Analysis of the structure of repetitive occurrence in time series of atmospheric circulation patterns and thunderstorms

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Periodic structures that show themselves in many-year series of the number of days with different atmospheric circulation patterns and with thunderstorm activity in Western Siberia and Kazakhstan in the period 1891–1996 are analyzed using the wavelet transform method. Most parameters exhibit long-term (greater than 18 years), medium (7–10 years), and short (2–6 years) periodicity. Relationships between peculiarities of the atmospheric circulation and thunderstorm activity are studied. Possible influence of the El Niño–Southern Oscillation phenomenon on the thunderstorm activity is discussed.

Introduction

The available instrumental data on numerous climatic characteristics attract more and more attention for revealing global and regional natural and climatic changes.[1] Interpretation of the revealed regularities is based on comparison of leading factors determining the observed changes in different regions of the planet.[2] In this paper, based on the study of periodic structures in time series, we compare the occurrence of atmospheric circulation patterns with the number of thunderstorm days at different geographic territories.

Atmospheric circulation is a very important climate-forming factor, and many-year variations of its types[3,4] affect zonal distribution of cyclonic activity, main cyclone paths, and, consequently, zonal distribution of many climatic characteristics, including the number of thunderstorm days at some or other territory. The below results of analysis of many-year series are concerned with the territory of Western Siberia in summer periods of 1891–1996.

Initial data and their processing

The Vangengeim classification of atmospheric circulation patterns[5] is the most convenient, because it is the result of generalization of various circulation mechanisms and allows the most significant climate changes to be revealed. According to the prevalent transport in the mid-latitude troposphere, three basic groups called western (W), eastern (E), and meridional (C) atmospheric circulation were separated. At the western circulation, low-amplitude waves quickly moving from the west to the east are observed in the troposphere. At C and E circulations, stationary large-amplitude waves are observed in the tropospheric depth. Their principal difference is that at C circulation an upper trough is formed over the European territory of Russia (ETR), Ural, and a part of Western Siberia (up to 80°E), and at E circulation a ridge is formed over this territory. Consequently, if E circulation prevails during a thunderstorm season, one can hardly expect a large number of thunderstorm days in Western Siberia and Kazakhstan. In this work, we used a catalog of monthly data about the number of days with some or other Vangengeim atmospheric circulation during the period 1891–1972 (Ref. 6) and similar data obtained in the Russian Hydrology & Meteorology Center for the more recent period.

To study variations of the thunderstorm activity, we used many-year data of visual observations of thunderstorms, namely, the number of thunderstorm days a year (T). The results discussed in this paper were obtained for southeastern territories of Western Siberia (Tomsk Region and Altai Krai), as well as northern, central, southern, and eastern parts of Kazakhstan. For investigation of variations of thunderstorm characteristics in Western Siberia, we used the data of 45 weather stations for the period 1936–1995 and three stations having about 100-year long observation series. For the Kazakhstan territory, we used the data of 74 stations for the period 1936–1985 and eight stations having 100-year and longer observation series. To reveal the periodic component in the series of many-year variation of the number of thunderstorm days, we applied the methods of the correlation theory of random processes and wavelet analysis.

Wavelet transformation of a one-dimensional signal consists in its expansion through scale changes s and shifts k in a basis constructed of a soliton-like function (wavelet) with certain properties. Every basis function characterizes both a certain spatial (temporal) frequency and its location in space (time). Formally, the wavelet transform of a discrete series X_n with the constant separation between the neighboring measurements δt can be written as a convolution of the series with the wavelet function ψ (Ref. 7):

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$$W_k(s) = \sum_n^{N-1} X_n \, \psi^* \left[\frac{(k-n)\delta t}{s}\right],$$

or

$$W_k(s) = \sum_n^{N-1} \hat{X}_n \, \hat{\psi}^*(s\omega_n) \, e^{i\omega_n k},$$

where

$$\hat{\psi}(s\omega_n) = \left(\frac{2\pi s}{\delta t}\right)^{1/2} \hat{\psi}_0[s\omega_n], \quad \int_{-\infty}^{+\infty} |\hat{\psi}_0(\omega)|^2 \, d\omega = 1;$$

asterisk * denotes complex conjugation; ^ denotes Fourier transform; ψ_0 is a basis wavelet function; N is the number of points in a series.

