Dynamics of climatic characteristics influencing vegetation in Siberia

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Received 24 August 2011
Accepted for publication 3 November 2011
Published 29 November 2011
Online at stacks.iop.org/ERL/6/045210

Abstract
The spatiotemporal pattern of the dynamics of surface air temperature and precipitation and those bioclimatic indices that are based upon factors which control vegetation cover are investigated. Surface air temperature and precipitation data are retrieved from the ECMWF ERA Interim reanalysis and APHRODITE JMA datasets, respectively, which were found to be the closest to the observational data. We created an archive of bioclimatic indices for further detailed studies of interrelations between local climate and vegetation cover changes, which include carbon uptake changes related to changes of vegetation types and amount, as well as with spatial shifts of vegetation zones. Meanwhile, analysis reveals significant positive trends of the growing season length accompanied by a statistically significant increase of the sums of the growing degree days and precipitation over the south of West Siberia. The trends hint at a tendency for an increase of vegetation ecosystems’ productivity across the south of West Siberia (55°–60°N, 59°–84°E) in the past several decades and (if sustained) may lead to a future increase of vegetation productivity in this region.

Keywords: regional climate change, climatic indices, spatially-referenced data, GIS

1. Introduction

As was shown [1–4], on-going climatic changes in Siberia are strongly pronounced and spatially non-uniform. Thus, temperature trends in the second half of the 20th century were quite high (more than 0.2 °C/10 yr). In some regions of West Siberia, near-Baikal regions, and the areas east of the Verkhoyansk Mountain Range (the so-called ‘hot spots’), a temperature rise of 0.5 °C/10 yr has been observed [5] and most of the warming occurred in the winter and spring seasons. Summer and autumn temperatures make less contribution to annual temperature dynamics [2, 5]. However, both spatial pattern and degree of temperature variations in this region have still not been determined in detail. Moreover, in this region there were no reliable estimates of a precipitation pattern change. For example, trends obtained from observations and reanalysis data are contradictory [6]. Namely, seasonal precipitation trends based upon in situ observations show negative dynamics of precipitation amount (2–5 mm/10 yr). In contrast, trends obtained from reanalysis datasets show precipitation increasing at 2–5 mm/10 yr. For temperatures, reanalysis data are in good qualitative agreement with in situ data but are quantitatively different. In the upper-latitude regions, reanalysis temperature values are higher than the observed temperature and in the middle-latitude regions, reanalysis temperature trends are less than trends obtained from instrumental observations [6]. The above suggests that further studies of spatiotemporal behavior of climatic characteristics in the region are required.
Structure and functioning of vegetation cover are closely connected to environmental conditions on the regional scale. Being the most important physical parameters of the environment, meteorological factors strongly influence all aspects of vegetation development, namely, they determine growth potential, biodiversity and productivity [7]. Significant temperature increases in Siberia are expected to have profound effects on Siberian vegetation [8]. Tree response to climate trends is most likely to be observed in the forest–tundra ecotone, where mainly temperature limits tree growth, and spring and autumn temperature variations determine the beginning and end of the growing season [9]. For example, analysis of forest–tundra ecotone dynamics in the Western Sayan Mountains in Southern Siberia showed an increase in forest stand crown closure, upward tree-line and regeneration shift, and the transformation of Siberian pine and fir Krummholz into arboreal forms. Closed stands were increasing in the area and advancing their upper boundary at an altitudinal rate of 0.6 m yr\(^{-1}\), and sparse stands are being transformed into closed stands. It was also found that these changes correlated positively with temperature trends [9].

The objective of this paper is to document a more detailed spatiotemporal pattern of dynamics of surface air temperature and precipitation in Siberia (50\(^\circ\)−130\(^\circ\)E, 50\(^\circ\)−72\(^\circ\)N) focusing on relevant bioclimatic indices controlling structure and functioning of vegetation cover. To achieve this goal, available observational and reanalysis data are compared using approved statistical methods. Thereafter, datasets that are statistically consistent with reliable in situ meteorological observations were selected and used in trend analysis. Specifically, the main characteristics of annual and seasonal behavior of meteorological variables and indices characterizing growing season were studied. Among these indices are (a) growing season length with daily mean temperatures exceeding 5\(^\circ\)C, (b) sums of growing degree days with temperatures exceeding 5\(^\circ\)C over the calendar year, (c) annual and seasonal precipitation totals, and (d) daily precipitation intensity.

