Variability of subtropical jet stream in the troposphere of the Northern Hemisphere in the second half of XX century

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The spatiotemporal variability of the subtropical jet stream (SJS) speed was studied using NCAR/NCEP reanalysis data for 1948–2005. The subtropical jet stream manifests itself as the leading flow of the west-east circulation in the troposphere of the Northern Hemisphere. The speed of the SJS is shown to increase in the cold period of a year by 1 m/s per 10 years. Some meaningful tendencies in changes of latitude and height of the position of SJS axis were not revealed. Correlations of time series of the stream velocity and the series of indices of the North Atlantic and South Oscillations, Wolf numbers, and Earth angular rotation velocity were considered. The effect of the North Atlantic Oscillation on the SJS speed is significant in October–December, of the South Oscillation – in January–April. Negative correlation was found between the Earth angular rotation velocity and the jet speed for summer months. It is shown that the closeness of the correlation increases if not initial series are considered, but their wavelet spectra.

Since the air temperature gradient in troposphere is directed from the equator to poles, thermal wind is directed from the West to the East in both hemispheres. It is well-known that in high-altitude frontal zones, in which the horizontal temperature gradient between cold and warm air increases with altitude and wind speed at high-altitudes is very high, jet streams (JS) are formed on the axis with maximal wind speed equal to several kilometers per hour and an extent of several kilometers.

Depending on the types of air masses, separated by fronts, there are different JS in troposphere: arctic JS, JS of middle latitudes, and subtropical JS.[1] Subtropical jet stream (SJS) is observed in latitude region of 20–45°N, its axis is at a 12–14 km altitude (200–150 hPa). The wind speed at the axis can exceed 500 km/hour.[2]

A great amount of articles is dedicated to study of mechanism of the jet stream formation and spatiotemporal modes, the results of which are presented in monographs.[3,4] The authors of these monographs used the data on thermobaric fields and wind field, obtained with the help of the aerological sensing. The main disadvantage of such data is nonuniform distribution of sensing stations on the globe. Therefore, global fields of meteorological quantities obtained by reanalysis projects[5,6] are recently widely used in study of the atmospheric circulation processes. The main advantage of global reanalysis databases is spatiotemporal uniformity of output data.

The peculiarities of annual and seasonal variations of zonal atmospheric circulation with the use of wind circulation index, calculated along latitude circle have been investigated in Ref. 7. The NCEP/NCAR reanalysis data, as well as one of the versions of general atmospheric circulation models were used. It was revealed that for the surface at 200 hPa level, situated close to SJS axis, the characteristics of average zonal circulation in Northern and Southern Hemispheres were almost identical. As for some differences, seasonal migrations of SJS in Southern Hemisphere were somewhat larger than in the Northern Hemisphere. This refers also to the average seasonal maxima of zonal circulation. In the Northern Hemisphere subtropical jet stream is of apparent focal character with speed maxima at the south of Japan, the north of the Sahara, and over Florida.

The results of analysis of maximal wind levels in the Northern Hemisphere in summer seasons of 1958–2004 are presented in Ref. 8. The analysis was performed on the base of NCEP/NCAR reanalysis database. A tendency of maximum wind level lowering, reaching 30 hPa/10 years for some tropical and subtropical regions, was revealed. This tendency, related to temperature field restructurization in upper troposphere, was revealed, in particular, over Atlantics and West Africa.

New methodical approach to jet stream climatology was proposed in Ref. 9. This approach mainly deals with jet stream selection and their division into deeper and lower ones depending on the values of normalized shift of wind speed in a 200–500 hPa layer. This approach was used for both Hemispheres based on ERA-15 reanalysis data for 1979–1993. It has been revealed that in both

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Hemispheres annual JS cycle has a form of a smooth transition from a quasi-circular structure in summer to a helical one in winter. The difference of JS in both Hemispheres manifests itself by recurrence and meridian position of helical structures.