When constructing the wavelet transform $W_k(s)$ of a time series X_n, we used a Morlet wavelet well localized in the time and frequency spaces as a basis wavelet function.[7] In contrast to the Fourier transform, the wavelet transform provides a two-dimensional representation of the studied one-dimensional signal, and the frequency and shift are considered in this case as independent coordinates. Wavelet transformation can reveal singularities of the studied function. Thus, for example, the coefficients of wavelet transform of a smooth function are small, and they increase drastically if the functions have a singularity and show the position of this singularity by local extremes.

Analysis of many-year series for the presence of cycles

Analysis of occurrence of some or other atmospheric pattern may be important when looking for the causes for change in the thunderstorm activity over the territory under study in some or other period. Figure 1*a* shows the monthly mean occurrence of atmospheric circulation types in spring-summer (March–August) months of 1890–1995. It can be seen from Fig. 1*a* that *E* circulation prevailed in the period considered, although from the second half of the 1970s we can see a decrease in the number of days with this circulation. At the same time, a marked tendency to increase in the number of days with *C* circulation is seen. Comparing many-year behavior of the number of days with different types of circulation and the number of thunderstorm days a year for the same period, we see that the general tendency of the number of stormy days at the territory under study agrees rather well with the tendency of *C* circulation (Fig. 1*b*).

The periodicity in the series of the number of days with different types of the atmospheric circulation for March–August of 1890–1995 was sought using estimates of the autocorrelation function.[8] It was first found that the analyzed series are stationary with respect to both mathematical expectation and variance. The results are given in the Table.

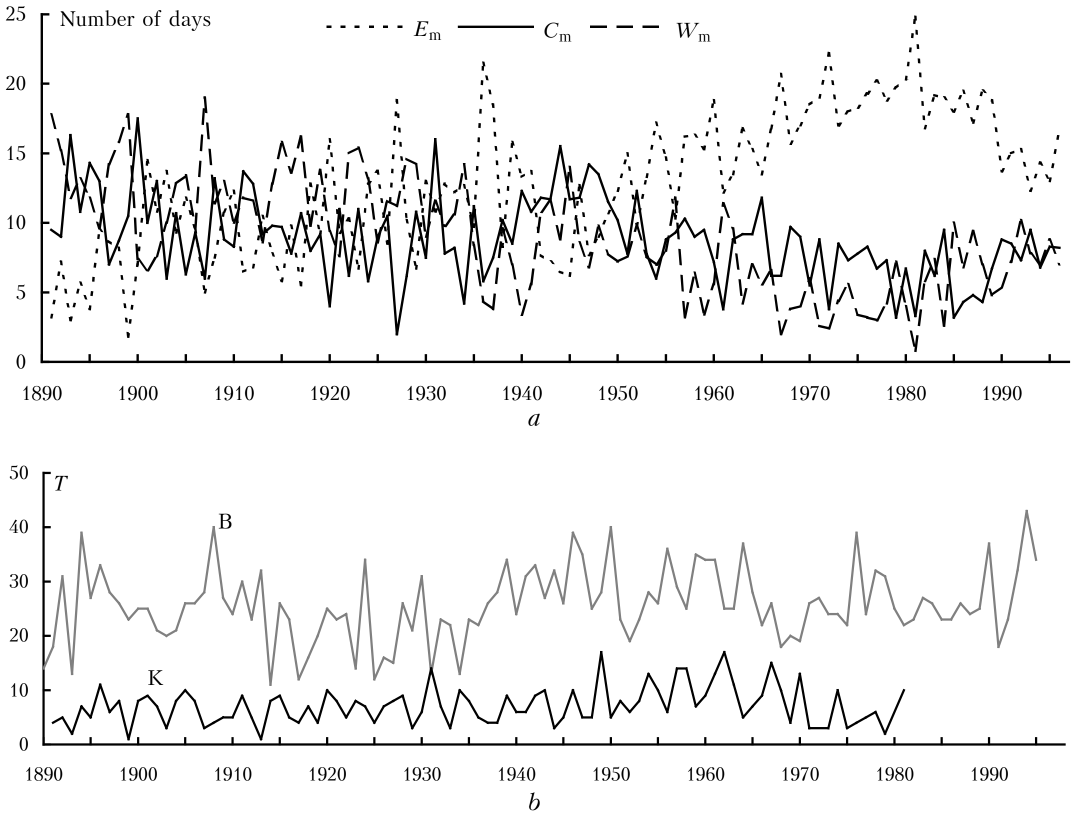


Fig. 1. Monthly mean occurrence (number of days) of atmospheric circulation types for March–August of 1890–1995 (*a*); number of thunderstorm days in the thunderstorm season of different years at Barnaul (B) and Kazalinsk (K) stations (*b*).

