LONG-TERM VARIABILITY OF SOLAR ACTIVITY AND COSMIC RAY EFFECTS ON THE LOWER ATMOSPHERE CIRCULATION

S.V. Veretenenko[1] and M.G. Ogurtsov[1,2]

[1]Ioffe Physical-Technical Institute RAS, St.Petersburg, 194021, Russia,
e-mail: s.veretenenko@mail.ioffe.ru;
[2]Central Astronomical Observatory at Pulkovo RAS, St.Petersburg, 196140, Russia

Abstract. In this work we studied the spatial and temporal distribution of long-term effects of solar activity (SA) and galactic cosmic rays (GCR) on the lower atmosphere circulation as well as possible reasons for the peculiarities of this distribution. The results of this study show that the SA/GCR effects on pressure variations in the lower troposphere are characterized by a strong regional variability which depends on the specific features of the atmospheric circulation in different regions. The distribution of the correlation coefficients between the pressure variations and sunspot numbers/GCR intensity was found to be determined by the climatic positions of the main atmospheric fronts. The most pronounced pressure changes associated with SA/GCR variations were detected in the areas of formation of the main elements of the large-scale atmospheric circulation (namely, the polar vortex at high latitudes and the polar frontal zone which is a region of intensive cyclogenesis at middle latitudes). It was also shown that the SA/GCR effects on pressure in the high-latitudinal region reveal a dominant 60 yr periodicity which seems to determine the atmosphere response to solar activity and GCR variations at middle and low latitudes. The detected changes in the sign of the SA/GCR effects on pressure variations in different regions were found to correlate with the changes in the large-scale circulation epochs which in turn may be caused by a long-term solar variability.

1. Introduction

Studies of solar-atmospheric links are of significant importance to understand the reasons for the Earth's climate variability and to forecast its future evolution. Importance of this problem has increased noticeably in recent years because of a lively discussion of the causes of Global Warming. However, it is known that the links observed between solar and climatic characteristics reveal instability both in time and space that sometimes gives rise to doubt a reality of solar activity influence on atmospheric processes. The aim of this work is to study the spatial and temporal distribution of long-term effects of solar activity (SA) and galactic cosmic rays (GCR) on pressure variations in the lower atmosphere and to consider possible reasons for the peculiarities of this distribution.

2. GCR effects on the troposphere pressure according to NCEP/NCAR 'reanalysis' data

As experimental base of this study we used the geopotential heights of the 700 hPa pressure level (GPH700) from NCEP/NCAR 'reanalysis' archive [Kalnay et al., 1996] for the period 1948-2006. To characterize the intensity of GCR fluxes, the data on the neutron monitor (NM) counting rate in Climax (geomagnetic cut-off rigidity 2.99 GV) were taken from ftp://ftp.ngdc.noaa.gov/STP/.

The distributions of the correlation coefficients between the mean yearly values of GPH700 (heights ~3 km) and GCR intensity *R(GPH700,NM)* are shown in Fig.1 for two different periods. The data presented demonstrate that the pressure changes associated with GCR variations are observed over the entire globe. However, we can see a strong regional and temporal dependence of the GCR effects. For both periods under study several large areas of positive and negative correlation are very distinctly manifested. Let us consider the distribution of the correlation coefficients for the period 1982-2000 (top panel) taking into account the climatic positions of the main atmospheric fronts according to [Khromov and Petrociants, 1994]. We can distinguish the following main regions:

1) The high-latitudinal region of positive correlation coefficients (*R(GPH700,NM)*~ 0.6-0.7, with the confidence level $P \geq 0.99$) in the Northern hemisphere. The boundaries of this region coincide with the climatic Arctic fronts separating cold air masses forming at high latitudes from warmer air masses of middle

