Comparative analysis of hydrothermal conditions of Tomsk region by using different drought coefficients

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Abstract. The global and regional climatic changes that have been most intense in recent decades are characterized by an increase in the frequency of extreme natural events which include droughts and periods of extensive moistening. Air temperature and precipitation are the main characteristics of climate indicating the changes in the droughts/extensive moistening. According to observations of weather stations of Tomsk region, air temperature has been changing very much since the 70s of the 20th century (during 1967-1997 from -0.6 to + 0.56°C and during 1970-2009 from 0.4 to 0.6°C/10 years). Since the mid-1980s, an increase in precipitation has been observed. For a detailed analysis of drought indices (HTC, S, SPI, and SPEI) in the present paper, we use observation data from the Tomsk region weather stations from May to September, 1966-2017. When calculating the indices, warming of the atmosphere, expressed through air temperature, as well as atmospheric humidification, characterized by precipitation, must be taken into account. Also, for a correct comparison of the hydrothermal conditions of different landscapes it is necessary to use normalized indicators. A comparative analysis of the different hydrothermal indices has shown that the S and SPEI indices most closely correspond to these requirements. They also most synchronously indicate droughts.

1. Introduction

Global and regional climatic changes that have been intensively occurring in the recent decades [1-5] are characterized by an increase in the frequency of extremes, which include droughts and periods of extensive moistening. Air temperature and precipitation are the main characteristics of climate indicating changes in the droughts/extensive moistening. A large number of different complex indicators based on these characteristics have been developed to determine droughts. Some indicators require only precipitation for calculation, and other complex indicators require soil moisture in addition to air temperature and precipitation. Some indicators (SPI, SPEI, Palmer index, etc.) allow taking into account changes in meteorological characteristics not only during the summer months, but also during the previous cold period that affect the hydrothermal condition of the soil and atmosphere at the beginning of the growing season.

In Russia, the following indicators are most often used to determine droughts: the Selyaninov hydrothermal coefficient (HTC) [6] and the Ped drought index (S) [7]. In 2009 WMO [8], along with regional indicators, proposed a standardized precipitation index (SPI) [9] for worldwide use. Currently there are various modifications of this index. One of the most frequently used is the standardized precipitation and evapotranspiration index (SPEI) [10].
The main goal of this work is a comparative analysis of various indicators of droughts and the determination of the indicator or the groups of indicators that best describe the hydrothermal conditions in Siberia.

Many researchers use different GIS applications to perform calculations and visualize results. The main tool of our work is the previously developed web-GIS “CLIMATE” [11-13] aimed at climate-ecological studies in a selected region and realizing the necessary integration of the results of retrospective and predictive modeling and observations (http://climate.scert.ru/). The ”CLIMATE” system, based on 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.

2. Objects, data, and methods
In previous papers [14, 15], a comparative analysis of the most well-known Russian and international indicators of aridity, such as the Selyaninov hydrothermal coefficient (HTC), the Ped drought index (S), the standardized precipitation index (SPI), and the standardized precipitation and evapotranspiration index (SPEI), was carried out for the territory of Western Siberia. The study used the Era Interim reanalysis [16] data from 1979 to 2017. Since the obtained results did not give an understanding of which of the indicators is better, it was decided to narrow the study area and perform a more detailed analysis. Tomsk region was chosen as the study area, and we used air temperature and precipitation data from meteorological stations of Roshydromet (“RIHMI-WDC”) [17]. There are 10 stations on the territory of Tomsk region (Aleksandrovskoye, Sredniy Vasyugan, Napas, Vanzhil-Kyнак, Pudino, Kolpashevo, Ust'-Ozernoe, Bakchar, Pervomayskoye, and Tomsk). It was also decided to take 3 (Severnoye, Bolotnaya, and Taiga) stations located close to the region (Figure 1).

Figure 1. Study area – Tomsk region.
The study period was chosen from 1966 to 2017, according to the direction of Roshydromet [17]. The homogeneity of the time series of precipitation was disturbed at least three times since 1966. In the first one, in the 30s of the last century, there was a massive transfer of stations to an open space, representative of several elements, but not of precipitation. In the second one, at the beginning of the 50s, a massive change in the measuring device was made. A precipitation gauge with a Tretyakov shield was installed. In the third one, since January 1966, a correction to wetting began to be applied directly at the station. After 1966 there were no changes in the measurement and processing and, therefore, the precipitation series can be considered homogeneous.

Calculation of hydrothermal indices, as in previous works [4, 16, 18], was performed using the web-GIS “CLIMATE”.

It is more correct to use normalized indicators when comparing the hydrothermal conditions in different landscapes and, therefore, the normalized anomaly of HTC (HTC$_{norm}$) (and not the HTC) was used in the work. When determining a drought, its intensity is taken into account according to the classification in Table 1.

### Table 1. Classification of droughts based on HTC$_{norm}$, S, SPI, and SPEI.

| Intensity of drought | HTC$_{norm}$   | Ped index | SPI/SPEI       |
|----------------------|----------------|-----------|----------------|
| weak                 | -1.25$< HT$C$_{norm} \leq 1$ | $1 \leq S < 2$ | -2$< SPI/SPEI \leq 1$ |
| medium               | -1.5$< HT$C$_{norm} \leq 1.25$ | $2 \leq S < 3$ | -3$< SPI/SPEI \leq 2$ |
| severe               | -1.75$< HT$C$_{norm} \leq 1.5$ | $3 \leq S < 4$ | -4$< SPI/SPEI \leq 3$ |
| extreme              | HTC$_{norm} \leq -1.75$ | $S \geq 4$ | SPI/SPEI$\leq 4$ |