Table. Cyclicity (number of years) in atmospheric circulation series

Cycle duration, yr	Atmospheric circulation		
	E	*C*	*W*
Short (< 5)	2–4	2	–
Medium (5–20)	10–11	–	–
Long (> 20)	20–22, 25, 45–47, 50–52	20–22, 37, 41	20, 25

As can be seen from the Table, using the method of the autocorrelation function, we found the periods multiple to the periods of solar activity, and the most pronounced is the 22-year cycle, which manifests itself in the sign of sunspot magnetic field polarity. This cycle was also found in the series of air temperature,[9] pressure,[10] and so on. In the opinion of Vitinskii et al.,[11] alternation of the sun magnetic polarity is a more significant factor than the sunspot level causing the 11-year cycle, and therefore it is most pronounced in the meteorological series.

Wavelet analysis of the time series of atmospheric circulation revealed the following regularities:

1. The duration of some cycles remains constant throughout the time axis. In particular, all periods of activity of the western circulation in summer months are stable, and the cycle duration is characterized by the period from 10 to 20 years (Fig. 2*a*).

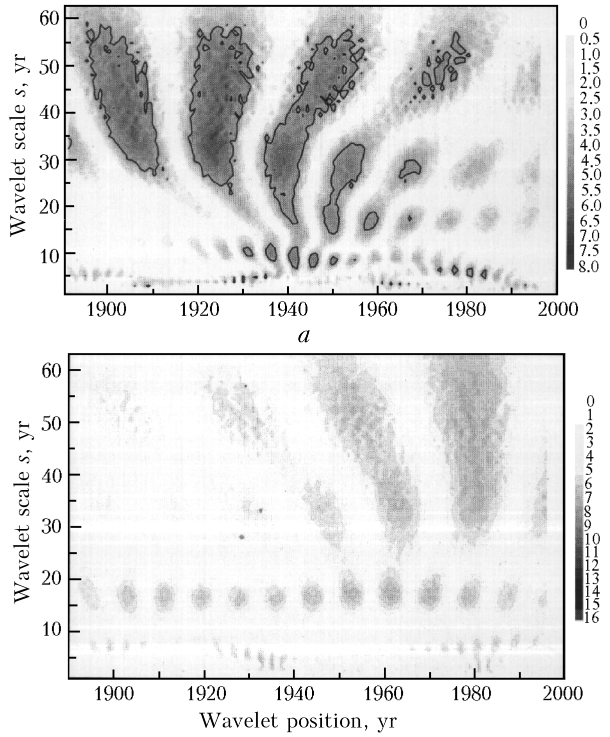
2. The amplitude of the cycles revealed is not constant throughout the time axis. This is especially a characteristic of the short- and medium-period cycles. Their amplitude in some decades of the period of interest may be 1.5–2 times higher than in the rest of the axis. The 33-year cycles (known as Bruckner cycles) are more pronounced in the amplitude. Climate parameters are characterized by this cycle almost all over the globe.

3. The eastern atmospheric circulation (Fig. 2*b*) is characterized by short-period (< 5 years), medium-period (7–8 years, 12–15 years), and long-period (25, 50 years) cycles. The highest amplitude is inherent in the semi-centennial cycle.

4. The meridional circulation is characterized by 3, 7–8, 10–15, and 45–50 year cycles. The semi-centennial cycle has the highest amplitude. However, in 1920–1935 the amplitude of the 5-year cycle was quite high as well. Besides, a spike of the 22-year cycle was observed in the 1940s.

5. As to the western circulation, 2–3, 8–9, 12–15, and 30 year cycles can be found in its time series. The about 20-year cycles are present in the data for the early twentieth century and after 1960. The highest amplitude is characteristic of the Bruckner 33-year cycle, but only in the period 1920–1940. Other cycles have comparable amplitudes. A feature of this circulation is the absence of semi-centennial cycles.