In Ref. 10 daily data of NCEP/NCAR reanalysis for 1948–2003 were used for the study of stream modes and low-frequency oscillations of the average zonal flow over Northern Hemisphere in winter. Deviations from average zonal values of zonal and meridian components of wind speed were analyzed. Intermonth oscillations of zonal flow with periods of 172 and 72 days were revealed. These periods were connected with the change of JS position and intensity.

In this paper, the spatiotemporal variation of subtropical jet stream characteristics for the period of 1948–2005 is considered and some connections are revealed between speed at JS axis with North Atlantic Ocean (NAO) and South Ocean (SOI) oscillations, solar activity oscillations, which are characterized by Wolf numbers (W), as well as with the Earth rotation angular velocity (Ω).

As the initial data, we used:

– NCEP/NCAR reanalysis databases for 1948–2005 (17 isobaric surfaces from 1000 to 10 hPa on a grid with 2.5×2.5° step by latitude and longitude) (http://www.cdc.noaa.qov/PublicData);

– data on nutation and Earth rotation speed change (http://hpiers.obspm.fr/eop-pc/ index.html);

– NAO, SOI geographical indices (http://www.cqd.ucar.edu/cas/jhurrell/indices.html);

– Wolf numbers (ftp://ftp.nqdc.noaa.qov).

Spatial-temporal characteristics of SJS

Figure 1 presents distributions in the meridian plane of zonal component of wind speed, averaged over time and latitude circles at different atmospheric levels from 1000 to 10 hPa for January and July, as well as their linear trends for 1948–2005.

A 30 m/sec isotach is considered as a border separating the jet streams. Midlatitude jet streams, observed at 40–60°N at 300 hPa level are not revealed at such scales of averaging. This is connected with high mobility of midlatitude JS and, consequently, their low repetition at a certain latitude. However, according to reanalysis data, these jet streams can be definitely distinguished in the analysis of a certain season and year.

As is seen in Fig. 1, averaged vertical position of SJS axis for many years corresponds to 200 hPa level. Average position of the stream in January is over 30°N and in July over 45°N. Averaged speed of stream axis is 35 m/sec in January and 16 m/sec in July. This dynamics is connected with seasonal transformation of the atmosphere thermobaric field.

