Hydrothermal conditions of South Eastern Siberia under the ongoing warming

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Abstract. A great increase in air temperature has been observed since 1976. Siberia is a region with most severe ongoing climate change. To monitor the extreme weather events is important. To evaluate moisture conditions we used the D.A. Ped index (Sᵢ). Monthly air temperature and precipitation data from 19 weather stations of South Eastern Siberia (50-60˚ N 90-120˚ E) were used for the index calculation during the vegetation period. During 1976-2010 the number of droughts in the study region was more than the number of excessive moisture periods. The maximal statistically significant trend (0.4-0.6 per 10 years) in Eastern Siberia was observed in May. The characteristics of the winter-spring period preceding the vegetation season were analyzed. Significant positive trends exist in the study area for the May temperature (0.5-0.9 °C per 10 years) and the May sum of positive temperatures (14-28 °C per 10 years). There are tendencies to increase the number of days with temperatures above zero in March (1-3 days per 10 years) and the sum of positive temperatures in April (5-16 °C per 10 years). The stable transition of air temperature over 0 °C shifts into early dates by 1-7 days every 10 years.

1. Introduction
The climate change issue attracts attention of researchers and is among the most important natural science issues. The research of climate trends of meteorological variables is presented in a number of publications. The review of recent publication shows that many scientists hold by an opinion that climate warming has been occurred in recent decades. However, some researchers believe that the temporary warming is occurring given the durable and slow cooling [1].

The air temperature is one of the most important indicators of climate change; therefore, particular qualities of the intra-annual fluctuations, the secular trend and interannual variability are well researched. The recent data shows that the surface air temperature increased by 0.6 ± 0.20 °C during the 20th century [2], [3]. However, the global warming was temporally heterogeneous. Three periods are singled out: warming up within the intervals of 1910-1945, the, low cooling within the 1946-1975 and intense warming since 1976.

These periods are characterized by spatial inhomogeneity, i.e. in some areas the warming is more intensive and in some regions even cooling than in others [4]. The largest positive trends in annual air temperature are observed mainly in the continental areas (Prebaikalie, Central Yakutia, the Far East) with values reaching 2-3.5 °C per 100 years [5], [6].
2. Methods

It should be mentioned that, the study of variations of single climatic elements furthered the study of the integral characteristics of the territory, which were different humidity or aridity indices, being in most cases combinations of air temperature and precipitation values. In Russia well-known Selyaninov hydrothermal coefficient is often used. But to study droughts in different landscapes index $S_i$, formula (1), suggested by D.A. Ped’, is the most appropriate. One drought or excessive moistening of a particular region in a warm season is characterized not by the air temperature and precipitation values, but by their anomalies compared to climatic norms:

$$S = \frac{\Delta T}{\sigma_T} - \frac{\Delta R}{\sigma_R}$$  \hspace{1cm} (1)

where $\Delta T, \Delta R$ are anomalies (deviations from the norm) of monthly air temperatures and precipitation, $\sigma_T, \sigma_R$ - mean-square deviations for the same parameters. The following conditions are used for determinations of the extreme events:

For droughts $\Delta T > 0$ and $\frac{\Delta T}{\sigma_T} > 0$, $\Delta R < 0$ and $\frac{\Delta R}{\sigma_R} < 0$, then $S_i > 0$.

For excessive moistening $\Delta T < 0$ and $\frac{\Delta T}{\sigma_T} < 0$, $\Delta R > 0$ and $\frac{\Delta R}{\sigma_R} > 0$, then $S_i < 0$.

We estimate the intensity of drought according the next rules: weak $1.0 < S_i < 2.0$; medium $2.0 \leq S_i < 3.0$; severe $S_i \geq 3.0$. The intensity of excessive moistening was divided into low $-2.0 < S_i < -1.0$; medium $-3.0 < S_i \leq -2.0$; high $S_i \leq -3.0$.

Daily temperature and precipitation obtained at weather stations during the vegetation period (May-September) were used for index $S_i$ calculation. Only weather stations with minimum (less than 5%) amount of missing data were used. Index $S_i$ was calculated for 19 weather stations located at the south of East Siberia (within rectangle with coordinates 50-60° N, 90-120° E) for a period of intense global warming (1976-2010) (Figure 1).