Wavelet analysis of the time series of occurrence of different atmospheric circulation patterns revealed not only cycles of different duration, but also the time location of their most pronounced manifestations, and thus allowed us to follow the change in various climatic characteristics in those periods.



b

Fig. 2. Amplitude spectra of wavelet transform of the number of days with meridional (*a*) and eastern (*b*) atmospheric circulation in June. The gray scale of the wavelet amplitude is shown to the right.

In the time behavior of the thunderstorm activity, short-, medium-, and long-period cycles with different duration over different territories were found based on the results of the earlier investigations[12] using estimates of the autocorrelation function. The 3–4-year cycle is most pronounced at all territories. The cycles with the periods of 5–6, 11–12, and 22–23 years, which are mainly associated with the solar activity, were found not for all regions.

Having analyzed the results of application of wavelet analysis to many-year series of thunderstorm activity, we can note the following.

1. The many-year variability of the thunderstorm activity is characterized by the cycles of short (3–4 and 5–6 years), medium (11–12 and 15–17 years), and long (22–25, 30, 50, and longer) periods.

2. The same cycles at some parts of the time axis may be more pronounced than at the rest of the axis. Thus, at the Semipalatinsk station (Fig. 3*a*), the 6–7-year cycle in the period 1960–1975 is more pronounced than in other years, while at the Tal'menka station this cycle is most clearly seen in the period 1955–1975.

3. At some stations (Taiga, Novyi Vasyugan (Fig. 3*b*), Kazalinsk), the duration of periods in the thunderstorm series smoothly decreases from 10 to 4 years and then smoothly increases up to 8–10 years. The shortest period falls on the 1940–1970s. These cycles are likely caused by reasons of the same genesis, but manifest themselves on the time axis with different periodicity.

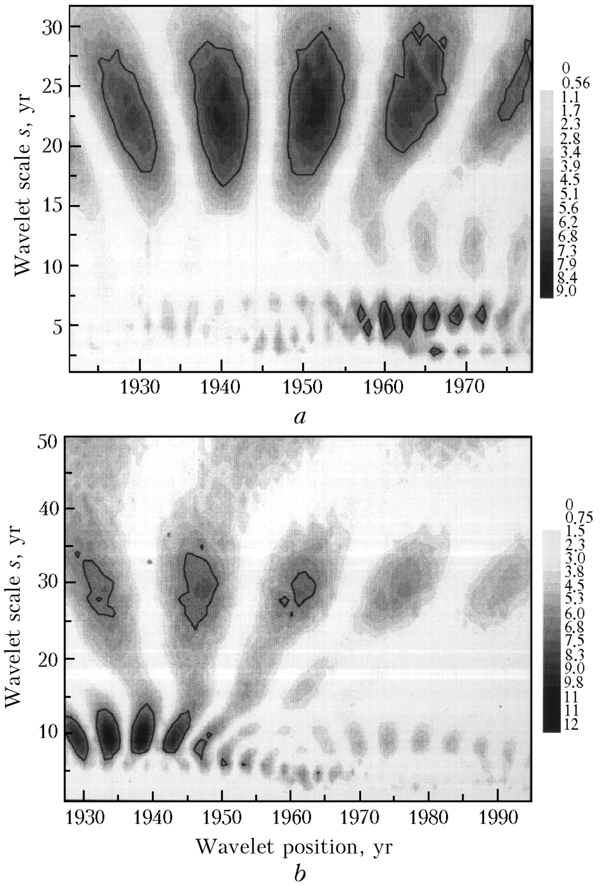


Fig. 3. Amplitude spectra of wavelet transforms of the number of days with thunderstorms at the stations Semipalatinsk (*a*) and Novyi Vasyugan (*b*). The gray scale of the wavelet amplitude is shown to the right.

4. It is important to note that the maximum in the thunderstorm activity over the territories of interest was observed in the 1950–1960, when peaks of several different-period cycles coincided, as can be seen from the above figures.

Results

Thus, applying different methods for revealing cyclic components in many-year series of occurrence of atmospheric circulation types and the number of days with thunderstorms over different territories, we found that these series are characterized by the presence of short-, medium-, and long-period cycles. In the atmospheric circulation series, the highest amplitude is inherent in 30–35-year and semi-centennial cycles. This fact is supported by the presence of synoptic epochs revealed earlier[3] that are characterized by prevalence of one type of atmospheric circulation for some decades.