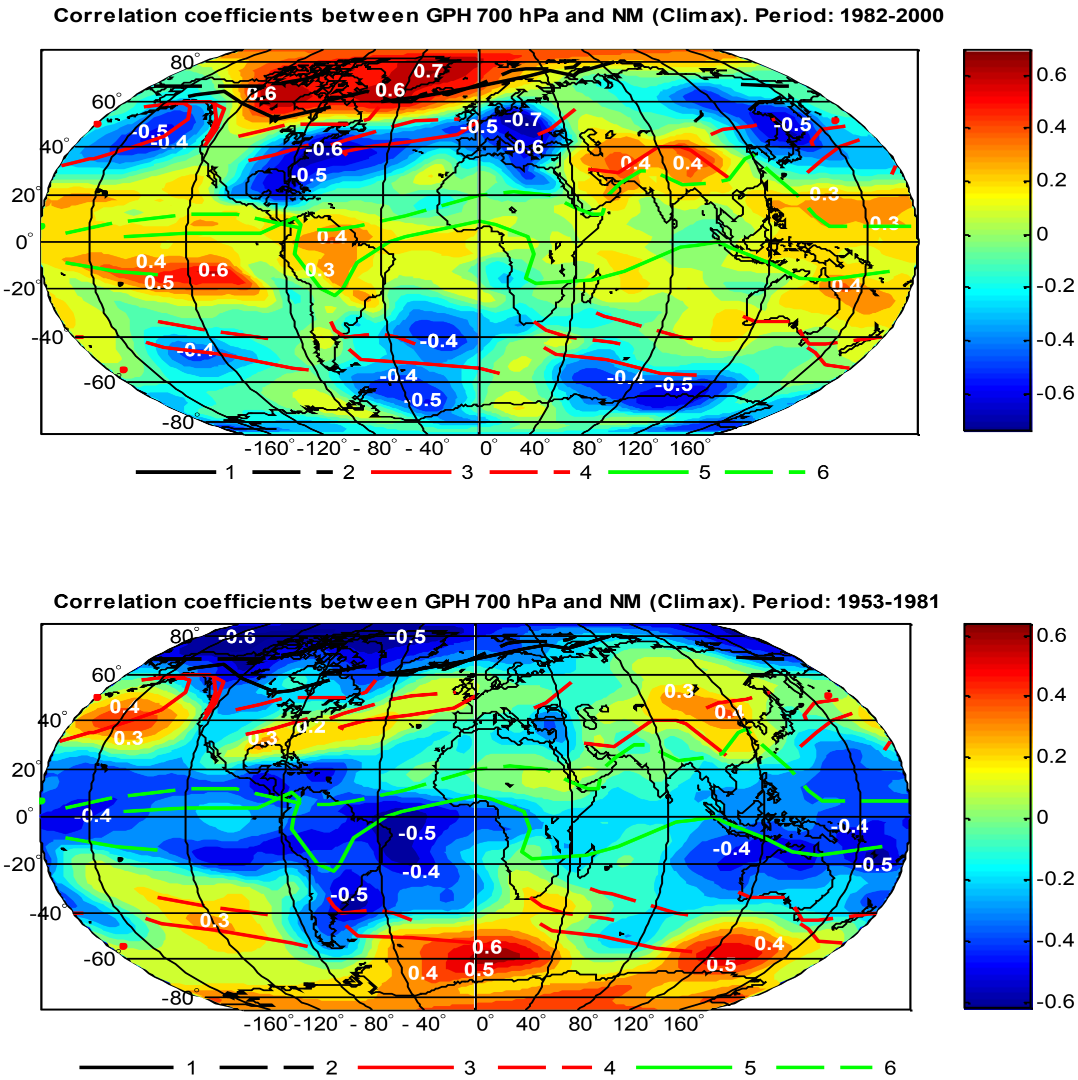

Fig.1. Global distribution of the correlation coefficients between mean yearly values of GPH700 and GCR intensity for the periods 1982-2000 (top panel) and 1953-1981 (bottom panel). Curves *1* and *2* show the climatic positions of Arctic fronts in January (solid lines) and in July (dashed lines). Similarly, curves *3* and *4* show the climatic positions of Polar fronts and curves *5* and *6* show the climatic positions of equatorial troughs.

latitudes. In the cold air mass near-surface Arctic anticyclones are usually formed, so the observed increase of pressure with GCR increase gives evidence for an intensification of anticyclones in this period.

2) The mid-latitudinal regions of negative correlation (*R(GPH700,NM)* ~ −0.5…−0.6, *P* = 0.95-0.99) in the Northern hemisphere coinciding with the climatic Polar fronts which separate air masses of middle latitudes from tropical ones. Most intensive formation and development of extratropical cyclones are known to take place at these fronts. So, the negative correlation between GPH700 and GCR at Polar fronts (a decrease of pressure with GCR increase) indicates an intensification of cyclonic activity at middle latitudes.