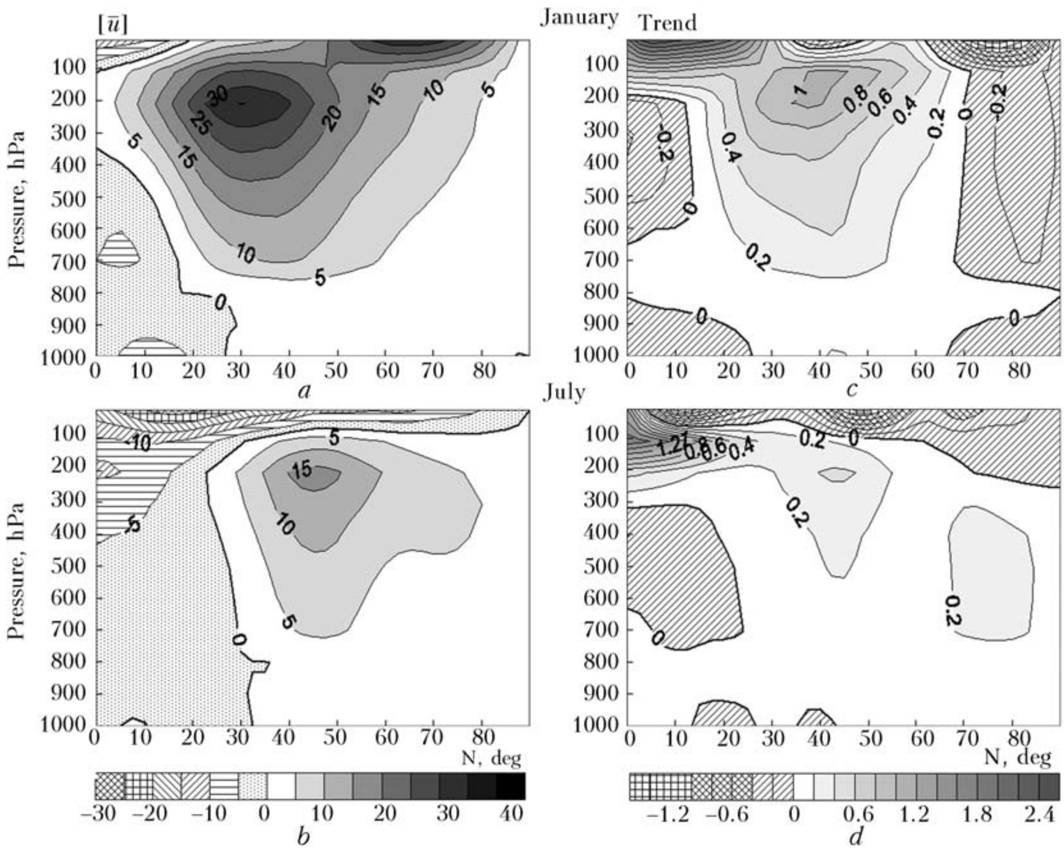


Fig. 1. Zonal component of wind speed averaged over time and latitude (m/sec) (*a* – January, *b* – July) and its trend (m/sec for 10 years) for 1948–2005 (*c* – January, *d* – July).

