

Spatiotemporal Scales of Warming Observed in Siberia

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The present climatic variations are caused by many factors of heliospheric, geospheric, biospheric, and anthropogenic origin. Their simultaneous account in mathematical modeling requires overcoming great difficulties related not only to computational procedures but also to the necessary verification of the modeling results. Although many of these difficulties have been overcome [1], further development of the theory of sensitivity of the models of climatic systems to small external forcing with regional peculiarities and the general regionalization of the existing climate models should enhance the significance of empirical data for individual regions of the planet. Moreover, the accumulated series of instrumental data on many regions of the planet exceed several times the needed time interval (30 yr), within which the average meteorological values characterize the climatic system. Statistical processing of such series allows us to verify the existing mathematical models not only for specific points of the calculated trajectory, but also for significant periods.

Preliminary studies of the scales of territories (spatial scales) and time periods (temporal scales), within which different dynamic characteristics of the climatic system have close values, are required to distinguish the possible regularities of the observed variations. During such investigations, the results of the analysis of instrumental data for vast continental territories, such as Siberia (approximately 10 mln sq. km), which is comparable in area with the entire European part of the Eurasian continent, are undeniably of interest.

In this paper, we describe the regularities of warming observed in Siberia, which characterize to the greatest extent the spatiotemporal scales of warming and simultaneously reflect the correlation of warming with the dynamics of global natural processes.

1. The scales of spatial inhomogeneity of warming observed in Siberia were determined from the results of the analysis of the linear trend of annual mean surface temperature. The linear trend was calculated on the

basis of the collected time series of monthly mean temperatures in the second half of the 20th century at 134 meteorological stations located in Siberia and the Far East [2]. The results of calculation were used to plot the contour lines of linear trends on the chart. Figure 1 shows a chart of spatial distribution of these trends in Siberia. Contour lines in this chart highlight the regions with different values of the trend over a period of 10 yr (different degrees of darkening) with a step of 0.1°C .

As seen from Fig. 1, the warming rate in the second half of the 20th century was sufficiently high over the entire territory of Siberia (more than 0.2°C for 10 yr) and very high in individual regions ($0.5^{\circ}\text{C}/10$ yr). Such regions can be called sources of enhanced warming. These mesoscale regions are confined first of all to East Siberia. As follows from the analysis of monthly mean temperatures, they are caused by a temperature increase in the winter months [2]. Comparison of the warming chart in Fig. 1 with the data of the Climatic Atlas of the USSR (1961) for 1881–1935 suggests that the zonality of the temperature regime in Siberia in the last decades became more even owing to the sources of enhanced warming. Dashed lines in Fig. 1 correspond to monthly mean temperatures in January (-28°C and -20°C) in the Climatic Atlas of the USSR. They divide Siberia into colder (north of the dashed lines) and warmer regions (south of the dashed lines). The dashed lines outline quite well the contour of regions with sources of enhanced warming.

The observed trend of leveling of the surface temperature zonality in Siberia can be explained by the evolution of atmospheric circulation in the last few decades. Indeed, analysis of spatial characteristics of the pressure field, which determines the regime of atmospheric circulation [3], showed that the pressure over virtually the entire territory of Siberia in the period under study decreased with a rate of 0.2 – 0.4 hPa/10 yr, which is sufficient for intensification of cyclonic activity [4]. Moreover, the analysis performed for each particular month showed that, like positive trends in the annual mean temperatures, negative trends in annual mean pressure are formed in the cold period of the year. This explanation agrees with data on the atmospheric circulation dynamics in the Northern Hemisphere, e.g., the increase in the index of meridional southern circu-