3) The region of positive correlation at low latitudes (*R(GPH700,NM) ~0.3-0.4, P* $\leq$ *0.9,* except for the North Pacific area). It is localized at the equatorial trough (or 'intertropical zone of convergence') which is a zone of convergence of air masses from both hemispheres ('trade' winds) and of tropical cyclogenesis.

4) The region of negative correlation at middle and high latitudes of the Southern hemisphere (*R(GPH700,NM)* ~0.4-0.5, *P* = 0.9-0.95).

In the period 1953-1981 (Fig.1, bottom panel) the regional character of the atmospheric pressure response to GCR variations remains the same, as in the period 1982-2000, i.e., the distribution of the correlation coefficients is determined by the positions of the climatic atmospheric fronts. However, the signs of the GCR effects in the regions mentioned above are opposite to those in 1982-2000. Thus, the spatial distribution of the GCR effects on pressure variations reveal a latitudinal and regional dependence which seems to be determined by the peculiarities of baric systems formed in different regions. The GCR effects may change a sign depending on the time period and the last change of the sign took place in the early 1980s.

Let us consider the time variations of the GCR effects. In Fig.2 (top) we can see the correlation coefficients between the mean yearly values of zonal GPH700(φ) and GCR intensity for sliding 11 yr periods. In Fig.2 (bottom) the similar correlation coefficients are presented, but for the values of GPH700 averaged over different latitudinal belts. The data presented in Fig.2 suggest long-term variations in the amplitude and the sign of the GCR effects on zonal pressure, with the change of the sign taking place in the 1980s almost simultaneously at all the latitudes. We can also note some regular features in the variations of the sliding correlation coefficients. The response of atmospheric pressure to GCR changes over the Northern polar region is always opposite to that over the Southern polar region. The GCR effects over the cyclogenetic region at middle latitudes in the Northern hemisphere and over the Northern polar region are also of opposite sign. The pressure changes associated with GCR changes over the intertropical convergence zone at low latitudes seem to be of the same sign as those over the Northern polar region.

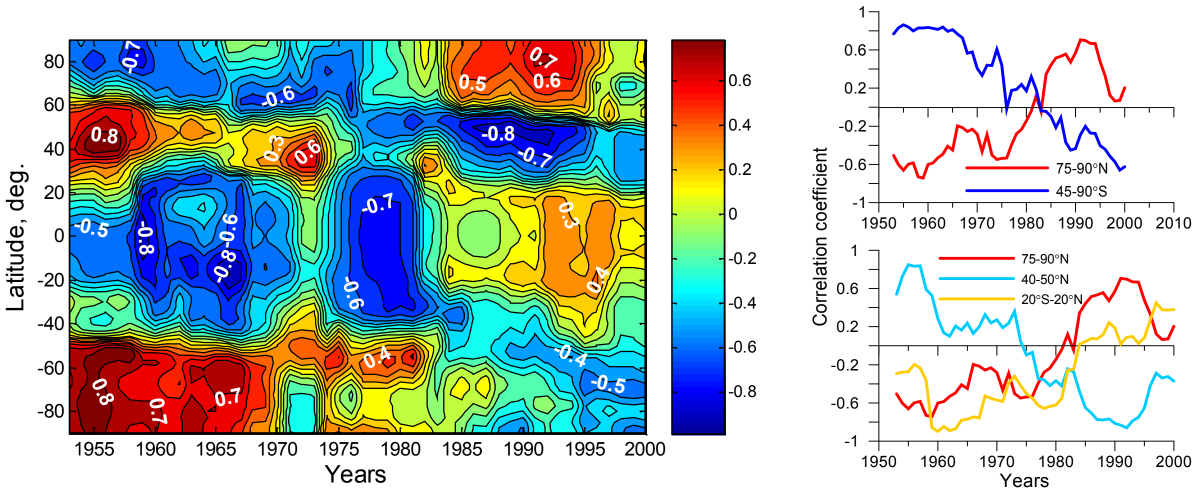

Fig.2. Time variations of the correlation coefficients between mean yearly values of zonal GPH700 and GCR intensity (left) and between mean yearly values of GPH700 averaged over different latitudinal belts and GCR intensity (right) for sliding 11 yr periods.