2. Data and methods

To understand the dynamics of the hydrothermal regime in the region under study, long-term observational series of meteorological quantities are needed. At present the most complete observational series are available at the Russian Institute of Hydrometeorological Information—World Data Center (RIHMI-WDC). The data are stored as specialized datasets comprising daily temperature and precipitation at 223 weather stations of the former USSR (http://meteo.ru/climate/dtemp.php). From these data we retrieved daily time series of 59 weather stations located in Siberia (figure 1). The selection criterion was the following: (1) period of observations should be at least from 1961 to 2007; (2) data gaps are no more that 3 days/month for each year (<36 days/yr).

Since the network of weather stations in Siberia is irregular and even sparse in some areas, conventional interpolation methods could not be used for obtaining reliable high-resolution fields of meteorological variables from observations. In this case, modeled data are used that properly account for geophysical features of the region and uniformly cover its territory. But geophysical fields, obtained as a result of the running of different global models having different data assimilation systems and initial data, differ from each other. Therefore a problem arises in the selection of a dataset which is most consistent with instrumental observations. To solve this problem, we compared different reanalysis data (ECMWF ERA INTERIM: 1989–2007 [10], ECMWF ERA-40: 1961–2001 [11], NCEP/DOE AMIP II [12]: 1961–2003 and NCEP/NCAR: 1961–2002 [13]) with observations. The following procedure of reconstruction of reanalysis temperature values at the weather stations’ locations was used. Firstly, we tested a set of interpolation methods comprising bilinear interpolation, third-order polynomial, inverse distance weighted, modified Shepard’s interpolation, and basic geostatistical kriging and found that the modified Shepard’s interpolation method [14] is the most exact to reconstruct the reanalysis data. The testing was done by reconstructing temperatures at relevant regular grid nodes from temperatures at the nodes of the doubled size grid and comparing them with those given in the reanalysis set. Thereafter, surface air temperature values from the reanalysis datasets were reconstructed at the weather stations’ location coordinates using the formulas of the modified Shepard’s method [14] and a special sub-grid with a node located exactly at the station location. At these station locations we also have in situ observations of the meteorological value which can be compared with corresponding interpolated reanalysis data. Third, for the reconstructed and in situ observed time series

Figure 1. Location of the 59 selected weather stations in Siberia. Figures in parentheses are the station numbers in the list.
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Figure 2. Root-mean-square deviation of differences between reanalyses data reconstructed at the station location and instrumental surface air temperature observations at this station (°C). Results are presented for each station over the 1991–2000 period. Numbers and locations of stations are shown in figure 1.

Figure 3. Differences between annual mean temperatures obtained from ERA Interim and ERA-40 datasets averaged over 10 yr (1991–2000).

Since ERA Interim and ERA-40 datasets are obtained by the same institution and the same instrumental observations were assimilated for creation of these datasets, there is an opportunity to make a composite time series for the entire 1961–2007 period. To exercise this opportunity, we calculated mean annual and monthly surface air temperatures for each dataset and averaged them over 10 yr (from 1991 to 2000) in common for both datasets. The differences for annual mean temperature and absolute differences for monthly mean temperatures between these datasets are presented in figures 3 and 4.

Figure 3 shows an average difference in annual mean temperatures equal to 0.5 °C. Monthly differences (figure 4) are larger in winter (0.63 °C on average) than in summer (0.38 °C on average). It should be noted that these differences calculated for each year vary even more. According to the Student $t$-test criterion, the observed differences are statistically significant and these temperature datasets have different distribution functions. Therefore it is impossible to combine ERA-40 and ERA Interim into one composite time series and so in our research of on-going dynamics of the surface air temperature in Siberia, we limit ourselves to the ERA Interim dataset and the time interval from 1991 to 2007.
It is more difficult to choose data for studying precipitation dynamics because gridded precipitation fields in all models are much less reliable than those for temperature. In figure 5, we show the result of annual precipitation data comparison, using the above-described procedure (the same as for temperature comparison), applied to datasets ERA Interim and APHRODITE JMA [15]. Note that the ERA Interim dataset is comprised of prognostic results obtained without observational data assimilation and the APHRODITE JMA dataset is comprised of fields obtained by interpolation of weather station observations.

