Regional tropospheric responses to long-term solar activity variations

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Abstract

The influence of ~200-year solar activity variations (de Vries cyclicity) on climatic parameters has been analyzed. Analysis of palaeoclimatic data from different regions of the Earth for the last millennium has shown that ~200-year variations in solar activity give rise to a pronounced climatic response. Owing to a nonlinear character of the processes in the atmosphere–ocean system and the inertia of this system, the climatic response to the global influence of solar activity variations has been found to have a regional character. The regions where the climatic response to long-term solar activity variations is stable and the regions where the climatic response is unstable, both in time and space, have been revealed. It has also been found that a considerable lag of the climatic response and reversal of its sign with respect to the solar signal can occur. Comparison of the obtained results with the simulation predictions of the atmosphere–ocean system response to long-term solar irradiance variations ($T > 40$ years) has shown that there is a good agreement between experimental and simulation results.

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1. Introduction

The investigations reported here were aimed at studying the effect of the ~200-year solar activity cycle (the so-called de Vries cycle) on climatic parameters in two Earth’s regions, i.e., Central Asia and the North Atlantic, during the last millennium and revealing regional responses to long-term solar activity variations. The investigations are important for several reasons. First, the ~200-year solar cycle is one of the most powerful solar cycles (Vasil’ev et al., 1999) and can be used as an example for considering the general problem of solar forcing of climatic parameters. Second, pronounced climate cyclicity with a period of 200 years has been revealed in a number of the Earth’s regions, such as Central Asia, and this cyclicity correlates well with solar activity (the correlation coefficient reaches 0.94) (Raspopov et al., 2005). Third, the North Atlantic region is characterized by a high temporal variability of climatic conditions, and it can be expected that the climatic response to long-term solar activity variations in it will differ from those in other regions of the Earth, and Central Asia, in particular. Fourth, a vast body of palaeoclimatic data with a high temporal resolution embracing centuries and millennia has been accumulated for these regions.

It should be noted that there is one more reason for the choice of the de Vries cycle for analysis of the effect of solar activity on climatic parameters. Estimates show
that internal periodicities in the atmosphere–ocean system do not exceed 60–80 years (Delworth et al., 1993, 1997; Polvakov and Johnson, 2000). Therefore, external forcing must exist to excite longer climatic periodicities. The external forcing for the 200-year climate oscillations is the de Vries cycle of solar activity, because no other external sources have been revealed in this range of periods.

2. Data and results

2.1. Solar activity

In order to analyze solar activity, we used the data on the 14C concentration in dated tree rings given by Stuiver et al. (1998). Fig. 1a shows results of a wavelet analysis (Morlet basis) of variations in the cosmogenic 14C isotope concentration in tree rings in the range of periods 100–300 years for the last 1500 years. These variations characterize solar activity oscillations because the 14C concentration is determined by the intensity of the cosmic ray flux modulated by solar activity. It can be seen from Fig. 1a that the ~200-year solar cycle was highly intense in the last millennium.

2.2. Palaeoclimatic data

2.2.1. Central Asia

Fig. 1 shows results of wavelet analysis (Morlet basis) of summer temperature variations for two regions of Tien Shan (Fig. 1b and c) and precipitation intensity on the Tibetan plateau (Fig. 1d) for the last millennium (Raspopov et al., 2005). The summer temperature variations in Tien Shan were reconstructed by two independent groups (Maksimov and Grebenyuk, 1972; Esper et al., 2003) by analyzing the tree ring widths of Juniperus turkestana. This juniper species grows at the altitudes higher than 2800–2900 m above sea level and its radial growth is precipitation-independent. Reconstruction of the variations in precipitation intensity on the Tibetan plateau was based on analysis of variations in tree rings of juniper Sabina przewalskii, whose radial growth is determined by the precipitation level at the site of its growth (Shao et al., 2005).

Comparison of Fig. 1a–d has shown that in the range of periods of around ~200 years the solar activity and climatic parameters in Central Asia behaved in a similar manner in the last millennium. To compare quantitatively the degree of correlation of Δ14C (radiocarbon concentration) variations and climatic oscillations in Central Asia, the initial data on Δ14C, variations in summer temperatures in Tien Shan and precipitations on the Tibetan plateau were filtered in the range of periods 180–230 years. For the curves filtered, the correlation coefficient between variations in Δ14C in the range of periods from 180 to 230 years and corresponding variations in summer temperatures in two regions of Tien Shan and precipitation variations on the Tibetan plateau were estimated to be 0.94, 0.73, and 0.84.

2.2.2. North Atlantic region

At present the palaeoclimatic data with the time resolution of one or several years are available for the North Atlantic region for the last millennium.