In the thunderstorm activity, the high amplitude is characteristic of several cycles: 5, 10–12, and 30 years at the territory of Western Siberia and 6–8, 16–18, 30, and 50 years at the territory of Kazakhstan. Thus, the high amplitude of the Bruckner and semi-centennial cycles in the atmospheric circulation series is also clearly seen in the thunderstorm series. However, as to the amplitude, short- and medium-period cycles of the thunderstorm activity are more pronounced than those of atmospheric circulation, and the durations of these cycles are only roughly similar. Consequently, the presence of small- and medium-scale cyclic components in the thunderstorm series is caused by other reasons, though depending on atmospheric circulation peculiarities. They are connected, in the first turn, with characteristics of cyclones causing appearance and development of thunderstorms. Since cyclone occurrence and trajectories are caused by the seasonal temperature contrast and the structure of the high-altitude baric field, they can vary significantly in different synoptic epochs and cause variations of climatic norms.

Based on the data on occurrence of cyclones of different genesis that cause thunderstorms over the territories of interest, we revealed mostly short-period cycles (because the time series was no longer than 20 years). The results obtained suggest the conclusion that occurrence of cyclones of different genesis is characterized by cycles of different periods. The occurrence of cyclones formed over Western Siberia and Central Asia has only the short-period component (2–4 years), and the medium-period cycles (6–8 years) were found in the occurrence series of cyclones coming from the ETR.

Besides, it is known that the many-year behavior of the polar high-altitude frontal zone (PHFZ) follows quite accurately the behavior of the solar activity,[3] and thus it determines the cyclone intensity and, consequently, thunderstorm activity. To confirm this hypothesis, we determined the intensity of cyclones carrying thunderstorms to the studied territory. It turned out that in the years with maximal solar activity the mean intensity of all cyclones is doubled as compared to the years with minimal solar activity. Consequently, the presence of cycles multiple to 11-year solar activity cycles in the thunderstorm series is caused, most probably, by the PHFZ intensity and its position, rather than only the presence of the cycle with the same period in the atmospheric circulation series.

Conclusion

The results presented are obtained rather at the level of correlations than at the level of deterministic relations. Therefore, the regularities obtained cannot be still unambiguously interpreted. Nevertheless, it seems interesting to note the following.

First of all, it should be noted that the 3–4-year cycle in the thunderstorm series is caused, most probably, by cycles in occurrence of local and southern cyclones causing thunderstorms.

The cycles with periods multiple of the solar activity cycles manifest themselves in the thunderstorm activity through the cyclone intensity. Besides, in the years, when large baric formations most typical of the studied territory are active, they likely suppress neighboring formations. Therefore, in the years with the maximal solar activity, the thunderstorm activity increases over not all territories, but only where most intense cyclones move.

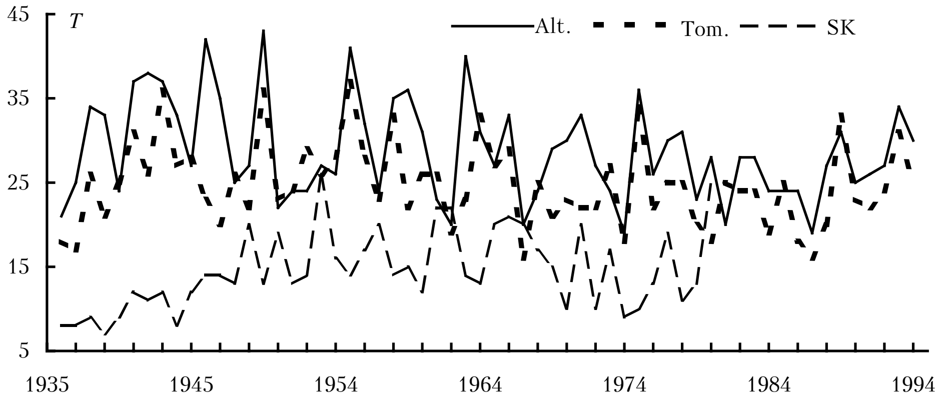


Fig. 4. Mean number of thunderstorm days at weather stations of the Tomsk Region (Tom.), Altai Krai (Alt.), and Southern Kazakhstan (SK).

