Development of computational module of regional aridity for web-GIS “Climate”

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Abstract. Modern global climate changes are characterized by a significant warming started in the late 1970s. According to the observation data, the average rate of warming in Russia for 1976-2012 was 0.43 °C/10 years. Additionally, the trend of annual precipitation for the same period in most parts of Russia is positive. To study the integral climate characteristics of a region, in particular, hydrothermal conditions, is of great interest. A new software module for the assessment of aridity was developed and added to an information and computing web system called “Climate”. The well-known hydrothermal coefficient of Selyaninov (HTC) was used with ECMWF ERA Interim reanalysis data for the period from 1979 to 2010. The input data (precipitation, temperature, HTC) were validated using observation data from weather stations. It was found that the ERA Interim data substantially (by 50%) underestimated the measured precipitation in the study region. The precipitation was corrected by the results. New spatially distributed precipitation and HTC data were obtained. The web system “Climate” is based on web and GIS techniques and is part of a hardware and software complex for “cloud” analysis of climatic data. It includes several climatological and meteorological datasets, as well as dedicated software modules for searching, selection, extraction, and visualization of data.

1. Introduction

Modern global climate changes are characterized by a significant warming in the late 1970s. According to observational data, the trend of average global warming reached 0.166 °C per 10 years for the period of 1976-2012, and 0.075 °C per 10 years for the period 1901-2012 [1]. The observed warming rate in Russia for the period of 1976-2012 is 0.43 °C per 10 years [2]. The trend of annual precipitation for 1976-2012 is positive in most parts of Russia. To study the integral characteristics of a region, especially hydrothermal conditions, is of great interest. These are described by coefficients depending on air temperature and precipitation. In this study, the well-known Selyaninov’s hydrothermal coefficient (HTC) [3] is used for the estimation of moistening and drought conditions of territories and the determination of moist and dry periods.

Traditionally, HTC is calculated in a manual or semi-automatic mode for a given territory with data from weather stations. This approach is very labour-consuming, requires significant time for multi-year observational data processing, and characterizes HTC only in regions with the weather stations. In combination with data of high sparsity of the weather stations network on the territories of Siberia and Far East, this significantly reduces the reliability of the obtained results.
In contrast to local observational data, global retrospective analysis (re-analysis) data are obtained on a regular grid and have global coverage. The recent development of the meteorological models and numerical schemes of observational data assimilation resulted in an improvement of quality and an increase in the spatial resolution of the global re-analyses. This allows using them for spatial distribution estimation of the territories’ moisture conditions. However, the big volumes of data (up to several terabytes) require powerful computing complexes for their processing, and the dedicated file formats used for storing data require specific programming skills. One of the most perspective approaches to solving this problem is using “cloud” computing, i.e., storing and processing of data on powerful servers providing remote access to the analysis tools and processing results via the internet [4].

In this study we estimate the aridity of South Siberia territory with re-analysis data using an information-computing web system (ICWS) called “Climate”. For this purpose, a new software module of ICWS for HTC calculation was developed. The web system “Climate” (http://climate.scert.ru) is based on a combined use of web and GIS approaches. It is part of a hardware and software complex for “cloud” analysis of climatic data with various archives of climatic data, as well as dedicated algorithms for their searching, extraction, processing, and visualization [5]. Use of this ICWS significantly facilitates and accelerates analysis of big volumes of geospatial data, allowing researchers to perform complex climate data analysis using desktop PCs with internet connection.

2. Methods and approaches

2.1. Drought estimation techniques

Heat and moisture are the main factors of agricultural productivity. Herein the greatest productivity loss is done by droughts due to air temperature anomalies and deficit of precipitation either during the vegetation period or in the preceding autumn-winter period [6]. All historical drought observations show high vulnerability of the population and economy to them in the world. A drought occurs when precipitation, during some period of time, is observed below the average value. A detailed study of the agro-climatic conditions of a territory by their aridity degree is required to develop a land-use planning strategy in regions with high agricultural activity. In numerous papers devoted to the study of droughts, different approaches to droughts detection and determination of their characteristic types and forming conditions are considered; the most representative aridity indices are developed; and catastrophic droughts analysis and catalogization are performed [3, 7-10]. However, D.A. Ped showed [11] that there is no any recognized quantitative index of a drought. Also, studying droughts, some other dedicated indices are used. These indices are calculated using indicators of soil water balance and soil moisture deviation from the optimal condition, duration of these periods, amplitude of moisture reserves variation, monthly anomalies in soil moisture, drought periods length and average monthly values of temperature and precipitation, positive amplitudes of temperature anomalies and negative precipitation anomalies [12-15].

