A comparative assessment of the aridity indices for analysis of the hydrothermal conditions

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Abstract. Comparison between hydrothermal coefficient of Selyaninov (HTC), Ped` drought index (Si) and indices SPI, SPEI are presented. Indices were calculated for the territory of Southern Siberia (50-65 N, 60-120 E). Functionality of the web-GIS “CLIMATE” was extended by a software module based on the integrated package to calculate indices. The ECMWF ERA-Interim reanalysis data on air temperature and precipitation were used as input data for the study. Analysis were carried out for the warm season from 1979 to 2017. The highest coefficients of linear correlation were obtained by comparing SPI and SPEI (0.8-0.9), Si and HTC (0.7-0.9) from June to August. Distribution of the number of strong and extreme droughts over the study period according to SPI and SPEI indices is the same, 2-3 strong droughts was observed per period. According to the analysis of Si, the highest frequency of strong droughts (up to 4) was observed also in July and August. But it was recorded only at the Sayan Mountains region. According to the results of the anomaly of HTC analysis, June and August are most droughty (2-3 strong droughts per period). The identified intensity and duration of droughts, based on these indices do not always coincide.

1. Introduction
When studying the geographical features and dynamics of changes in the natural environment, in addition to studying the vibrations of individual climatic elements, it is of particular interest to study the integral characteristics of the territory, in particular hydrothermal conditions. The latter are described by different coefficients, which in most cases represent a combination of air temperature and precipitation. Great importance is given to the climatic features of the emergence and spatial distribution of droughts. Drought is a complex natural phenomenon with the strongest regional anomalies of temperature and humidity (precipitation, soil moisture content) [1]. In general, a drought means a temporary decrease in the humidity of the environment in relation to its average state. Due to the complex nature of the drought, it is usually limited to studying one of its sides, manifested either in the atmosphere or in the soil. A qualitative analysis of the climate humidification conditions of previous decades makes it possible to give a more accurate prediction of arid / wet periods in which specialists from different branches of science and economics are interested.

Numerous works devoted to the study of droughts consider various methods for determining it, the characteristic types and conditions for the formation of this phenomenon, the most representative aridity indices are being developed, the catastrophic droughts are analyzed and the drought cataloged [2, 3 etc.]. Meanwhile, as indicated by D A Ped’, there is no generally recognized quantitative
indicator of drought. In recent years a number of works have been devoted to comparison of aridity indices [4].

2. Objects, data and methods

The comparative analysis of the most known Russian and international quantitative indicators of aridity, such as the hydrothermal Selyaninov coefficient (HTC), the Ped’ aridity index (S.), the standardized precipitation index (SPI) and the standardized precipitation and evaporative index (SPEI) for the period 1979-2017 years was performed.

The hydrothermal coefficient of Selyaninov [5] is now widely used in the practice of Roshydromet as the main quantitative indicator of the ratio of heat and moisture. The values of the coefficient are determined by the following formula:

\[ HTC = \frac{\sum r}{\sum t > 10} \]

where \( \sum r \) is the sum of precipitation during the vegetation period at air temperature above 10°C, \( \sum t > 10 \) is the sum of air temperature over the vegetation period with a temperature above 10°C. Based on this definition, the HTC is the ratio of precipitation amounts over a certain period to sums of temperatures above 10°C, reduced by a factor of 10, over the same period. Thus, the hydrothermal coefficient as an indicator of the assessment of the territory according to humidification conditions has an advantage over precipitations that characterizes not only the incoming part of the water balance, but also the unproductive expenditure of moisture (evaporation from the soil surface, vegetation, etc.), closely related to the air temperature. Therefore, the HTC criteria for determining the drought and its intensity depend on the moisture content and are variable throughout the territory. To reduce this dependence, it is advisable to estimate the negative anomalies of the HTC with respect to its mean value, normalized to its standard deviation [6].

The Ped’ index [7] is a simple algebraic difference of the normalized air temperature and precipitation anomalies for a given time interval (often in a month):

\[ S_i = \frac{\Delta t_i}{\sigma_t} - \frac{\Delta r_i}{\sigma_r} \]

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

Ped’ index does not depend on the moisture content of the territory and therefore can be applied for a vast area, which includes several zones with different humidity regimes. Also, it clearly does not depend on the average values of temperature and precipitation, since the drought is determined in relation to them.