Northern Scandinavia. Finnish scientists have constructed a dendrochronological series embracing 8000 years for the Lapland region (Northern Finland). For the last 2000 years this series was given by Lindholm and Eronen (2000). Summer temperatures for Northern Scandinavia have been reconstructed on the basis of this series. Fig. 1e presents results of wavelet analysis (Morlet basis) of the reconstructed series of summer temperatures in the range of periods 100–300 years. It can be seen from Fig. 1e that the enhancement of ~200-year climatic variations occurred only in the second half of the last millennium and that during the preceding period their amplitude was low. Also, maximum correlation is found for a period longer than the conventional value of 200 years.

Svalbard. By using the data for the cores from Austfonna and Lomonosovfonna glaciers, Isaksson et al. (2005) plotted variations in relative concentrations of the 18O isotope (δ18O) in ice with nearly a one-year time resolution for the last 800 years. According to Isaksson et al. (2005), the δ18O variations reflect well the temperature variations in the Longyearbyen region on Spitsbergen and also temperature variations in the North of Norway in Vardö. Fig. 1f and g show results of wavelet analysis (“Mexican Hat” basis) of δ18O variations for Austfonna and Lomonosovfonna glaciers, respectively, in the range of periods of up to 256 years (Isaksson et al., 2005). It is evident from Fig. 1f and g that the amplitude of the ~200-year climatic variations increased only at the end of the last century, like in Northern Scandinavia.

Greenland. Of high importance for this region are the palaeoclimatic data that characterize variations in atmospheric circulation. Meeker and Mayewski (2002) carried out analysis of the wind-carried aerosols in the cores of Greenland ice from borehole GISP2 and performed classification of aerosols according to their source, i.e., the oceanic origin (sea salt sodium – ssNa) and continental origin (non-sea salt potassium – nssK). The time resolution of the samples was ~2.4 years. Analysis of variations in the concentration of these aerosols gives information on the prevailing type of atmospheric circulation during different time intervals. Meeker and Mayewski (2002) carried out spectral–temporal analysis of variations in the ssNa and nssK concentrations in Greenland ice for the last 1400 years. Results of analysis are shown in Fig. 1h and i. It is apparent that, in contrast to Svalbard and Northern Scandinavia, the ~200-year climatic variations are present during the entire 1400-year interval. However, around the 1400–1600s the character of the atmospheric circulation changed and about 400 years ago the export of continental aerosols (nssK) became prevailing and arrival of oceanic aerosols (ssNa) decreased. Possibly, it is just this change
in the atmospheric circulation that led to the increase in the amplitude of ~200-year climatic variations in the region of Svalbard and Northern Scandinavia in the second half of the last millennium. Existence of 200-year dust modulation in the GISP2 ice core has shown also by Ram and Stolz (1999).
3. Discussion

The results of wavelet analysis of climatic variations in the range of periods of the ~200-year solar cycle shown in Fig. 1 indicate that there exists a climatic response to a solar signal. In Central Asia the developments of climatic and solar variations have a high correlation coefficient (from 0.73 to 0.94). However, for the North Atlantic region the interrelation between climatic and solar periodicities is not so unambiguous. Greenland is characterized by a stable development of the ~200-year climatic oscillations, while an increase in the 200-year oscillation amplitudes on Svalbard and in Northern Scandinavia was reliably detected only for the second half of the last millennium.

The regional features of the climatic response to global forcing mentioned above can be interpreted from the standpoint of the nonlinear response of the atmosphere–ocean system to external forcing. Fig. 2a shows a map with the simulation predictions of the temperature response of the atmosphere–ocean system to long-term variations (T > 40 years) in solar irradiance (Waple et al., 2002). As can be seen from the simulation results, the same solar irradiance variations lead to both positive and negative temperature responses in different regions. In addition, there are border regions (for instance, the North Atlantic) where the response to long-term variations in a solar signal can be absent or change the sign. This situation occurred in the last millennium on Svalbard and in the north of Scandinavia (Fig. 1f and g). In our case these are 200-year variations. The crosses on the map (Fig. 2a) show the regions of Tien Shan and Tibetan Plateau for which the data on climatic variations are given in Fig. 1b and d. As can be seen, these regions are in the zone of a pronounced positive response to solar forcing. At the same time, Greenland is in the zone of a pronounced negative response to solar forcing. This is likely to be responsible for a pronounced manifestation of the 200-year climatic signal in the regions mentioned above, including Greenland, and a high correlation with the 200-year solar activity cyclicity. As follows from thermodynamic considerations, the differences in surface temperatures of such vast territories as Greenland and Eurasia must give rise to large-scale atmospheric circulation. Since the surface temperatures in these regions vary with the period of solar activity, the circulation processes

![Fig. 2. (a) Results of simulation of the spatial distribution of surface temperatures when the atmosphere–ocean system is affected by long-term solar irradiance variations (T > 40 years) (Waple et al., 2002). The asterisk (the North Atlantic region) and crosses show the sites the climatic data for which were used in our paper; (b) variations in annual average temperatures in the Northern Hemisphere for 1954–2003.](image-url)
will have a similar periodicity, i.e., ~200-year in our case. The existence of the ~200-year modulation of the aerosol concentration in Greenland ice is a direct manifestation of the circulation processes discussed.