The 7–8-year cycles of the thunderstorm activity over the studied territory are caused by occurrence of cyclones coming from the ETR. It is still impossible to say what is the cause of this cycle, but investigation in the last two decades showed that the most considerable and important signal in the interannual variations of many climatic characteristics is connected with the El Niño–Southern Oscillation (ENSO) phenomenon, which is observed with the periodicity of 2–7 years and induces statistically significant anomalies in different regions of the globe.

The relations between anomalies of meteorological fields and the ENSO phenomenon for different regions were intensely studied,[13] and they were revealed not only for the Pacific region, but for the whole planet. As to the territories studied in this paper, it was found[13] that one of the territories with high negative correlation between the time series of the Southern Oscillation index (SOI) and air temperature is located in Southern Kazakhstan and Central Asia. It is still hard to speak whether there is a possible effect of the Southern Oscillation on the thunderstorm activity at the territories under study, and if so, it shows itself through alternation of circulation processes favoring the appearance and development of thunderstorms.

It should be necessarily noted that in thunderstorm series of some stations the cycles of one period can transform smoothly into cycles of other, shorter or longer, period, that surprisingly coincide with the El Niño periods. A rather close agreement is also observed for the boundaries of crucial periods (for example, 1970), when the cycle period changes both in the series under study and in the El Niño series. At the same time, this manifests itself differently at different stations. If in 1920–1970 the El Niño cycle was 5–7 years, then such cycles in these years were revealed in thunderstorm series only for some stations (Barnaul, Zaisan, Novyi Vasyugan). At the Kazalinsk station, such cycles were noticed throughout the time axis since 1890, and at the Tal'menka and Atbasar stations they arose only in the 1950s. After the 1970s, the 7–8-year cycles at most stations (8 of 10) either had a low amplitude or were absent.

Comparing the plots of the thunderstorm activity for territories as a whole (Fig. 4), it is important to note that in the years of El Niño activity the thunderstorm activity was not very high, as a rule, over the territories of interest. Based on the above analysis it is hard to assert that the El Niño phenomenon certainly affects the thunderstorm activity over these territories, but we also cannot deny the possibility of such effect.

References

1. M.V. Kabanov, Atmos. Oceanic Opt. **15**, No. 1, 95–99 (2002).

2. N.V. Vakulenko, A.S. Monin, and Yu.A. Shishkov, Dokl. Ros. Akad. Nauk **371**, No. 6, 802–805 (2000).

3. M.Kh. Baidal, *Climate Variations in the Kustanai Region in the 20th Century* (Gidrometeoizdat, Leningrad, 1971), 154 pp.

4. A.L. Kats, *Seasonal Variations of the Global Atmospheric Circulation and Long-Term Forecasts* (Gidrometeoizdat, Moscow, 1960), 269 pp.

5. G.Ya. Vangengeim, Izv. Akad. Nauk SSSR, Ser. Geogr. Geofiz. **10**, No. 5, 405–416 (1946).

6. A.A. Girs, *Macrocirculation Method of Long-Term Meteorological Forecasts* (Gidrometeoizdat, Leningrad, 1974), 488 pp.

7. C. Torrence and G.P. Compo, Bull. Amer. Meteorol. Soc. **79**, No. 1, 61–78 (1998).

8. J.S. Bendat and A.G. Piersol, *Engineering Applications of Correlation and Spectral Analysis* (Wiley, New York, 1980).

9. V.F. Loginov, *Character of Sun–Atmosphere Relations* (Gidrometeoizdat, Leningrad, 1973), 48 pp.

10. M.Sh. Bolotinskaya, in: *Sun–Atmosphere Relations in Theory of Climate and Weather Forecasts* (Gidrometeoizdat, Leningrad, 1974), pp. 80–86.

11. Yu.I. Vitinskii, A.I. Ol', and B.I. Sazonov, *Sun and the Earth's Atmosphere* (Gidrometeoizdat, Leningrad, 1976), 352 pp.

12. V.P. Gorbatenko, Atmos. Oceanic Opt. **13**, No. 11, 951–954 (2000).

13. G.V. Gruza, E.Ya. Ran'kova, L.K. Kleshchenko, and L.N. Aristova, Meteorol. Gidrol., No. 5, 32–51 (1999).