The standardized SPI precipitation index [8] was recommended by WMO in 2012 to all National Meteorological and Hydrological Services around the world to characterize meteorological droughts in addition to other drought indices they use in their work [9]. To calculate this index, only precipitation data are actually used, and it is desirable to have data series at least 20-30 years (optimally 50-60 years or more). SPI can be calculated for different time scales (1, 3, 6, 12, 24 and 48 months), which allows to identify different types of droughts. This indicator is comparable in any points of its calculation (the location of meteorological stations or grid nodes) and does not depend on zonal wetness. A detailed description of the algorithm for calculating this index is given in [10].

In order to take into account such an important factor as evaporation, in 2010 Vicente-Serrano S.M. et al. [11] upgraded the SPI into a standardized precipitation and evapotranspiration index (SPEI). To calculate SPEI, the difference between the sum of precipitation and potential evapotranspiration (PET) is used, which is a simple indicator of the water balance. The simplest version of the calculation of PET is possible through the equation of Tronthwaite [12], the parameters of which are the average
temperature over the period and the latitude of the point for which the calculation is performed. There is a more complicated version of PET calculation through the Penman-Monteith equation [13], which takes into account a larger number of parameters (radiation balance, wind speed and water vapor deficit at a height of 2 m). The algorithm for calculating the SPEI index is similar to the algorithm for calculating SPI, a detailed description of it can be found in [14]. This index can also be calculated for different time scales (1, 3, 6, 12, 24 and 48 months), it is also comparable at any points of its calculation (meteorological station locations or grid nodes) and does not depend on zonal wetness.

The classification of droughts for each index is shown in table 1.

| Drought intensity | Normalized anomaly of HTC | Ped’ Index | SPI/SPEI |
|------------------|---------------------------|------------|----------|
| Weak             | -1.25 < ΔHTC\text{norm} ≤ -1 | 1 ≤ Si < 2 | -2 < SPI/SPEI ≤ -1 |
| Medium           | -1.5 < ΔHTC\text{norm} ≤ -1.25 | 2 ≤ Si < 3 | -3 < SPI/SPEI ≤ -2 |
| Severe           | -1.75 < ΔHTC\text{norm} ≤ -1.5 | 3 ≤ Si < 4 | -4 < SPI/SPEI ≤ -3 |
| Extreme          | ΔHTC\text{norm} ≤ -1.75 | Si ≥ 4 | SPI/SPEI ≤ -4 |

The main tool in our work for the calculation of these indices is the previously developed web-based GIS "CLIMATE" [15]. The "CLIMATE" system, built on the basis of web and GIS technologies, is 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 the 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. To calculate the hydrothermal Selyaninov coefficient and the Ped’ index, software modules have been previously developed and integrated into the system [16, 17].

To calculate the normalized anomaly of the HTC on the basis of the old module, a new one has been developed. To calculate SPI / SPEI, it was decided to use the finished statistical package (https://cran.r-project.org/web/packages/SPEI/index.htm) [11] of the programming language R (https://www.r-project.org/). A detailed description of the procedure for integrating R language packets into the web-GIS "CLIMATE" is presented in [18]. Based on this statistical package, a software module for the SPI / SPEI calculation system has been developed.

Many researchers use the observation data obtained on the meteorological station network to calculate the hydrothermal conditions of the territory. In this paper, 6-hour temperature and precipitation data of the European ERA Interim reanalysis [19] with a grid spacing of 0.75 × 0.75 ° were used as the initial data for calculating the above-mentioned drought quantitative data. Previously, the reanalysis precipitation data was corrected according to weather station data [20], which allowed to improve their quality on the average. The procedure of comparison with weather station data and the subsequent correction of sediment reanalysis data was proposed and described earlier in [16]. Calculations were performed for each month of the warm season (May-September) for the period from 1979 to 2017 for the territory of Southern Siberia (50-65 N, 60-120 E). Using a monthly scale allows us to treat the identified droughts only as atmospheric.