Figure 1. Weather station map.
Administratively, the study area includes the southern regions of the Krasnoyarsky Krai, the Irkutsk Region, the Republic of Buryatia, the Chita Region. The study area can be divided into three physical geographic regions (Southwest of Central Siberian Plateau, Predbaikalie, and Zabaikalie). Usually weather stations are located in the river valleys. Mountain areas in the present paper were not investigated. Only Inga station is located in the foothills of the Eastern Sayan Ridge.

We studied long-term variations of index $S_i$ for vegetation period (from May to September) for 1976-2010. May is a critical month for drought. During cyclonical activity periods in July and August a sufficient or extreme moistening is usually registered. Averaged values for the vegetation period do not reflect actual extreme events revealed for single months. Then, the territory covered by droughts in different years was evaluated. The maximum drought area was observed in May.

3. Results

Analysis hydrothermal conditions for the study area showed that the repeatability of the weak drought is more than a repeatability of the low excessive moistening during the vegetation period. But the repeatability of periods of medium and high excessive moistening is higher than the repeatability of periods with medium and severe drought.

Forecasting, of a single meteorological characteristic and complex indices such as $S_i$, is one of the main tasks in climatology. Its reliability is determined by the sufficient information base, which includes long-term data of instrumental observations from weather stations. However, data from the majority of Siberia stations were registered only from 1930's. The Irkutsk station had more information on air temperature and precipitation since the late 19th century. We calculate the index for the long-term weather station Irkutsk since 1882. Significant trends were found in May. However, the amplitude of interannual fluctuations increases in recent decades. In different months this increase occurs due to the prevalence of extreme deviations of either positive or negative sign. For example, the positive extremes prevail in June, negative - in July, August and September. Thus, we can talk about a redistribution of dry and wet periods within the vegetation season. The number of weak atmospheric droughts has increased in all months of the vegetation season. The number of periods with weak excessive moisture is decreases. The extreme events with medium intensity have complicated the structure of changes.

Comparison of the $S_i$ indices for the long period (1891-2010) with the $S_i$ indices for the period of the most intense warming (1976-2010) have shown that more than half of the cases of extreme events (droughts or excessive moistening) are observed in the last 35 years (Table 1). For example, in September from 1892 to 2010, twenty-one weak droughts were observed, and most of the weak droughts (10-11 cases) were recorded after 1976. The severe droughts and the high excessive moistening have the highest influence on the terrestrial ecosystems. In particular, in May and June during the period 1976-2010 in Irkutsk three or four severe droughts observed no one severe drought was registered in the previous period. Repeatability of periods of excessive moistening increased only in July (medium intensity) and in August (high intensity).

| Period    | Drought | Excessive moistening |
|-----------|---------|----------------------|
|           | $1 < S_i < 2$ - Weak | $2 < S_i < 3$ - Medium | $S_i \geq 3.0$ - Severe |
|           | $V$ | $VI$ | $VII$ | $VIII$ | $IX$ | $V$ | $VI$ | $VII$ | $VIII$ | $IX$ | $V$ | $VI$ | $VII$ | $VIII$ |
| 1891-2010 | 14 | 17 | 17 | 21 | 21 | 7 | 6 | 8 | 6 | 6 | 4 | 3 | 3 | 3 | 0 |
| 1976-2010 | 5 | 5 | 5 | 10 | 11 | 3 | 2 | 5 | 3 | 4 | 4 | 3 | 1 | 1 | 0 |
|           | $1 < S_i < 2$ - Weak | $2 < S_i < 3$ - Medium | $S_i \geq 3.0$ - High |
|           | $V$ | $VI$ | $VII$ | $VIII$ | $IX$ | $V$ | $VI$ | $VII$ | $VIII$ | $IX$ | $V$ | $VI$ | $VII$ | $VIII$ | $IX$ |
| 1891-2010 | 16 | 19 | 18 | 20 | 13 | 8 | 8 | 7 | 9 | 10 | 2 | 0 | 3 | 1 | 1 |
| 1976-2010 | 4 | 5 | 1 | 5 | 2 | 0 | 3 | 4 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
Tendencies of changes in $S_i$ index were calculated for the 35-year period (1976-2010). Trend values in most cases are statistically insignificant (Figure 2).

![Figure 2](image_url)

Figure 2. Trends of $S_i$ index for the period 1976-2010
statistically significant trend: ★ - positive, ● - negative ($p<0.05$)
statistically insignificant trend: ○ - positive, ● - negative ($p>0.05$).