Thus, all the Earth's atmosphere is involved in the disturbances associated with GCR variations, the amplitude and the sign of GCR effects on the troposphere pressure depending on the region under study. The processes developing in different latitudinal regions seem to be closely interconnected. The GCR effects over all the regions reveal long-term oscillations with the simultaneous changes in the correlation sign.

3. Solar activity effects on the surface pressure according to MSLP data

To study a temporal variability of the SA/GCR effects on a longer time scale, we used the surface pressure data from MSLP (Mean Sea Level Pressure) archive (ftp://ftp.cru.uea.ac.uk) and relative sunspot numbers W (ftp://ftp.ngdc.noaa.gov/STP/). The surface pressure (SP) data in this archive are available only for the Northern hemisphere (latitudes 15-85°N) for the period 1873-2000.

In Fig.3 the correlation coefficients *R(SP, W)* between mean yearly values of zonal surface pressure and sunspot numbers for sliding 11-yr periods are presented. We can distinctly see the long-term variations in the correlation coefficients at polar and subpolar latitudes, with the maxima taking place in the 1910s and in the 1960-70s (cf. also Fig.4, top panel). This suggests a roughly 60 yr periodicity in solar activity effects on atmospheric circulation in the high-latitudinal region, which is really confirmed by the results of the spectral analysis. Indeed, the data in Fig.4 (right panel) show a dominant ~60 yr harmonic in the Fourier spectra of the correlation coefficients for the latitudes above 60°N.

The ~60 yr periodicity in the correlation coefficients of zonal pressure and sunspot numbers was found to prevail in the region of polar and subpolar latitudes. At middle latitudes (the region of extratropical cyclogenesis) this periodicity gets weaker and the ~22 yr harmonic seems to strengthen (Fig.4, bottom panel). At subtropical latitudes 30-35°N the 60 yr harmonic gets dominant again. Let us also note the opposite sign of the SA/GCR effects in the high-latitudinal and the mid-latitudinal areas, as it was observed earlier for the GCR effects.

Thus, the results of the study carried out on the base of MSLP data confirm long-term changes in the SA/GCR effects on the troposphere circulation. These effects may strengthen, weaken and even change

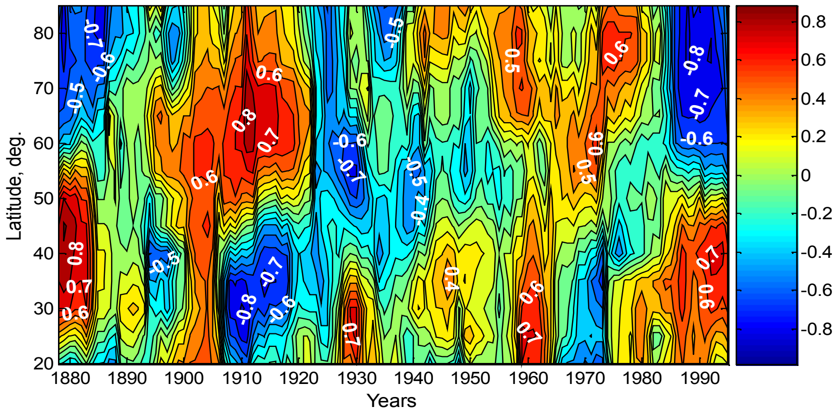

Fig.3. Time variations of the correlation coefficients *R(SP, W)* between mean yearly values of zonal surface pressure in the Northern hemisphere and sunspot numbers for sliding 11 yr periods.