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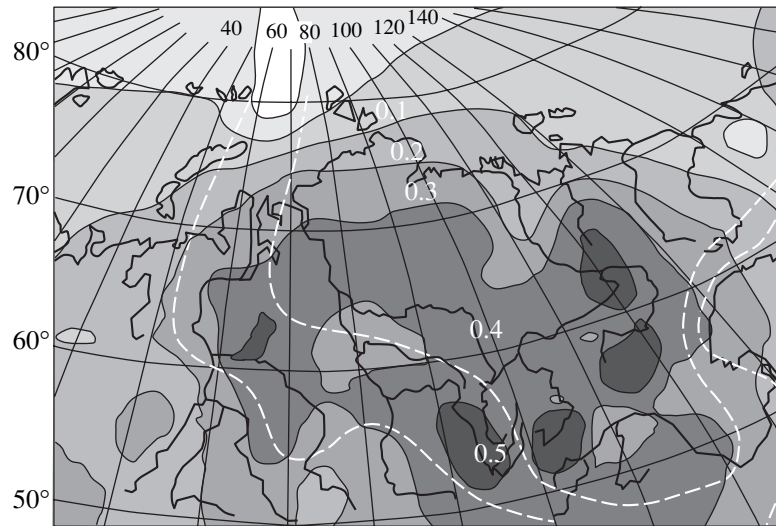


Fig. 1. Chart of linear trends of warming, 1965–2000. Comparison with contour lines for January (upper and lower lines denote -28 and -20°C , respectively) during the period from 1881 to 1935.

lation and decrease in the index of the northern circulation in the 20th century [5].

2. The scales of temporal variability of warming observed in Siberia were distinguished using the methods based on wavelet analysis, which demonstrated its efficiency in the processing of multiscale signals and fields [6]. Unlike the Fourier transform, we use in this case local basis functions, which allow us not only to determine the structure of the time series, but also to trace the dynamics of its components. The wavelet image of time series $X(t)$ was determined as

$$W(a, b) = |a|^{-1/2} \int_{-\infty}^{\infty} X(t) \psi^* \left[\frac{t-b}{a} \right] dt,$$

where ψ^* is the basis of the decomposition obtained using continuous scale transformations and transfer of the parent wavelet $\psi(t)$ with arbitrary values of the basic parameters (scale coefficient a and shift parameter b). Restrictions of this method related to the scales of time periodicities are determined by the so-called reliability triangle [6], which determines the maximal reliable scale up to $\frac{100}{2\sqrt{2}} \approx 30$ yr if the length of the time

series is 100 yr. The given estimate is correct for the family of DOG-wavelets, e.g., the Morlet wavelet, which was used as the basis for our analysis. At the chosen time sampling of the time series equal to 1 yr, the reliably estimated minimal scale of possible periodicities is equal to 2–3 yr.

In order to illustrate the obtained results of the analysis, Fig. 2 shows a wavelet spectrum of 120-yr-long time series for annual mean surface temperatures in Tomsk. In the coordinates with absolute values of the wavelet transform $|\text{Re}(W(a, b))|$ coefficient (Fig. 2), one can clearly see darker areas for periodicities with

higher amplitude. The observed regularities of warming are obvious compared to the time series for Tomsk shown in the upper panel of Fig. 2. In particular, it is evident that statistically significant periodicity scales in the time series analyzed here not only exist but also evolve. For example, quasi-decadal periodicities, i.e., periodicities with oscillation scales of 10 yr transformed into smaller periodicities with scales of 5–7 yr at the end of the 19th century and in the second half of the 20th century, remained constant only in the first half of the 20th century. Quasi-semidecadal (5 yr) and quasi two-year fluctuations are manifested only sporadically. In the 20th century, periodicities with scales of oscillations equal to 20–30 yr gradually transformed into periodicities with scales of 15 yr (and a decreasing trend) and 30–40 yr by the end of the century. Figure 2 and comparison of similar wavelet images of time series of surface temperature in several Siberian towns [7] show that transformation of statistically significant periodicities continued in the 20th century simultaneously in the entire Siberian region. This can be explained by the change in the role of global factors of climate formation.

3. In order to distinguish the role of the natural global processes in the transformation of periodicities of warming observed in the study region, we carried out a correlation analysis between wavelet spectra of annual mean temperatures in West Siberia and wavelet spectra of planetary indices, which characterize the atmospheric circulation, such as the North Atlantic Oscillation (NAO) and Southern Oscillation Index (SOI), as well as the index of solar activity (Wolf number). Such an approach seems preferable for the elucidation of long-range correlations as compared to the correlation analysis of time series, which is complicated by many factors of various scales.