According to a Russian drought classification [9], the following types are distinguished: atmospheric, soil, and atmospheric-soil. The Russian classification is more oriented to the drought effects and takes into account the environment of a drought. It differs from the American one [16]. That is why the Russian classification is more useful for understanding the physical nature of droughts. For example, it was shown [17] that an atmospheric-soil drought occurs due to a prolonged atmospheric drought and is intensified by a soil drought. Also, during some years a soil drought was intensified by an atmospheric one, and an atmospheric-soil drought is characterized by a combination of soil and atmospheric droughts.

The adverse agroclimatic phenomena significantly reduce the agroclimatic potential. During an atmospheric drought we observe active heating and relative desiccation of the air processes in the absence of rainfalls and a large income of solar radiation.
Selyaninov’s hydrothermal coefficient (HTC) is a well-known technique for territory moisture conditions estimation in Russia. It is assumed that the sum of temperatures is close to evaporation from an optimally moist field and can, therefore, be taken as the maximum evaporation, i.e. evaporability. This coefficient represents the ratio of precipitation for some time period to the sum of temperatures higher than 10 °C divided by 10, for the same period. Thus, the hydrothermal coefficient, as an index of territory estimation by moisture conditions, has an advantage over the precipitation, characterizing not only the income water balance (precipitation), but also the non-productive outcome of water (surface and vegetation evaporation, etc.) closely linked to the overall level of the air temperature. According to many studies [18], this index is not only applicable for comparative moisture estimation of areas with significantly different thermal conditions, but also used as a comparative moist characteristic of the individual months as well.

2.2. HTC computing module
To calculate Selyaninov’s hydrothermal coefficient, the ICWS “Climate” functionality was extended by a dedicated software module. The module was developed using Interactive Data Language (IDL) v. 6.0. The algorithm is based on a well-known formula for calculating the HTC [3]:

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

Here \(\sum r\) is precipitation during a vegetation period with air temperature above 10 °C, \(\sum T_{>10}\) is the sum of temperatures during a vegetation period with air temperature above 10 °C.

The vegetation period was calculated on the basis of a technique presented by Ped [19].

To estimate the accuracy of the aridity index HTC calculated using reanalysis data, the results obtained were compared to the HTC calculated using observation data from weather stations in the study area. For this, the HTC values calculated at the nodes of the re-analysis grid were interpolated into the coordinates of the stations using a linear interpolation method. With the results of the comparison, a correction of the re-analysis precipitation was performed using linear regression at all nodes of the re-analysis grid for the study area.

The software module was integrated into the software framework of ICWS “Climate” and linked to all its resources, including various datasets and modules for processing and visualization of results.

3. Results
Using the above-developed software module and the ECMWF (European Centre for Medium-Range Weather Forecasts) ERA Interim [20] re-analysis spatial fields of temperature and precipitation, Selyaninov’s hydrothermal coefficient was calculated for the territory of Southern Siberia (50°-65° N, 60°-115° E) for the period from 1979 to 2010. For quality assessment of the results obtained, HTC was also calculated using local observation data from the weather stations. Then temperature, precipitation and calculated HTC values were interpolated from the re-analysis grid to the coordinates of the weather stations.

A reanalysis and observation data comparison showed a slight difference in the temperature values (average -0.86 °C or -6.77%) and a significant discrepancy in the precipitation and hydrothermal coefficients (average 55% and 50%, respectively). Detailed results of the calculations are presented in Table 1. Similar findings were obtained by T.M. Shulgina [21].

Next, a correction of the precipitation data was performed using linear regression. The observational data on daily precipitation were taken as the dependent variable, and the re-analysis daily precipitation interpolated to the coordinates of weather stations was taken as the independent variable. The correction was performed separately for each year and month of the vegetation period (from May to September) for the study area. After the correction the mean deviation between the re-analysis and observational daily precipitation significantly decreased. Similarly, the HTC values also changed. For the corrected daily precipitation and HTC, the mean deviations during the vegetation
period are -3.38% and 3.02%, and RMSs are 10.74% and 21.48%, respectively. Detailed results of the calculations are presented in Table 2.