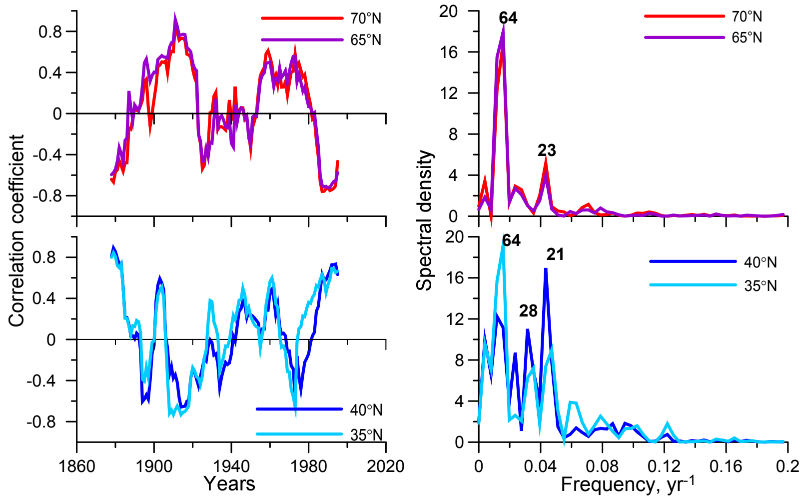

Fig.4. Time variations of the correlation coefficients *R(SP, W)* between mean yearly values of zonal surface pressure at polar/middle latitudes and sunspot numbers for sliding 11 yr periods (left); the Fourier spectra of these correlation coefficients (right).

a sign depending on the time period. An important feature of the temporal structure of the SA/GCR effects is a roughly 60 yr periodicity observed at all the latitudes under study. An existence of this periodicity shows that the observed changes in the character of solar-troposphere links are not accidental and, then, suggests some physical mechanism for these changes.

4. Discussion of the results

As we have seen, the SA/GCR effects on pressure variations are observed over the entire globe and their sign and amplitude change depending on the region. Thus, the disturbance associated with these factors extends over all the Earth's troposphere, but in different regions this disturbance manifests itself in different ways. Let us consider possible reasons for the regional peculiarities of the observed disturbance.

It is known that the most important elements of the large-scale circulation of the atmosphere at high and middle latitudes are the polar vortex, the planetary frontal zone and extratropical cyclones/anticyclones. The polar vortex (PV) is a large-scale cyclonic circulation forming in the cold polar air and extending from the middle troposphere to the stratosphere (the pressure level 500 hPa and above). At the same time a high pressure area arises near the surface due to the high density of cold air. In the Northern hemisphere PV is usually centered over Canada. As the polar vortex is formed, a circular motion of air masses isolates the cold air inside it from the warmer air of middle latitudes, which results in an increase of the temperature gradients at the vortex edge. The planetary frontal zone usually involves several individual frontal zones (the regions of high temperature contrasts) girding the whole hemisphere or its larger part. Frontal zones are characterized by an enhanced frequency of atmospheric front formation. The high temperature contrasts in the frontal zones and at the corresponding fronts create favorable conditions for cold advection contributing to the intensification of cyclonic vortices. Thus, cyclonic activity, i.e., formation, development and movement of extratropical cyclones and anticyclones, is closely related to the planetary frontal zone.

Let us consider the SA/GCR effects in the regions of formation of the main elements of the macro-circulation. In Fig.5 we can see the sliding correlation coefficients $R(SP_{reg}, W)$ for the values of surface pressure averaged over the regions of the polar vortex and of the Polar frontal zone (PFZ) near the eastern coasts of North America. This PFZ is a part of the planetary frontal zone and a cyclogenetic region. Having compared the data in Fig.4 and 5, we can conclude that the SA/GCR effects are most pronounced in the areas of the polar vortex and the North Atlantic PFZ. Indeed, the regional correlation coefficients reach larger absolute values than the zonal ones and the ~60 yr periodicities in their time variations are also more distinctly seen. Thus, namely the effects in the areas of the main elements of the macro-circulation make the most important contribution to the effects observed on zonal pressure at high and middle latitudes.