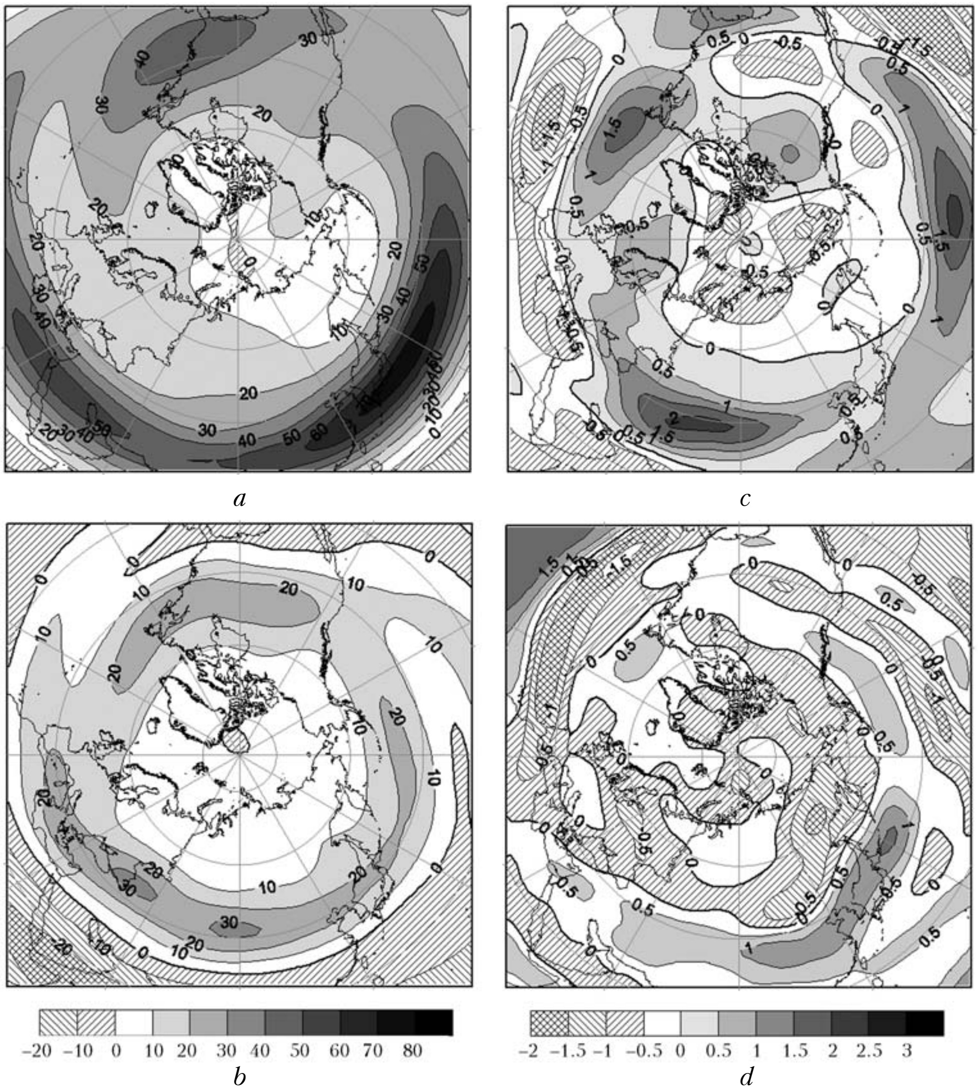


Fig. 2. Distribution of time-averaged zonal component of wind speed (m/sec) along latitude circles at 200 hPa surface (*a* is for January, *b* is for July) and the corresponding trends (m/sec for 10 years) (*c* is for January, *d* is for July).

Temperature gradient "equator–pole" has its maximum in cold season, decreasing in summer due to continent heating.

Distribution of wind speed trends indicates a general tendency of west transport intensification, which is the highest in winter period. The wind speed on SJS axis increases by 1 m/sec for 10 years in January and by 0.4 m/sec for 10 years in July. At the same time, circulation at 10–200 hPa level, i.e., in the lower troposphere, significantly varies in January. In summer period, the tendency of West wind attenuation both as equatorial jet stream and winter cyclonic polar vortex attenuates. In summer the tendency of East wind attenuation is observed only in equatorial atmosphere between 200 and 100 hPa, while the east circulation intensifies in moderate and polar latitudes.

Distribution of time averaged wind component $\bar{u}$ along latitude circles on a 200 hPa surface and distribution of the corresponding trends are shown in Fig. 2. The pattern of spatial distribution of $\bar{u}$ corresponds to the pattern obtained in Refs. 7 and 9.

In winter time the maximal speed of west wind in the Eastern Hemisphere at an 200 hPa level is observed in 25–30°N over the Arabian peninsula (with the speed up to 55 m/sec) and in north-west part of Pacific Ocean (the speed up to 75 m/sec). Jet stream attenuates in eastern part of Pacific Ocean (down to 26 m/sec) moving toward the south (22°N). In the Western Hemisphere, the maximal speed on the axis of jet stream is achieved at north-east of the Atlantic Ocean, i.e., Sargasso Sea (up to 46 m/sec). Above the east coast of Atlantic Ocean, the wind speed decreases down to 22 m/sec and on the maps of average many-year wind the jet stream bifurcates. The southern part of the stream goes at 15°N and the northern one at 50°N.

In summer months the speed of zonal transport decreases and the axis of jet stream moves toward the North to 40–45°N. In July, the maximal wind zone (speed up to 26–32 m/sec) moves from Mediterranean Sea through Caspian Sea and Kazakhstan to Gobi desert (China).

The zone of eastern winds exists in equatorial latitudes during the whole year. In January the eastern transport is observed in Eastern Hemisphere up to 10°N. The wind speed in the equator region does not exceed 15 m/sec. The eastern transport intensifies in July covering latitudes to 30°N. In July, eastern winds over Arabian Sea achieve 25 m/sec.

Distribution of wind speed trends in Fig. 2*c, d* indicates that the wind intensifies in the areas of its maximal values and a tendency of movement of these areas toward the east is observed.

Correlation analysis of time series

For further consideration, time series of zonal-averaged wind speed component on horizontal axis of jet stream at 200 hPa level were formed. Averaging was performed both for latitude circle and latitude segments, corresponding to European (0–60°E), Siberian (60–120°E), Far East (120–180°E), Pacific (120–180°W), American (60–120°W) and Atlantic (0–60°W) sectors. Further, lateral correlation of the series, obtained by this method, of wind speed ($[u]$), time indices of North-Atlantic oscillation, South oscillation, Wolf numbers, and angular rotational velocity of Earth were calculated.