Table 1. Reanalysis and observation data comparison.

|          | May   | June  | July  | August | September |
|----------|-------|-------|-------|--------|-----------|
| Precipitation, % |       |       |       |        |           |
| Average  | -51.58| -56.99| -55.51| -55.76| -54.74   |
| RMS      | 7.65  | 4.61  | 6.00  | 4.84   | 6.04     |
| Maximum  | -26.34| -40.18| -39.12| -45.16| -31.71   |
| Minimum  | -64.03| -64.32| -66.63| -63.89| -63.65   |
| Temperature, °C |       |       |       |        |           |
| Average  | 1.04  | 1.06  | 0.93  | 0.80   | 0.48     |
| RMS      | 1.37  | 1.85  | 2.11  | 1.92   | 1.19     |
| Maximum  | 4.14  | 5.26  | 5.85  | 4.91   | 3.30     |
| Minimum  | -0.62 | -1.73 | -1.38 | -1.35  | -0.88    |
| HTC, %   |       |       |       |        |           |
| Average  | -46.18| -51.60| -55.44| -51.90| -48.80   |
| RMS      | 17.28 | 10.22 | 10.40 | 8.83   | 12.64    |
| Maximum  | -14.74| -22.64| -27.28| -31.01| -8.92    |
| Minimum  | -72.32| -64.10| -83.00| -75.40| -68.63   |

Table 2. Corrected reanalysis and observation data comparison.

|          | May   | June  | July  | August | September |
|----------|-------|-------|-------|--------|-----------|
| Corrected precipitation, % |       |       |       |        |           |
| Average  | -3.41 | -3.73 | -3.58 | -2.87  | -3.31     |
| RMS      | 11.54 | 8.80  | 10.52 | 11.91  | 10.94     |
| Maximum  | 25.94 | 10.50 | 22.47 | 20.84  | 25.62     |
| Minimum  | -22.46| -21.07| -29.54| -26.23 | -22.43    |
| Corrected HTC, % |       |       |       |        |           |
| Average  | 4.61  | 5.64  | 5.02  | 2.93   | 6.93      |
| RMS      | 29.12 | 18.78 | 18.71 | 16.55  | 24.24     |
| Maximum  | 116.70| 47.37 | 24.08 | 39.42  | 71.75     |
| Minimum  | -48.02| -16.67| -63.41| -24.25 | -34.94    |
The differences between the long-term HTC values before and after the daily precipitation correction are shown in Figures 1 and 2.

**Figure 1.** Long-term HTC values for Southern Siberia for the vegetation season calculated using ECMWF ERA Interim data for 1979-2010: a – uncorrected daily precipitation, b – corrected daily precipitation.

**Figure 2.** Long-term HTC values for Southern Siberia in August calculated using ECMWF ERA Interim data for 1979-2010: a – uncorrected daily precipitation, b – corrected daily precipitation.

4. Conclusions
The above-developed software module and the ICWS "Climate" significantly facilitate and speed up the calculations of aridity indices using observation and re-analysis data. In this work, the ICWS "Climate" provided functionality to calculate and visualize HTC for the territory of Southern Siberia from 1979 to 2010 (the user can change the boundary conditions). It allowed assessing the geographical distribution of hydrothermal conditions for the region. The results are represented by net CDF files, georeferenced maps and layers available as downloadable files or web services [22]. They can be easily transferred to online and desktop GISs for further cross-analysis with other spatial products, e.g. for estimation of the drought impact on vegetation productivity in the region. Since the hydrothermal indices are integral characteristics of the heat-moisture conditions of the area, special attention should be paid to the quality of the initial data. It was found that the Era Interium data substantially (by 50%) underestimate the measured precipitation in the study region. Adjustment of the re-analysis daily precipitation using the linear regression coefficients allows us to correctly estimate the spatial distribution of the HTC over the area, thus increasing the quality of droughts detection and estimation of extra moisture conditions in the study area.
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