Raspopov and Dergachev (2005) have shown that in the last century the climate was under the influence of the rising branch of the 200-year solar cycle. Therefore, it can be expected that climatic variations in the North Atlantic in the last century can be similar to the results of simulation shown in Fig. 2a. Fig. 2b presents the observed variations in surface annual average temperatures in the Northern Hemisphere for 1954–2003 (Impact of warming Arctic, http://www.cambridge.org; http://www.acia.uaf.edu). As it is evident, the general pattern of these variations in the North Atlantic region corresponds to the results of simulation given in Fig. 2a. Indeed, the regions of the North Atlantic are in the border zone of the positive and negative temperature trends for the last 50 years. Both on Svalbard and in Northern Scandinavia the variations in annual temperatures are not appreciable. At the same time, Greenland is characterized by a stable negative temperature trend.

The palaeoclimatic data for Greenland indicate that around the 1400–1600s there occurred a changeover of the atmospheric circulation regime for the climatic oscillations with a period of the order of 200 years. It is evident from comparison of climatic oscillation regimes in Greenland and Northern Scandinavia that, as mentioned above, after the 1400–1600s the amplitude of the 200-year oscillations in Northern Scandinavia increased. This means that the boundary of the positive climatic response to solar forcing moved northwards for this range of periods. It can be seen from Figs. 1e and f that the displacement of the boundary of the positive climatic response to solar forcing to higher latitudes reached the latitudes of Svalbard in 200 years after Northern Scandinavia, i.e., to the 1750–1800s. Thus, the positions of the boundaries of the regions with a stable and unstable climatic responses to long-term solar activity variations did not remain the same. This conclusion also follows from the simulation of the influence of solar irradiance variations with different periodicities on the atmosphere–ocean system. Waple et al. (2002) have shown that the regions of positive and negative climatic responses to decadal and secular variations in solar irradiance have different configurations. In addition, the configurations of these regions can change depending on the time of lag of the climatic response relative to the solar signal, which was confirmed by our analysis.

Fig. 3a shows results of wavelet analysis of summer temperature variations in Northern Scandinavia in the range of periods 50–300 years for the last 1500 years, and Fig. 3b presents variations in summer temperatures in Northern Scandinavia in the range of periods 163–276 years obtained by wavelet filtering (Morlet basis). In the bottom, the graph of expansion of Alpine glaciers in Central Europe is given (Haeberli and Holzhauser, 2003). Fig. 3b clearly demonstrates a sharp increase in the amplitudes of the ~200-year climatic variations beginning from the 1400s, which is confirmed by the wavelet analysis (Fig. 3a). It is important to emphasize that the curves of summer temperature variations in the north of Scandinavia and variations in the expansion of Alpine glaciers are similar for time interval mentioned. It is known that variations in glacier expansion follow deep solar activity minima (Wolf, Spoerer, Maunder, and Dalton) spaced by approximately 200-year (Haeberli and Holzhauser, 2003; Eddy, 1976). The major difference of the curves compared is the depth of modulation of the
variations in glacier expansion during the time interval before the 1400s: variations in glacier expansion in this time interval are deeper and more pronounced than temperature variations in Northern Scandinavia. This is likely to be due to the fact that Central Europe (Fig. 2a) is in the zone of a pronounced positive response of the atmosphere–ocean system to long-term solar forcing. Thus, a more detailed investigation of the climatic response to long-term solar activity variations has additionally confirmed that the North Atlantic belongs to the region where the climatic response considered can change its sign and intensity with time and along the Earth’s surface (Meeker and Mayewski, 2002). It should be noted in conclusion that the time interval of the 1400–1600s is the time of transition from the Medieval Temperature Optimum to the Little Ice Age, and the modification of the atmospheric processes in the North Atlantic is the reflection of the global change in the climatic processes during this time interval.

4. Conclusions

Analysis of experimental data and simulation results has shown that the climatic response to long-term solar activity variations has a regional character. In a number of regions, such as Central Asia and Greenland, this response is stable. At the same time, the North Atlantic region belongs to the zone of a weakened and ambiguous climatic response to long-term solar activity variations, including the 200-year ones. The configurations of the regions of a weakened climatic response to solar forcing and their geographical positions can change with time and depending on the atmospheric circulation character.

The regional character of the climatic response is due to a nonlinear nature of the response of the atmosphere–ocean system to solar forcing. In the 1400–1600s, a drastic change in the atmospheric circulation corresponding to the 200-year solar periodicity occurred in the North Atlantic region. This change in the atmospheric circulation is likely to be one of the manifestations of the global rearrangement of atmospheric circulation during the transition from the Medieval Climatic Optimum to the Little Ice Age.

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