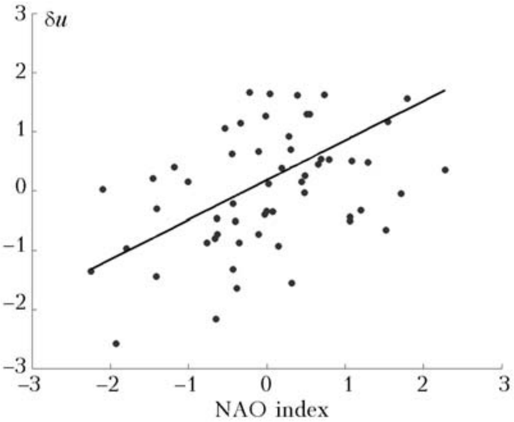
The results of correlation analysis for wind speed zonal component $[u]$ averaged over latitude circle on the jet stream axis are presented in Table for each month and for a year on the whole. Correlation coefficient values statistically important with a 90% confidence probability were revealed.

Table. Correlation coefficients between series of longitude-averaged wind speed on JS axis (200 hPa) and series of geophysical indices

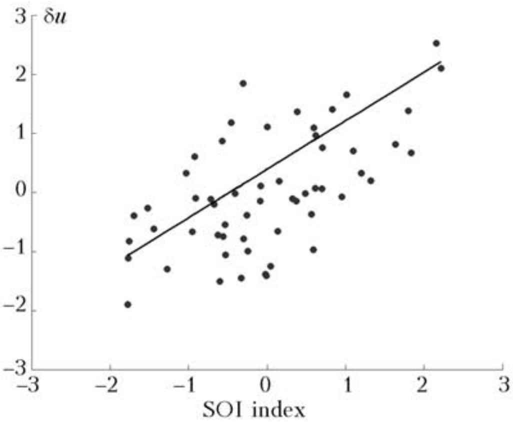
Month	NAO	SOI	W	Ω
1	0.11	**0.3**	0.25	–0.01
2	–0.1	**0.49**	0.03	–0.03
3	–0.1	**0.41**	0.15	–0.09
4	–0.08	**0.38**	–0.01	–0.16
5	–0.05	–0.03	–0.09	0.07
6	–0.15	0.04	0.2	**–0.31**
7	0.12	0.17	–0.03	**–0.3**
8	0.11	0.08	–0.1	**–0.45**
9	**0.42**	–0.26	0.07	–0.2
10	**0.42**	–0.16	–0.15	0.01
11	**0.3**	0.12	0.05	0.07
12	0.05	0.00	–0.23	–0.05
Year	–0.09	0.17	–0.08	–0.24

It is seen that significant positive (though not very close) relation of averaged zonal component of wind on the jet stream axis with NAO indices exists in the period from September to November. This relation also exists in October–January period in the European sector. Southern oscillation is significantly connected with $[u]$ from January to April; therewith, the closeness of the relation significantly increases (up to 0.62) in the Pacific sector.

Figure 3*a* shows the connection of variations of zonal component of the wind speed on the jet stream axis $\delta u = (u - \bar{u})/\sigma_u$ (σ_u is the standard deviation) with values of NAO indices for the succession of January months in 1948–2005 in the European sector. Figure 3*b* shows the similar relation for pairs of values of δu and SOI indices for January months in 1948–2005 in Pacific sector.



a



b

Fig. 3. The relation between monthly averaged values of wind speed zonal component and monthly averaged values of geophysical indices. January: *a*) δu – NAO, European sector; *b*) δu – SOI, Pacific sector.

It follows from Fig. 3*a* that a prolonged NAO phase is connected with wind speed increase on SJS axis in European sector in cold season. As it is known,[11] in this case a deepening of the Iceland minimum, and intensification of the Azores maximum take place, as well as trajectories of cyclone shift towards the North of Europe, being the cause of mild winters in this region. In the negative NAO phase, the speed of wind on SJS axis decreases, the Iceland minimum is filled, the Azores maximum attenuates, cyclone trajectories acquire a zonal character, and European winters become more severe.

