate the frequency of droughts of different intensities, and the duration and beginning of the dry period. Archives of the calculated characteristics were obtained, as well as a set of cartographic layers to carry out further analysis of the hydrothermal conditions in the territory of Siberia. The precipitation reanalysis data had been corrected according to the observation data using the above-proposed approach.

The analysis of cartographic material showed that in a large part of Southern Siberia in 1979-2017, from May to September, there is a statistically significant increase in the air temperature and a small change in the precipitation. The trends of the $S_i$ drought index in the summer months are multidirectional and, on average, there has been no significant change in the hydrothermal conditions over the past 40 years. However, in recent years the duration of droughts has increased during the growing season, there has been an increase in the frequency of extreme events, both drought and excessive moistening ones. Most intensive droughts have been observed in August in the north-eastern part of the territory and in the West-Siberian Plain. More than half of the extreme and severe droughts have been observed after 2000. The duration of drought periods in the growing season is 2-3 months on average, but in some years the duration can be 4-5 months.

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