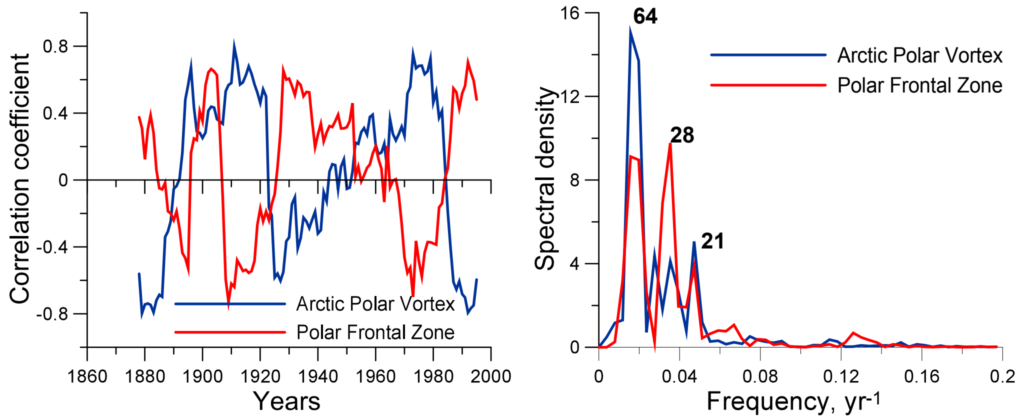

Fig.5. Time variations of the correlation coefficients $R(SP_{reg}, W)$ between mean yearly values of surface pressure over the regions of the polar vortex (Canada-Greenland) and of the North Atlantic Polar frontal zone with sunspot numbers for sliding 11 yr periods (left); the Fourier spectra of these correlation coefficients (right).

It should also be noted that the SA/GCR effects in the regions of the polar vortex and the North Atlantic PFZ usually have opposite phases, i.e., an intensification of a high pressure area in the region of the polar vortex formation is accompanied by a decrease of pressure in the region of the Polar frontal zone in the North Atlantic that implies an intensification of cyclonic activity, and vice versa. This suggests that the processes developing in these regions as a response to solar activity variations are closely interconnected.

Thus, the spatial distribution of the pressure variations associated with solar activity and cosmic rays seems to be determined by their influence on the main elements of the large-scale circulation of the atmosphere, i.e., the polar vortex and the planetary frontal zone (extratropical cyclogenesis area). Let us stress an importance of processes developing in the polar vortex area where the ~60 yr periodicity was found to be the most distinctly seen. This is also a region of precipitation of low-energy component of GCR strongly modulated by solar activity. The GCR variations in the 11 yr solar cycle are most pronounced at the heights ~15-25 km [Bazilevskaya et al., 2008], i.e., at the heights of the vortex formation. An intensification of the polar vortex due to SA/GCR variations may result in a decrease of heat exchange between low and high latitudes and, then, to an increase of temperature gradients in the planetary frontal zone and an intensification of extratropical cyclogenesis**.** Hence, one can suggest that the SA/GCR effects on the evolution of the polar vortex play an important part in the physical mechanism of solar-atmospheric links.

Let us consider possible reasons for the temporal variations of the SA/GCR effects on the atmospheric circulation. In Fig.6 the time variations of the correlation coefficients $R(SP, W)$ for zonal pressure at polar latitudes are compared with long-term variations in the development of the main forms of the large-scale circulation according to the classification by Vangengeim and Girs [e.g., Vangengeim, 1952]. The zonal circulation form W is characterized by rapidly moving small-amplitude waves in the pressure field, whereas the meridional circulation forms C and E are characterized by slowly moving or stationary large-amplitude waves. The forms C and E differ by the opposite disposition of troughs and crests. The data in Fig.6 show that the latest change of the sign of the SA/GCR effects in the early 1980s was preceded by the noticeable changes in the evolution of all the circulation forms. For the previous changes of the correlation sign no similar simultaneous transformations of the circulation epochs were found. However, one can note that the periods of negative correlation of pressure in the polar region with sunspot numbers (or positive correlation with GCR intensity) coincide with the periods of increasing frequency of the meridional form C and vice versa. Besides, the annual frequency of the form C reveals ~60 yr periodicity as well as the SA/GCR effects.

