The stratospheric polar vortex as a cause for the temporal variability of solar activity and galactic cosmic ray effects on the lower atmosphere circulation

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Abstract. In this work we continue studying possible reasons for the temporal variability of long-term effects of solar activity (SA) and galactic cosmic ray (GCR) variations on the lower atmosphere circulation. It was shown that long-term oscillations of the amplitude and sign of SA/GCR effects on troposphere pressure at high and middle latitudes are closely related to the state of a cyclonic vortex forming in the polar stratosphere. A roughly 60-yr periodicity was revealed in the vortex strength affecting the evolution of the large-scale atmospheric circulation and the sign of SA/GCR effects. The results obtained suggest an important part of the polar vortex in the mechanism of SA/GCR influence on the troposphere circulation.

1. Introduction
Our previous study [1] revealed that the temporal structure of SA/GCR effects on pressure variations at middle and high latitudes is characterized by a pronounced ~60-yr periodicity which is apparently due to the epochs of the large-scale atmospheric circulation. In this work we continue studying possible reasons for this periodicity, as well as a contribution of the stratospheric polar vortex in the mechanism of SA/GCR effects on the lower atmosphere circulation.

2. Experimental data and their analysis
The stratospheric polar vortex is a large-scale cyclonic circulation forming in a cold air mass and extending from the middle troposphere to the stratosphere over the polar region. It plays an important part in a variety of atmospheric processes. In particular, air cooling to low temperatures (~80°C) in the vortex area assists to the formation of polar stratospheric clouds (PSC), with chemical processes on PSC particles catalyzing ozone destruction [2]. The vortex state influences the evolution of large-scale dynamic processes in the atmosphere, e.g., the North-Atlantic Oscillation polarity [3]. The rotation of cold and warm epochs in the Arctic seems to be related also to the vortex state [4].

A circular motion in the vortex isolates cold polar air from warmer air of middle latitudes creating sharp temperature gradients at the vortex edges. The typical location of the vortex as the low temperature area in the stratosphere is shown in figure 1a, the NCEP/NCAR reanalysis data being used [5]. The temperature chart is superposed with isolines of vertical geomagnetic cutoff rigidity R [6]. It is seen that the area of the vortex formation is characterized by low rigidities. So GCR particles with a broad energy range may precipitate here including the low energy component strongly modulated by solar activity and ion production rate in this area is higher than at middle and low latitudes [7].
Figure 1. a) Distribution of mean monthly temperature (°C) in the stratosphere in January 2005. The temperature minimum is indicated by an asterisk. Red lines show vertical geomagnetic cutoff rigidities (in GV) [6].
b) Height dependences of the temperature minimum in the Arctic air mass and the maximum magnitude of temperature gradients at its edges in January 2005. The dashed line shows the ion-pair production rate in free ambient air at polar latitudes ($R = 0.6$ GV) [7].

In figure 1b the height dependences of the characteristics of the Arctic air mass where the vortex is formed are compared with that of ion production rate caused by GCR in free air at polar latitudes [7]. The vortex is most pronounced at the 50-30 hPa levels (20-25 km) where the minimum of stratospheric temperatures and the maximum of temperature gradients are observed. The 11-yr modulation of GCR fluxes is the strongest at these heights [7]. The largest values of ion production rate are observed at the heights 200-100 hPa (10-15 km), i.e., in the lower part of the vortex where temperature gradients start increasing. Thus, the vortex location seems to be favorable for the mechanisms of solar activity influence on the atmosphere circulation involving GCR variations.

Let us consider the spatial pattern of GCR effects on troposphere pressure. It was shown [1] that these effects change the sign depending on the evolution of meridional circulation. Figure 2 shows the distributions of the correlation coefficients $R(GPH700, NM)$ between tropospheric pressure and GCR intensity characterized by yearly values of geopotential (gp) heights of the 700 hPa level GPH700 [5] and the neutron monitor counting rate $NM$ in Climax, respectively, for the epochs of enhancing and weakening meridional circulation (the C form according to Vangengeim-Girs classification [8]).

Figure 2. Distribution of the correlation coefficients $R(GPH700, NM)$ between tropospheric pressure and GCR intensity for the periods of increasing (a) and decreasing (b) intensity of the C form of meridional circulation.
C form is characterized by stationary or slowly moving large-amplitude waves in the pressure field, with a height crest forming over the eastern North Atlantic. It is seen that in the period of its enhancement (figure 2a) GCR increase is accompanied by a growth of pressure in the polar region and a lowering of pressure at middle latitudes, i.e., by a simultaneous intensification of polar anticyclones and extratropical cyclones (figure 2a). When the meridional circulation weakens, the pressure variations correlated with GCR intensity change the sign (figure 2b). Most appreciable correlations, the statistical significance being 0.95-0.99 according to the random phase test, were detected in the vortex area, independently of the circulation epoch and the correlation sign.