The maximum of statistically significant trends of the $S_i$ were registered in May. At six of the nineteen weather stations the increase of the $S_i$ was observed with rates 0.4-0.6 per 10 years. In July, the number of droughts increases only at three weather stations of Predbaikalie (Nizhneudinsk, Irkutsk, and Kirensk) and at weather station Barguzin in Zabaikalie. In June, aridity increase at the weather station Mogocha, in August - at the weather stations Eniseisk and Nizhneudinsk. In
September, a statistically significant increase in the number of droughts was not observed. At Barguzin station (Zabaikalie) increase of the moistening is found in August and September. We have studied changes in area averaged indices $S_i$ for regions. Increasing of aridity in the Southwest of Central Siberian Plateau is observed only in May, in Predbaikalie - in May, July and August. In Zabaikalie statistically significant trends were not observed.

To reveal influences of winter periods on the vegetation period the following climatic characteristics of the winter-spring period, which was preceded by the vegetation period, were analyzed:

- Precipitation in November-March, mm ($R_{XI-III}$)
- April Precipitation, mm ($R_{IV}$)
- May Precipitation, mm ($R_{V}$)
- March temperature, °C ($T_{III}$)
- April temperature, °C ($T_{IV}$)
- May temperature, °C ($T_{V}$)
- The sum of air temperatures above 0 °C in March, °C ($\sum T>0_{III}$)
- The sum of air temperatures above 0 °C in April, °C ($\sum T>0_{IV}$)
- The sum of air temperatures above 0 °C in May, °C ($\sum T>0_{V}$)
- The number of days with temperatures above 0 °C in March ($N_{T>0, III}$)
- The number of days with temperatures above 0 °C in April ($N_{T>0, IV}$)
- The number of days with temperatures above 0 °C in May ($N_{T>0, V}$)
- Date of transition of air temperature through 0 °C ($D_{T>0}$)
- Maximal snow depth, cm ($H$)
- Date of final loss of snow ($D_{H<0}$)

We have analyzed the tendencies for the above listed characteristics. Statistically significant positive trends of the May temperature (0.5-0.9 °C per 10 years) and of the sum of positive temperatures in May (14-28 °C per 10 years) exists at the whole study area. The number of days with temperatures above zero increases in March (1-3 days per 10 years) at the Southwest of Central Siberian Plateau, and the sum of positive temperatures increases in April (5-16 °C per 10 years) in Zabaikalie. These changes can considered as a consequence of changes in the dates of stable transition of air temperature through 0°C. All weather stations show a shift to earlier dates (1-7 days per 10 years). Statistically significant changes (3-7 days per 10 years) were observed at a half of the studied stations.

Graphs of long-term changes of some climate characteristics are presented for some weather stations (Figure 3). These characteristics have statistically significant trends on most weather stations. Weather stations are located in different parts of the study area (Bolshaya Murta - Southwest of Central Siberian Plateau, Zhigalovo - Predbaikalie, Ivolginsk – Zabaikalie). The linear trend equations are shown on the figures. Positive trends in most cases (except the date of the spring transition temperature through 0°C) were registered. The trend of precipitation for the cold period is positive at many weather stations, but it is statistically significant only at three stations (Bolshaya Murta, Aginskoe, Nizhneudinsk).

Conditions of the preceding cold period have a negligent effect on $S_i$ index, which was calculated for the five months of the vegetation season. This is confirmed by the correlation analysis. In most cases, the linear correlation coefficients are not statistically significant. As expected, the maximum correlation was observed between the characteristics of the winter-spring period and indices $S_i$ in May. The statistically significant correlation coefficients (0.47-0.85) were obtained between $S_i$ index for May and hydrothermal conditions of the same month (the precipitation - 17 stations, the monthly air temperature - 18 stations, the sum of air temperatures above 0°C - 17 stations). Also, $S_i$ index in May depends on the precipitation from November to March (5 cases) and on the sum of temperatures above 0°C in March (5 cases).
Characteristics of the cold period have almost no effect on the indices for June and July. Some increase in correlation coefficients observed in August. The higher correlation coefficients will be observed in the study of correlation of parameters for the current and the previous months. It is claimed by our previous study.