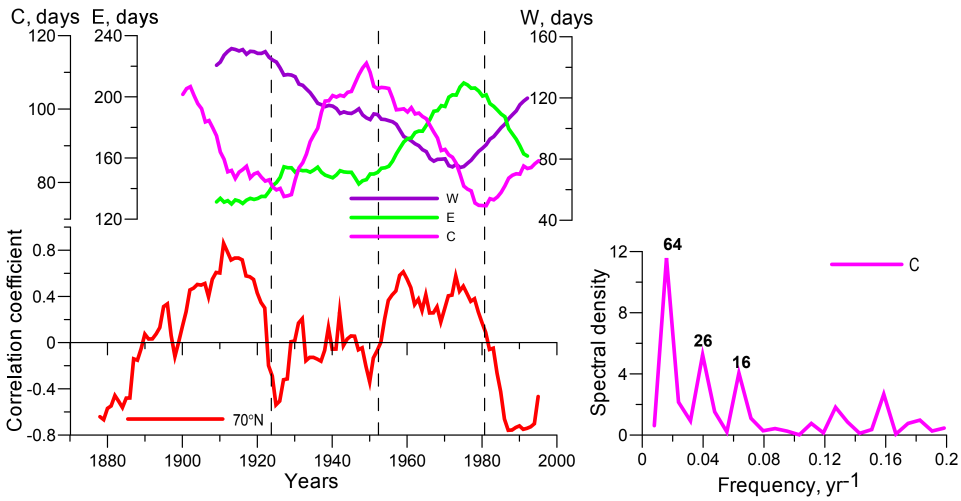

Fig.6. *Top:* Annual frequencies of occurrence (number of days during a year) for the main forms of the large-scale circulation (20 yr running averages). *Bottom:* Correlation coefficient *R(SP, W)* between mean yearly values of zonal pressure at 70°N and sunspot numbers for sliding 11 yr periods (left) and the Fourier spectrum of the annual frequency of occurrence for the meridional form C (right).

Thus, the detected changes of the sign of the SA/GCR effects seem to be caused by the changes of the epochs of the large-scale atmospheric circulation. The development of the meridional circulation form C is likely to determine a sign of the SA/GCR effects. In turn, the evolution of the large-scale circulation forms may be related to long-term variations of solar/geomagnetic activity. Indeed, the change of the circulation epochs in the late 1970s – early 1980s coincided with the change of the N-S asymmetry of solar activity [Nagovitsyn, 1998] as well as with the anomalies of the evolution of global magnetic fields of the Sun, the growth of the dipole magnetic moment gave place to its decrease [Obridko and Shelting, 2009].

5. Conclusions

This study showed that the disturbances of the troposphere circulation associated with SA/GCR variations take place over the entire globe. The spatial structure of the observed pressure variations is determined by the influence of SA/GCR on the main elements of the large-scale atmospheric circulation (the polar vortex, the planetary frontal zone and extratropical baric systems). The temporal structure of the SA/GCR effects on the atmosphere circulation at high and middle latitudes is characterized by a ~60 yr periodicity, with the changes of the correlation sign taking place in 1890-1900, the early 1920s, the 1950s and the early 1980s. The ~60 yr periodicity is likely to be due to the changes of the epochs of the large-scale atmospheric circulation. A sign of the SA/GCR effects seems to be related to the evolution of the meridional circulation C form. A mechanism of the SA/GCR effects on the troposphere circulation may involve changes in the development of the polar vortex in the stratosphere of high latitudes. Intensification of the polar vortex may contribute to an increase of temperature contrasts in frontal zones and an intensification of extratropical cyclogenesis.

Acknowledgments

This work was partly supported by the Program of the Department of Physical Sciences RAS “Plasma processes in the Solar system” (VI-15) and RFBR grants 07-02-00379, 09-02-00083, 10-05-00129.

References

Bazilevskaya, G.A., et al. (2008), Cosmic Ray Induced Ion Production in the Atmosphere. *Space Science Reviews*. 137, 149-173.

Kalnay, E. et al.(1996), The NCEP/NCAR 40-year reanalysis project. *Bull.Amer.Meteorol.Soc*., 77, 437-472.

Khromov, S.P., and M.A. Petrociants (1994), *Meteorology and Climatology*. 520 pp. Moscow University Press, Moscow.

Nagovitsyn, Yu.A. (1998), The north-south asymmetry of solar activity as a nonlinear process. Short- and long-term variations. *Bulletin of Main Astronomical Observatory*. 212, 145-153.

Obridko, V.N., and B.D. Shelting (2009), Anomalies in the evolution in the global and large-scale solar magnetic fields as the precursors of several upcoming low solar cycles. *Lett.Astronom.Journ*., 35, 279-285.

Vangengeim, G.Ya. (1952), Principles of the macro-circulation methods of long-term meteorological forecasts for the Arctic. *Trudy AANII*, 34, 314 pp.