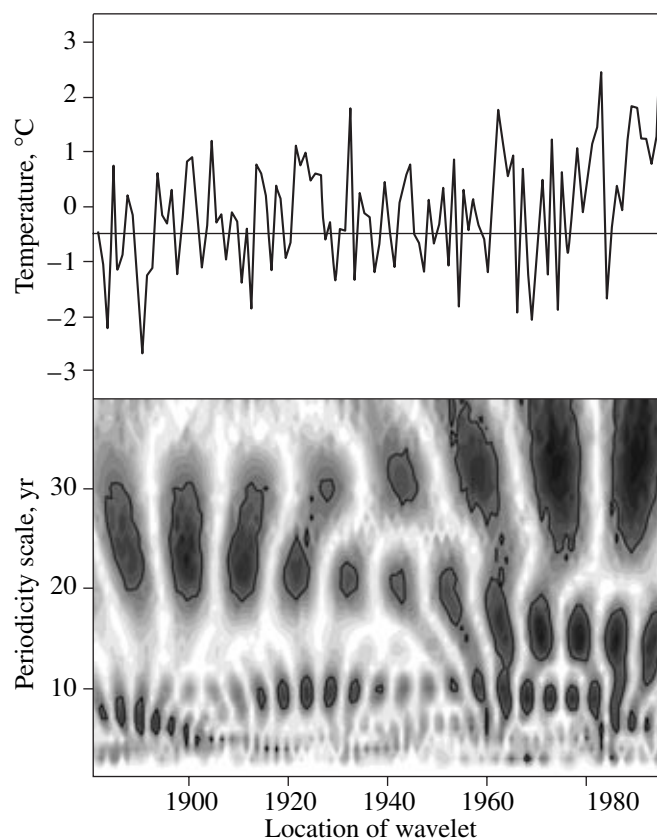


Fig. 2. Time series of annual mean temperature (upper panel) and its wavelet spectrum (lower panel) for Tomsk.

Figure 3 shows results of the wavelet correlation analysis for time series of the surface temperature and NAO index. The upper panel demonstrates temporal dynamics of correlation coefficients between periodicities of different scales. Statistically significant values of correlation coefficients (>0.3) are highlighted with different hatchings. The lower panel shows phase shifts for correlated periodicities (their values are also denoted by different hatchings). It is evident that phase shifts for periodicities of small scales (5–7 yr) are lacking; phase shifts for periodicities of medium scales (10–15 yr) are equal to 1–3 yr; and phase shifts for periodicities of greater scale (30–40 yr) increase to 7 yr.

The time correlation for solitary periodicity with a scale of 30–40 yr is of special interest among the obtained results. The distinguished periodicity with higher wavelet correlation in the 1940s–1980s can be considered a climatic phenomenon of this period. Taking into account the phase shift, the time of its beginning coincides with 1950, which was a turning point in the evolution of the general atmospheric circulation in the 20th century [3]. The time of its end coincides with 1980 [8]. Curves of the mean power of the solar cycle

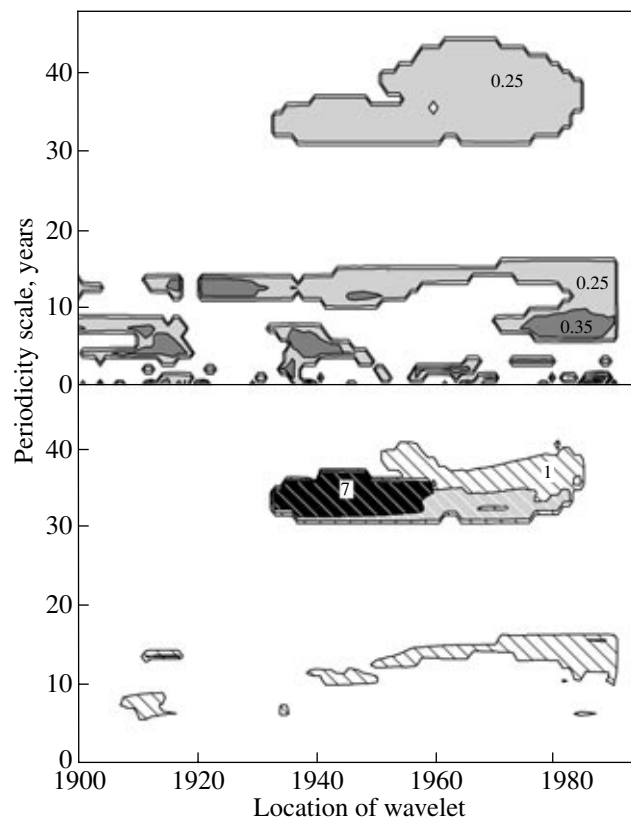


Fig. 3. Correlation of wavelet spectra between the annual mean surface temperature (T) and the NAO index: correlation coefficients of wavelet spectra (contour lines with a step of 0.1°) (upper panel); phase shifts for wavelet spectra (contour lines with a step of 2 yr, the maximal value is 7 yr) (lower panel).