Figure 3a shows the time variations of SA/GCR effects on tropospheric pressure on a longer time scale, the MSLP data (ftp://ftp.cru.uea.ac.uk) being used. The correlation coefficients $R(SLP, R_z)$ between yearly values of sea-level pressure ($SLP$) at high latitudes (60-85°N) and sunspot numbers reveal a pronounced—60-yr periodicity. We can see that, indeed, a positive correlation between pressure in the vortex region and sunspot numbers ($a$ negative correlation with GCR fluxes) occurs in the periods of decreasing frequency of the C form of meridional circulation and vice versa (figure 3b).

Let us consider long-term variations of the vortex characteristics, using NCEP/NCAR reanalysis data [5]. In figure 3c we can see anomalies of the vortex strength characterized by the difference of zonal gp heights $\Delta H$ between the latitudes 40 and 65°N for the 500 hPa level. Anomalies of stratospheric temperatures averaged over the region 60-90°N are shown in figure 3d. We can see that

![Correlation coefficient](image1)

**Figure 3.** a) Time variations of the correlation coefficients between yearly values of troposphere pressure at high latitudes and SA/GCR characteristics for 15-yr sliding intervals: red and blue lines show $R(SLP, R_z)$ and $R(GPH700, NM)$, respectively.

b) Annual frequencies of occurrence (number of days during a year) of the C form of meridional circulation (15-yr running averages).

c) Anomalies (deviations from climatic means) of yearly values of the difference of zonal gp heights $\Delta H$ between the latitudes 40 and 65°N for the 500 hPa level.

d) Anomalies (deviations from climatic means) of yearly values of stratospheric temperature at the 50 hPa level in the high-latitude region 60-90°N.

The vertical dashed lines show the moments of the correlation reversals. The thick red lines at the panels c) and d) show the $3^{rd}$ order polynomial fits of the data.
in ~1950-1980 the polar vortex was weak. It was manifested as a decrease of pressure gradients between high and middle latitudes and an increase of stratospheric temperature in the vortex area. In ~1980-2010 the vortex was strong, the pressure gradients were enhanced and the temperature was low. The vortex evolution suggests a ~60-yr periodicity, the transitions between its different states occurring in the 1950s, 1980s and apparently near the 2010s. These transitions coincide well with those between cold and warm epochs in the Arctic detected in surface temperatures [4]. These epochs reveal a similar ~60-yr periodicity, a strong (weak) vortex corresponds to a warm (cold) epoch. As figure 3 shows, the sign reversals of SA/GCR effects coincide with the transitions between the different states of the vortex. When the vortex is strong (~1980-2010) meridional processes intensify and GCR increase is accompanied by an enhancement both of cyclonic activity at middle latitudes and anticyclone formation at polar ones, these effects being highly significant. When the vortex is weak (~1950-1980) the meridional circulation weakens and GCR effects change the sign. Thus, the ~60-yr variation of the amplitude and sign of SA/GCR effects on troposphere pressure seem to be closely related to the vortex state and the corresponding changes of the large-scale atmospheric circulation.

A possible reason for the sign reversals of SA/GCR effects may be changes in the troposphere-stratosphere coupling caused by different conditions for propagation of planetary waves during the periods of a strong or weak vortex [9]. As a result, the stratosphere influences the troposphere only when the vortex is strong and planetary waves are reflected back to the troposphere. When the vortex is weak only the troposphere influences the stratosphere. Thus, if GCR produce any effect in the stratosphere in the period of a strong vortex, this effect may be transferred to the troposphere and intensify dynamic processes in it. Intensification of the vortex seems to contribute to an increase of temperature contrasts in tropospheric frontal zones and, then, enhance extratropical cyclogenesis. So we can see noticeable changes in the development of extratropical cyclones and polar anticyclones in this period. When the vortex is weak the stratosphere does not influence the troposphere, SA/GCR effects on extratropical cyclogenesis weaken; this seems, in turn, to influence the formation of Arctic anticyclones. As the vortex strength reveals a ~60-yr variation, this may explain the detected temporal variability of SA/GCR effects on tropospheric pressure.

Thus, the results above allow to suggest that the mechanism of SA/GCR effects on the troposphere circulation involves changes in the vortex state. As the vortex evolution is closely related to radiative processes, these changes may be due to radiative forcing resulting from variations of cloudiness and aerosol content associated with SA/GCR variations.

3. Conclusions
The results of this study suggest that the evolution of the stratospheric polar vortex plays an important part in solar-climatic links. The vortex location is favourable for the mechanisms of solar activity influence on the lower atmosphere involving GCR variations. The strength of the vortex reveals a roughly 60-yr periodicity which seems to influence the large-scale atmospheric circulation and the sign of SA/GCR effects on the development of extratropical baric systems.

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