Long-term variations of the $S_i$ index and the characteristics of the preceding cold period at the weather station Chara (Zabaikalie) are shown at Figure 4. Medium droughts were registered in 1993 and 2002, and medium excessive moistening events were observed in 1983 and 2006. The average value of each characteristic for long-term period (1976-2010) is shown in the first row of Table 2.
The mirroring change of deviations for five climatic characteristics occurs at weather station in years with the excessive moistening and droughts. As shown before, the precipitation of the cold period, May precipitation May temperature, as well as the sum of the temperature and the number of days with temperatures above 0°C in May contribute to the moistening conditions in May. Red and blue cells are marked positive and negative deviations from the mean.

**Table 2. Deviations (italics) of characteristics of the preceding cold period at the weather station Chara (Zabaikalie) from the mean.**

| Year | S\textsubscript{i} | R\textsubscript{X\textsubscript{i}} | R\textsubscript{Y} | T\textsubscript{min} | T\textsubscript{1\textsubscript{IV}} | T\textsubscript{V} | \Sigma T\textsubscript{X\textsubscript{Y}} | \Sigma T\textsubscript{X\textsubscript{Y}} | N\textsubscript{X\textsubscript{Y}} | N\textsubscript{X\textsubscript{Y}} | D\textsubscript{X\textsubscript{Y}} | H | D\textsubscript{H\textsubscript{X\textsubscript{Y}}} |
|------|----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----|----------------|
| Mean (1976-2010) | 19.9 | 13.5 | 44.1 | -16.8 | -3.6 | 5.6 | 16.5 | 178.4 | 7.3 | 28.3 | 113.2 | 16.1 | 107.7 |
| 1983 | -2.9 | 17.1 | 4.9 | 95.2 | -14.9 | -5.9 | 4.5 | 0.0 | 142.2 | 0.0 | 27.0 | 122.0 | 11.0 | 102.0 |
| 1992 | 2.12 | 25.7 | 10.7 | 14.7 | -15.9 | -4.1 | 8.3 | 2.6 | 256.0 | 3.0 | 31.0 | 120.0 | 14.0 | 90.0 |
| 2002 | 2.4 | 20.8 | 11.8 | 21.5 | -9.7 | -1.5 | 9.3 | 24.1 | 289.8 | 9.0 | 30.0 | 113.0 | 2.0 | 96.0 |
| 2006 | -2.27 | 12.8 | 12.0 | 68.8 | -18.1 | 0.2 | 4.6 | 54.8 | 145.2 | 18.0 | 28.0 | 105.0 | 18.0 | 100.0 |

The other deviations are distributed more spontaneously. The date of final loss of snow cover and the maximal snow depth do not change the S\textsubscript{i} index even in May. Perhaps this is due to the fact that Eastern Siberia is characterized by small depth of snow. Snow cover is completely disappears in March or early April. Snow cover characteristics have small effect on the characteristics of atmospheric moisture in May. The role of the snow cover will be more significant if we use information about soil moisture and soil-atmospheric phenomena. If we analyze the changes in the index in the neighboring territories, the snow height of impact could be significant. For example it may be in Western Siberia, where the average snow depth is much greater. The area of this study is situated at the center of the Asian continent, is characterized by sharply continental climate. Here, the temperature is a major contributor to the change of aridity.

**4. Conclusions**

The following conclusions were obtained in the analysis of changes of hydrothermal conditions in the south of Eastern Siberia:
- The frequency of weak drought and weak excessive moistening periods is almost constant. The number of drought and excessive moistening with medium and severe intensity in the 1976-2010 has increased compared with 1891-1975.

- Maximum change in hydrothermal conditions in the south of Eastern Siberia occurred in May. Seven out of nineteen weather stations have positive trends of Si over the last 35 years.

- From the considered climatic characteristics of the preceding cold period, only the precipitation during the cold period and the sum of positive temperatures for March affect the atmospheric drought / excessive moistening at the beginning of the vegetation season.

- For a comprehensive analysis of drought / excessive moistening during the vegetation season in addition to the meteorological station data, in particular the conditions of the preceding cold period, in the future we should use the characteristics of the soil and vegetation. We will evaluate not only atmospheric but also atmospheric and soil drought / excessive moistening periods. In addition to the expanded Ped’ index $S_i$, enhanced by soil component we can use other complex indices (eg the Palmer index).

Acknowledgements
The authors thank the Russian Foundation for Basic Research for support of this work under the grant № 14-05-00502.

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