A suite of such comparisons showed that the APHRODITE JMA dataset is closest to real precipitation observations in Siberia. The RMSE for this dataset is the least and it is consistent with observational data at the 0.05 significance level. As APHRODITE JMA precipitation fields present interpolated stations’ observations, the spatial RMSE differences are partially explained by the JMA interpolation method which does not capture Siberian landscape features. Thus, the ERA Interim dataset with spatial resolution of 1.5° × 1.5° and time step of 6 h for the period of 1991–2007 was used to study the dynamics of surface air temperature in Siberia (50°E–130°E, 50°N–72°N). Precipitation dynamics was assessed based on the daily data from the APHRODITE JMA dataset with spatial resolution of 0.5° × 0.5° over the period 1979–2007.

To assess long-term changes of the hydrothermal regime and their influence on vegetation in Siberia, we consider the main characteristics of the annual and seasonal behavior of meteorological variables and climatic indices listed in section 1. These climatic indices show well the thermal and hydrological dynamics in Siberia and represent the main characteristics controlling the vegetation dynamics [16, 17].

The dynamics of climatic indices has been assessed by linear trends with coefficients, determined by the least-squares method, that characterize the mean rate of changes at the time interval considered. The statistical significance of changes is determined using the two-tailed Student t-test criterion [18]. All calculations were made using IDL (the Interactive Data Language [19]) on the basis of a specially developed computational module of the developed web-GIS information–computational system [20]. The computational module has access to data archives. It allows easy interactive data analysis and visualization. The resulting fields are saved in graphical forms as well as in digital files available for subsequent analyses.

3. Results

3.1. Dynamics of mean air temperatures and precipitation

The spatiotemporal dynamics of surface air temperature in Siberia is characterized by linear trends for the 1991–2007 period estimated for annual, seasonal and monthly mean temperatures (figure 6). Spatial pattern of annual surface air temperature changes observed in Siberia (figure 6(a)) has warming spots in West Siberia (0.8–1.6°C/10 yr) and a few cooling spots in the central part of East Siberia (from −0.2 to −0.5°C/10 yr). This pattern directly depends upon seasonal temperature trends. In particular, the temperature changes in winter (December–February; figure 6(b)) presented by warming spots in northern and southern parts of West Siberia are formed mostly due to positive temperature trends in December. In East Siberia there are locations with negative temperature trends (from −0.8 to −1.6°C/10 yr), which are formed mostly due to temperature decrease (from −0.5 to −2.5°C/10 yr) in December and January. In summer (June–August), figure 6(c) shows a significant temperature decrease, up to −1.2°C/10 yr, in central and southern parts of West and East Siberia as a result of a clearly pronounced temperature decrease in June. Temperature variations in July and August are less pronounced. Temperature increase (0.6–1.2°C/10 yr) occurs mostly in the northern parts of Siberia. The central part of East Siberia is generally characterized by temperature decrease (from −0.2 to −0.5°C/10 yr).

Temperature variations in spring (figure 6(d)) and autumn (figure 6(e)) are of particular interest because in these seasons the following development processes important for the vegetation occur: snow melt, beginning and end of the growing season, late spring and early autumn frosts. In particularly, temperature increases in April (up to 1.5°C/10 yr) in East Siberia and in May (0.4–0.9°C/10 yr) in West Siberia. Autumn warming is also observed in West Siberia (2.4°C/10 yr on average), while in East Siberia temperature decrease is observed (−1.8°C/10 yr).
Figure 6. Trends of surface air temperature for the 1991–2007 period averaged for: (a) year, (b) winter, (c) summer, (d) spring, and (e) autumn.

Figure 7. Trends of precipitation totals for winter (a) and summer (b) during the 1991–2007 period.

Analysis of precipitation dynamics during the past two decades shows that there are no pronounced changes of precipitation in Siberia in winter (figure 7(a)). Precipitation decreases only in the northern part of West Siberia where the trend reaches 40 mm/10 yr mostly due to precipitation decrease in January and February. Analysis of precipitation
dynamics in summer also revealed a negative trend up to $-90 \text{ mm/10 yr}$ in West Siberia (figure 7(b)). Precipitation changes in East Siberia are not large; trends are about $20 \text{ mm/10 yr}$. Analysis of monthly precipitation dynamics revealed its increase in East Siberia in June, mostly in the southern and southeastern parts where the trend reaches 18–37 mm/10 yr. Significant precipitation increase in all East Siberia is observed in June, trends reach 45 mm/10 yr, while in West Siberia precipitation decreases ($-70 \text{ mm/10 yr}$). There are no precipitation changes in August and its contribution to seasonal precipitation dynamics is small.