3. Results and discussion

3.1. Climatic characteristics of the territory

According to the observations of meteorological stations of Tomsk region, changes in the average annual air temperatures have been observed since the 70s of the 20th century. Their growth is especially pronounced in the subtaiga zone. According to the data of the Tomsk weather station, the average annual air temperature changed from -0.6 to +0.56 °C in 1967-1997. If we assume that the trend is linear, its parameters were $+0.67$ °C/10 years [19]. In the following decade, the warming process accelerated. This is confirmed by studies of other authors [20], who noted a rise in the air temperature from 1970 to 2009 according to meteorological stations throughout the region at a rate of 0.4-0.6 °C/10 years, and individual months of the cold period (February-March) trends reach 1.5-1.7 °C/10 years. Since the warming rate is greater than in the Northern Hemisphere, this may be due to the deviation from the long-term norms of the characteristics of the regional circulation [21]. Analysis of the obtained data showed that the greatest changes occurred in the cold part of the year and, especially, in the central phase of the winter season [22]. Since the mid-1980s, an increase in the precipitation amounts has been observed. The trends in the annual precipitation have a positive direction, which reaches a maximum due to the precipitation during the cold period (October-April), especially in Aleksandrovskoe, Tomsk, and Kolpashevo [20].

The average long-term spatial characteristics of the climate (air temperature and precipitation) and the current trends of their changes were estimated using the web-GIS “CLIMATE”. Figure 2 shows the spatial distribution of the air temperature and precipitation amount for individual months according to the ERA-Interim reanalysis with a grid of 0.75 × 0.75° for 1979-2017 for the territory of Tomsk region.
In winter, there is a latitudinal distribution of the air temperature in the territory. The average long-term air temperatures in January vary from -23 °C in the north of the region to -16 °C in the south-east. In July, the temperature field is more homogeneous: the average monthly temperatures are from
17 to 19 °C. The values of air temperature trends according to reanalysis data for 1979-2017 differ significantly from the estimates obtained by other authors for 1967-1997 [19] and 1970–2009 [20]. The winter months are characterized by negative trends throughout the region (up to -1.0 °C/10 years in the south-west), and in summer, by positive ones (up to + 0.4 °C/10 years in the south-east). In the summer months in Tomsk region, the precipitation is about 2 times more than in winter. On average, over the period under consideration the precipitation reaches 60–90 mm in July and 20–40 mm in January. The long-term changes in individual months are mostly statistically insignificant (-1 ... -4 mm/10 years in January and -8 ... + 8 mm/10 years in July).

3.2. Analysis of the calculation of indices

Correlation analysis confirmed the synchronicity of changes in the considered indices of droughts. However, the identified extreme events in individual years (intensity, duration of droughts) do not always coincide. For a more detailed analysis of the indices, in this work we used the series of observations of meteorological stations of Tomsk region from May to September (the sum of precipitation and air temperature) for 1966-2017.

For the majority of meteorological stations in the region in May and September, the HTC was not calculated due to the absence of average daily air temperatures above 10 °C in the observation series (which is a necessary condition for the calculation). Consequently, the relationship between the HTC and other indices for May and September was not defined. In other cases, statistically significant correlation coefficients were obtained. The closest relations were observed at the beginning of the growing season (May, June).

Despite some differences in determining the intensity of droughts, the analysis for a long-term period made it possible to identify phenomena of severe and extreme intensity that correspond to the characteristics given in Table 1. The driest months during the study period were May (1999, 2004), June (1981, 1982, 1983, 2012), July (1998, 1999, 2012), August (2003, 2016), and September (1966, 2016). In this time most meteorological stations recorded a state of severe or extreme drought. In 2012 and 2016, the dry period lasted 2-4 months throughout Tomsk region. In most cases drought is observed in the first months of the growing season. However, in 1966, 2011, and 2016, according to the results for all calculated indices, droughts were observed in August-September at many meteorological stations, with medium humidification at the beginning of summer.

In recent years the frequency of hydroclimatic extremes has increased [2, 15]. In this connection, the hydrothermal conditions were analyzed in more detail since 2000. 100% coincidence (9 cases) in determining the state of drought was shown by a comparison of the S and SPEI indices (Figure 3). At the same time, according to the calculations of the Ped index, in most cases the drought was determined as severe, and in June 2012 and September 2016 as extreme. The SPEI values in all cases correspond to a weak drought. The SPI index behaves similarly; only a weak drought was observed in the territory (8 cases). The analysis of the HTC_norm showed coincidence with the other indices in 4 cases.
Figures 3. Changes in hydrothermal indices (circles indicate cases of drought) in Tomsk region average for all stations.

4. Conclusions
The study of atmospheric droughts is an important component of landscape monitoring. At the same time, the correct choice of indicators of droughts is important. A comparison of the most frequently used Russian and international drought indices yielded statistically significant correlation coefficients. The closest relations are observed for the beginning of the growing season (May, June). A cause of atmospheric droughts can be high air temperatures and/or lack of precipitation. The limiting role of these factors may vary during the growing season and depending on the landscape. Thus, when calculating the indices warming of the atmosphere, expressed through air temperature, as well as atmospheric humidification, characterized by the amounts of precipitation, must be taken into account. Also, for a correct comparison of the hydrothermal conditions of different landscapes it is necessary to use normalized indicators. The above comparative analysis of the different hydrothermal indices has shown that the S and SPEI indices most closely correspond to these requirements. They also most synchronously indicate droughts in individual months. The driest months during the study period were May (1999, 2004), June (1981, 1982, 1983, 2012), July (1998, 1999, 2012), August (2003, 2016), and September (1966, 2016). In these months, most of the meteorological stations recorded severe or extreme droughts.
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