and the Irkutsk surface temperature (averaged over the solar cycle), which were previously synchronous for a century, started to diverge after this year (see Fig. 11 in [8]). Coincidences between climatic events and the time boundaries of the phenomenon mentioned above are not incidental, but related to its nature. Long-term phase shifts point to a significant correlation between the warming observed in the region not only with low-inertia mechanisms due to the atmospheric circulation, but also with higher inertia circulations in the oceans.

Figure 4 presents the results of correlation wavelet analysis for other planetary indices (SOI and Wolf numbers). They confirm the notable influence of the global processes on the observed regional warming. It is seen that the correlation between Wolf numbers (Fig. 4, upper panel) is stable for periodicities of 10–12 yr. Higher values of the correlation coefficient in the 1960s correspond to the period marked by the climatic phenomenon mentioned above. It is seen in Fig. 4b that small-scale periodicities of a statistically significant correlation of wavelet spectra are manifested for the SOI index less frequently than for the NAO index (Fig. 4, lower panel). This is natural under conditions of the

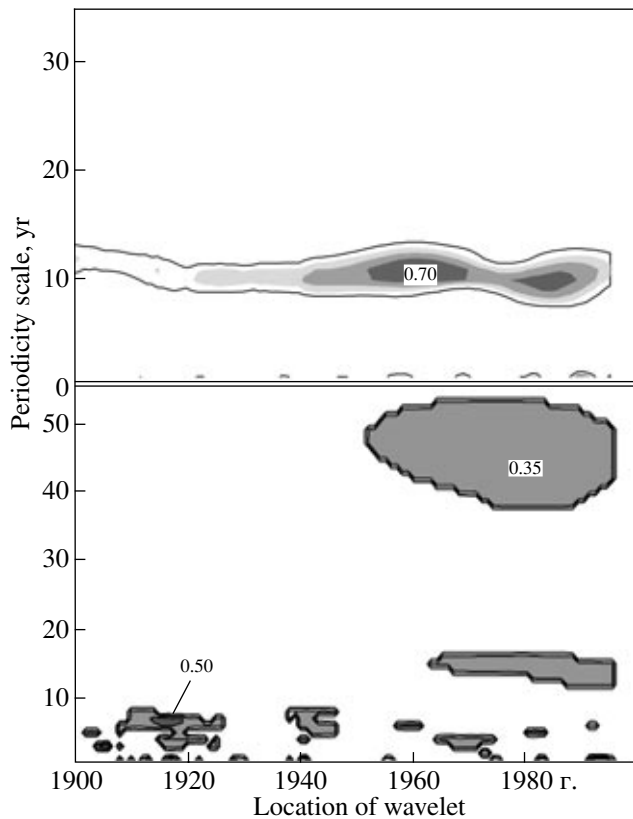


Fig. 4. Correlation of wavelet spectra between the annual mean surface temperature (T) and Wolf numbers (upper panel) and the SOI index (lower panel); darker areas correspond to higher correlation coefficients (the values are shown in the plot).

domination of westerly transport over the territory of West Siberia. At the same time, one can see stable correlation for both the large-scale periodicity and the NAO index at least in the region with the boundaries

shifted in time (in the 1950s–1990s) and scale (40–60 yr) relative to the correlation in Fig. 3.

In conclusion, we note that the analysis of instrumental data presented above revealed not only the spatiotemporal scales of warming in Siberia, but also several peculiarities in the correlations between surface temperatures in the region with planetary indices typical of global natural processes. The main peculiarities of these correlations are as follows: they are statistically significant only for certain time scales and time periods characterized by phase shifts for the correlated observation series. These peculiarities are of principal importance for modeling regional climatic systems and developing an empirical basis for such models.

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