Spring and autumn precipitation also has no clearly pronounced dynamics. Only in September does precipitation decrease up to 40 mm/10 yr in the central part of West Siberia. Thus, we can conclude that the summer months (June, July and August) make the main contribution to the precipitation dynamics and the largest spatial precipitation non-uniformity is observed in July.

Analysis of precipitation intensity and number of days with precipitation exceeding a preset threshold (1, 10 and 20 mm) shows that there are no changes in precipitation days ($\geq1 \text{ mm}$), excluding the northern part, where an increase of precipitation days is observed (up to 5 days/10 yr). Precipitation totals are also increased in this region. However, there are no trends in precipitation intensity either in this region or in Siberia as a whole on the annual time scale (figure 8).

### 3.2. Dynamics of bioclimatic indices

When temperature exceeds $5^\circ\text{C}$, vegetation growth begins [21]. Therefore analysis of climatic parameters in this period is of great interest, when studying climate–vegetation interactions. A day on which mean daily temperature is above $5^\circ\text{C}$ and that criterion is satisfied for the next five days should be considered as the beginning of the growing season. An autumn day when the above criterion was not satisfied for a sequence of five days should be considered as the growing season end [22].

Positive dynamics of spring and autumn temperatures (compare with figure 6) resulted in an increase of the growing season length (figure 9). In the north of Siberia, the number of warm days with daily mean temperature above $5^\circ\text{C}$ increased by up to 15 days/10 yr. Growing of this index is observed with latitude increase. Analysis of the dynamics of the sum of the growing degree days with daily mean temperature $>5^\circ\text{C}$ has revealed its increase by 40–70$^\circ\text{day/10 yr}$ on average (figure 10).

At the same time, an observed summer temperature decrease (up to $-0.6^\circ\text{C/10 yr}$) in central and south parts of West and East Siberia does not impact on the dynamics of growing season length and the sum of the growing degree days. However, this cooling might influence the vegetation dynamics process.

Undoubtedly heterogeneity of changes of surface air temperature and precipitation would have a response in the dynamics of biological processes, for example, in the change of vegetation spatial distribution and the dynamics of net primary production. Results of the modeling of regional and global forest evolution processes accounting for climate variations indicate increases of forest ecosystem productivity by 5–30% [23]. The above comparison of trends
of the growing season length, sums of the growing degree days and precipitation totals, directly influencing vegetation productivity, revealed the areas where climatic changes’ influence is the most pronounced. In particular, an increase of the growing season length is observed in the south of West Siberia (55°–60°N, 59°–84°E), which is accompanied by a statistically significant increase of sums of the growing degree day temperatures.

Thus, the observed changes suggest a possibility of increase in vegetation productivity in the south of Siberia. We realize that vegetation response to climate changes depends not only on temperature and precipitation dynamics but also on other climatic characteristics. For example, increasing temperature may also increase vapor pressure deficit of the air, and thereby increase transpiration rates, resulting in adverse effects upon drier regions. Further analyses are needed and now they can be based on the archive of bioclimatic indices obtained during the present cycle of investigations. The time series of these indices can serve as a testbed for assessments of the on-going vegetation distribution response to climatic changes and strengthen the reliability of projections of future vegetation productivity.

4. Conclusions

- Comparison of different modeled datasets and instrumental observations has revealed that the data on surface air temperature from ECMWF ERA Interim reanalysis (1989–2010) and the precipitation data from the APHRODITE JMA (1951–2007) dataset are consistent with observations made at Siberian weather stations.

- The latest changes (1991–2007) of surface air temperatures over Siberia include winter warming spots in its northern regions. In the last two decades, precipitation dynamics is less pronounced. It includes (a) a decrease in West Siberia, (b) a weak increase in East Siberia, and (c) no changes in precipitation intensity and in the number of precipitation days.

- Analysis of the latest dynamics of the growing season length, sums of the growing degree days within the growing season, and precipitation totals revealed a region in the south of West Siberia (55°–60°N, 59°–84°E), that is most favorable for net primary production increase.

- An archive of bioclimatic indices created during this study can serve as a basis for further detailed investigations of vegetation productivity dynamics and its response to climatic changes.

Acknowledgments

The authors acknowledge partial financial support for this research from the Russian Foundation for Basic Research (projects 10-07-00547a and 11-05-01190a) and the Ministry of Education and Science of the Russian Federation (contract 07.514.11.4044).

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