In the Pacific sector in cold period, the speed of wind on JS axis increases in positive phase of SOI index (Fig. 3*b*) and decreases in the negative phase. It is well-known that these phases correspond to El-Nino and La-Nino phenomena, during which the surface temperature of the eastern part of Pacific Ocean increases (El-Nino) and decreases (La-Nino) by approximately 2–5°C relative to the climatic standard.

The corresponding increase or decrease of air temperature over ocean surface intensifies or attenuates “equator–pole” thermal gradient, causing changes of wind speed on SJS axis shown in Fig. 3*b*. The similar dependence of the indices of circulation along the latitude circle was revealed in Ref. 12. Table shows the absence of correlation of wind speed on SJS axis with Wolf numbers, which characterize the variation of the solar activity.

As for the connection between SJS speed and angular velocity of the Earth rotation, it shows a significant anticorrelation during June–August, i.e., in the period, when the position of the stream is shifted to higher latitudes. Disturbing influence of irregularity of the Earth rotation on the atmospheric circulation is discussed in Ref. 13, where the change in the Earth rotation velocity causes a change in atmosphere rotation velocity and, consequently, a redistribution of air masses among polar and tropical latitudes. With the increase of the Earth rotation velocity the pressure decreases in moderate and polar latitudes and increases in subtropical maximum. An opposite pattern is typical for the Earth rotation velocity decrease. Additional inter-latitude barometric gradient is equal to 6.7 hPa [13] due to many-year quasiperiodical changes of Earth rotation angular velocity.

For comparison, the values of baric surface pressure gradient, obtained by a standard midlatitude model of the Northern Hemisphere can be presented.[14] According to this model, pressure difference between 30 and 60°N is 7 hPa in December–January and 4 hPa in June–July. These estimates show that in summer period thermal-conditioned “equator–pole” pressure gradient attenuates, thus simplifying the appearance of additional pressure gradient in SJS speed, for example, conditioned by the Earth rotation velocity variations. Variation directivity of additional gradient provides for the anticorrelation of $[u]$ and Ω.

Correlation analysis of wavelet-spectra

It is known[15] that actual climatic series in some frequency bands have oscillations, which can be regarded as nearly harmonic either all along the series or along individual time intervals. The frequency ranges, in which these oscillations occur, can be found by the Fourier transform. However, wavelet transform method is much more efficient in this case, because it allows one to follow the oscillation evolution along the whole time axis.

We used this method for analysis of low-frequency oscillations in the series of wind speed on SJS axis, geophysical indices, and finding statistical relations between these oscillations. The analysis procedure was the following: time series of wind speed on the SJS axis, NAO and SOI indices, Wolf numbers, and angular velocity of the Earth rotation for 1948–2005 underwent the wavelet transform with the use of a high quality parent Morlet wavelet.[16]

Using the obtained matrices of wavelet transformation coefficients, we calculated the coherence matrices, which reflect temporal dynamics of connection between oscillations in wind speed series and oscillations in other index series. Scale-averaged values of the coherence coefficients, i.e., average values of coefficients throughout the time series, were calculated on the basis of these matrices.[17] The integration was conducted in narrow regions, centered at oscillation scales of 5, 7, 11, 15, 22, and 30 years. We chose these scales, because they are often used in spectral analysis of different climatic series.[17] The wavelet-spectrum of zonal-averaged wind speed on SJS axis indicates the presence of oscillations throughout 5–30 year scale. The most stable are quasi-decennial and 20–25-year scale oscillations. On the whole, the spectrum indicates non-stationary character of oscillation processes

Coherence matrices, which characterize the relations between the oscillations in Wolf numbers and zonal averaged wind speed on SJS axis series for January (*a*) and July (*b*) are presented in Fig. 4.