To perform a comparative statistical analysis of quantitative indicators of droughts in the "CLIMATE" system, additional software modules were developed to calculate the Pearson correlation coefficient, the number of severe droughts and the percentage of coincidences in the occurrence of severe droughts. All characteristics are calculated in each node of the reanalysis grid for each month from May to September for the entire study period.
3. Results and discussion

At the first stage of the work, a comparison of the aridity index series for individual months within the growing season (May-September) was carried out. The method of Pearson's linear correlation was used. In the mountain regions and in the north of the territory in May and September, the Selyaninov HTC was not calculated due to the absence of average daily air temperatures above 10°C in the series of observations (which is a prerequisite for the calculation). Consequently, the relationship between the HTC and other indices for May and September in the mountains is not defined. Statistically significant correlation coefficients were obtained by comparing the SPI and SPEI, ΔHTC norm and Si series. The closest connections are observed during the active vegetation period (June-August). The correlation coefficient between SPI and SPEI is maximal in June-July (r = 0.9-1.0) throughout the territory. The relation is weakening in August in the territory of Western Siberia to r = 0.8 and almost disappears in September in the territory (r = 0.2-0.4), remaining statistically significant only in the mountain areas in the south of the territory (r = 0.6-0.7). In May, the correlation coefficients are negative (r = -0.6...-0.7), but statistically significant. If there is insufficient amount of precipitation in May, the change in the sign of the coefficient is affected by the inclusion in the SPEI calculation formula of potential evapotranspiration. The linear relationship between the series of the Ped’ index and the normalized anomalies of the HTC was traced throughout the warm period. The maximum connection (| r | = 0.8-0.9), as in the case of comparison of SPI and SPEI indices, is observed in June-July. In August, the average in the territory of the value | r | = 0.6-0.7 with a maximum (| r | = 0.8) in the Ob-Irtysh interfluve and the middle values of the Yenisei. In August, the correlation coefficient of ΔHTC norm and Si at the greater part of the territory is not statistically significant, except for the foothills of Altai and Sayan Mountains, where | r | = 0.6-0.7. In May, the correlation coefficients are significant (| r | = 0.6-0.8) in the south of the territory, the north and the mountains areas are characterized by statistically insignificant correlation coefficients or no data (average daily air temperatures above 10°C are not observed).

When assessing the distribution of the number of severe and extreme droughts over the period under study, similar results were obtained using the SPI and SPEI indices. Repeatability of severe droughts in the coverage of the entire territory is maximal in July and August (2-3 droughts per period). However, hotspots with maximum repeatability (up to 5 droughts per period) were detected in May and August. According to the results of analysis S, the highest frequency of severe droughts (up to 4) is also observed in July and August. But, unlike SPI and SPEI data, it is recorded only in the Sayan Mountains region. According to the results of the analysis of the normalized HTC anomalies, the most droughty summer months (June-August), with a uniform distribution of the frequency of droughts throughout the territory (2-3 droughts per period).

Of particular interest in the study of contemporary climate change is the assessment of extreme events, which include strong and extreme droughts. According to research [3], the general drought is better identified by the spread of the negative anomaly of the Selyaninov HTC. Therefore, we compared the cases of observation of severe and extreme droughts, identified by means of different indices with the presence of the indicated phenomena, determined by the anomalies of the HTC. As a result of the calculations, it was found that the maximum number of coincidences for ΔHTC norm and Si (7.5% of the territory) is observed in determining severe droughts in June and August. That is, less than 10% of the territory for the period under consideration, the proposed aridity indices show identical results. In most cases, both in space and in time, the consistency of the conclusions obtained in the analysis of various indices is absent. Since all indices considered give a numerical representation of the intensity of droughts, it is necessary to use the characteristics of vegetation or the state of the soil cover as a criterion for the intensity of drought in the future.

4. Conclusions

The highest coefficients of linear correlation were obtained by comparing the indices SPI and SPEI (0.8-0.9), Si, and ΔHTC norm (0.7-0.9) during the active vegetation period (June-August). In the foothills correlation coefficients are high (about ± 1.0), which is explained by the large contrasts of the sums of
atmospheric precipitation on the windward and leeward slopes, in comparison with the flat territory. In the remaining cases, the relationship between the aridity indices is statistically insignificant ($\pm 0.2$) over most of the territory under consideration. Synchronicity of changes in the aridity indices in question is confirmed by high correlation coefficients between them. However, the identified extreme events in some years (intensity, duration of drought) with the help of these indices do not always coincide. In order to determine the most representative index of aridity in the territory of southern Siberia, it is proposed to use long-term series of vegetation characteristics.

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