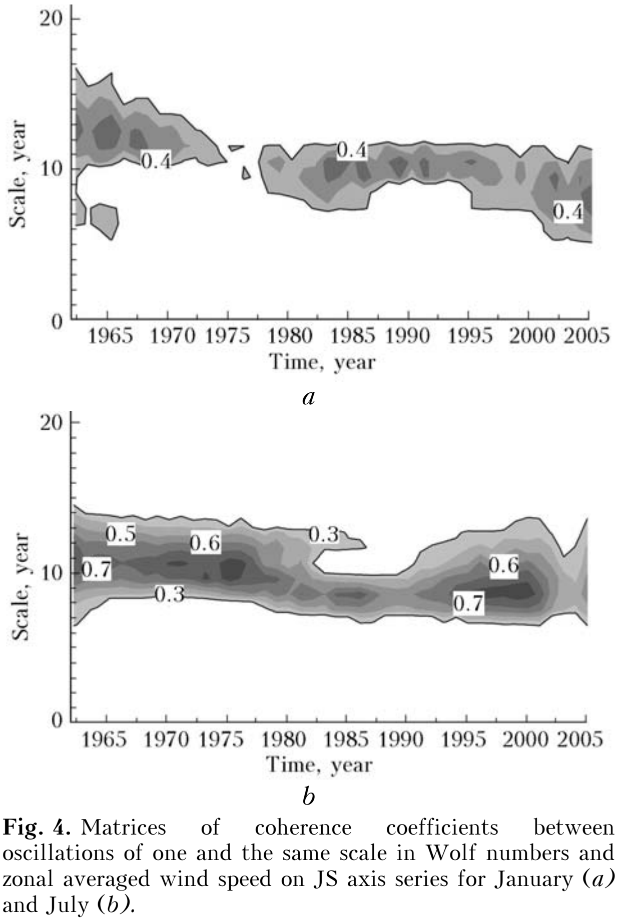


Fig. 4. Matrices of coherence coefficients between oscillations of one and the same scale in Wolf numbers and zonal averaged wind speed on JS axis series for January (*a*) and July (*b*).

Although the correlation of initial series (see the Table) does not manifest itself, the correlation of "inner" 11-year structures in both series is quite high in all seasons with average coherence coefficients changing from 0.3 to 0.63 in different months. As it is seen in Fig. 4, local values of coherence coefficients can be significantly higher. The relation between 11-year solar activity cycle and inner oscillating structure of such scale of SJS speed can not be easily explained.

At present, different mechanisms are used in explanation of solar-troposphere relations.[18] The dynamic mechanism, first proposed in Ref. 19, is most suitable for our study. It is based on the fact that the energy, which appears in troposphere during meteorological phenomena, propagates upward by gravity waves and then is reflected from upper atmospheric layers under certain conditions. The reflected waves interfere with the waves propagated upward; such being intensified or attenuated, that leads to intensification or attenuation of the wave source. Thus, the upper atmosphere is a modulator of tropospheric processes.

In our case, the JS kinetic energy can be the wave energy source (Rossby waves). A part of this energy is transported upward by waves and if the conditions for wave transmission or reflection periodically occur in stratosphere during the 11-year cycle, the relation indicated in Fig. 4 can be explained.

The potential existence of such mechanism is proved by the results of numerical modeling of winter stratosphere circulation.[20] It turns out that during attenuation of a vortex in lower stratosphere the upward wave propagation ceases, retrieving with the vortex restoring. Thus, the lower troposphere acts as a valve, which either lets the wave beam go into stratosphere or blocks it, depending on the state of the vortex.

The relations of stream speed oscillations with those in the NAO and SOI series of indices are of a more complicated character. This character is closer for NAO ($r > 0.4$) at scales of 7, 15, 22 years oscillations, for SOI at scales of 5, 7, and 15 years oscillation.

Conclusion

Thus, variability of SJS characteristics appear to be related to variability of climatically significant planetary geophysical indices. Thermobaric field deformation on different levels of troposphere and stratosphere is the uniting mechanism of such relation. This deformation occurs at different types of the considered connections leading to the variation of horizontal baric gradient. As for the relations to North-Atlantic and southern oscillations, such deformation, caused by changes of centers of action is quite evident. A detailed mechanism of influence of solar activity variations and Earth rotation angular velocity on SJS characteristics is to be further studied.

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