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Cloud Anomalies at Midlatitudes of the Northern and Southern Hemispheres: Connection with Atmospheric Dynamics and Variations in Cosmic Rays

S. V. Veretenenko[a, b, *] **and M. G. Ogurtsov**[a, c]

[a]*Ioffe Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*
[b]*St. Petersburg State University, St. Petersburg, 199164 Russia*
[c]*Pulkovo Observatory, Russian Academy of Sciences, St. Petersburg, 196140 Russia*
**e-mail: s.veretenenko@mail.ioffe.ru*

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Abstract—Long-term correlations between the state of low clouds and variations in the flux of galactic cosmic rays (GCRs) were studied. It has been shown that the links between low cloud anomalies and GCR fluxes at midlatitudes of the Northern and Southern Hemispheres are caused by variations in the extratropical cyclogenesis intensity which correlated with changes of GCR fluxes in the period from the early 1980s to 2000. At the beginning of the 2000s, the correlation between cloudiness and variations of GCR fluxes was violated, a possible reason being a sharp weakening of the stratospheric polar vortices in the Northern and Southern Hemispheres, which resulted in the change of GCR contribution to the circulation of the lower atmosphere.

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1. INTRODUCTION

For the last two decades the mechanism of solar–climatic links, including cloud variations influenced by galactic cosmic rays (GCRs) and subsequent changes in the radiative–thermal balance of the atmosphere, has been widely discussed. Until recently this mechanism was supported by a rather high positive correlation between monthly values of low cloud anomalies (LCA) and GCR fluxes observed in 1983–1994 (March and Svensmark, 2000). In the early 2000s this correlation was violated, which caused doubts in the influence of GCRs on the cloudiness state and their role in the mechanism of solar–atmospheric links (Gray et al., 2010).

At present the question of the influence of GCRs on the cloud cover formation remains open. The currently available data provide evidence for both the existence of a link between clouds and GCR variations (e.g., Svensmark et al., 2009) and the absence of such a link (Krissansen-Totton and Davies, 2013). Along with cosmic rays, fluxes of total solar irradiance (TSI) (Kristjánsson et al., 2004) and ultraviolet (UV) radiation (Voiculescu and Usoskin, 2012) are considered as probable factors influencing cloudiness. Effects of GCRs and UV radiation on cloudiness variations are characterized by regional and altitudinal dependences (Voiculescu and Usoskin, 2012). Krymskii (2002) noted the difference between the latitudinal distribution of the TSI input with a maximum at the equator and that of atmospheric ionization due to GCRs, which promotes water vapor condensation and cloud cover increase, with the maxima at latitudes ~60° N(S), this difference may contribute to the development of meridional circulation. Thus, links of cloudiness with GCR fluxes and other solar activity phenomena turns out to be complex and insufficiently studied.

In the paper by Veretenenko and Ogurtsov (2015), it was shown that the correlation links between low cloud amount and GCR fluxes observed at midlatitudes of the Northern Hemisphere are indirect and caused by the influence of GCRs on the development of baric systems forming a cloud field. In turn, GCR effects on the extratropical cyclogenesis intensity probably depend on the state of the stratospheric polar vortex. In this paper, we analyze the correlation links between low cloud anomalies, dynamic processes in the troposphere, and GCR variations at midlatitudes of the Southern Hemisphere and compare them with the correlations earlier found for the Northern Hemisphere. We also analyze variations in the state of the Arctic and Antarctic polar vortices as a possible reason for temporal variability of the observed correlations.

2. EXPERIMENTAL DATA AND THEIR ANALYSIS

2.1. Variations in Low Clouds and Cyclonic Activity at Midlatitudes of the Northern and Southern Hemispheres

It is known that cloud formation is closely related to ascending atmospheric motions that result in cooling and condensation of water vapor (Vorob'ev, 1991). At extratropical latitudes, most large-scale upward air motions are associated with low-pressure systems (cyclones and troughs), which results in a close connection between cloud and pressure fields. A characteristic feature of the mentioned baric objects is the formation of strong systems of stratiform clouds Ns-As-Cs (nimbostratus, altostratus, and cirrostratus, respectively) connected with atmospheric fronts, as well as clouds caused by ascending motions arising due to the convergence of near-surface air flows to the center of a cyclone.

Let us consider changes in low cloudiness at midlatitudes of the Northern and Southern Hemispheres where intensive cyclonic activity takes place. The data of International Satellite Cloud Climatology Project (ISCCP-D2 archive) available on ftp://isccp.giss.nasa.gov/pub/data/D2CLOUDTYPES for the period from July 1983 to December 2009 were used as experimental material. According to the ISCCP classification, clouds are considered as low if the pressure at the cloud top $CP > 680$ hPa. Stratus (St), nimbostratus (Ns), and stratocumulus (Sc) clouds are considered as low level clouds. Low clouds may also include convective cumulus (Cu) clouds. The amount of clouds is determined as a fraction of the area covered by clouds (expressed as a percentage of the total area) when observed from a satellite. Low cloud anomalies (LCA) are calculated as the difference between monthly average amount of clouds of this type and the climatic value (i.e., the average for a given month over the whole period of observations).

Figures 1a and 1b present time variations of LCA taken from the ISCCP-D2 satellite data for the latitude zones 30°–60° N and 30°–60° S. It is seen that at midlatitudes of both hemispheres the temporal variations in LCA are characterized by negative linear trends. Deviations of LCA from the linear trends (Fig. 1c) are also similar to a great extent. The correlation coefficient between low cloud anomalies of the Northern and Southern Hemispheres is 0.82 if the trends are not removed and 0.62 if the trends are removed (Fig. 1d).

Let us compare variations in low clouds at midlatitudes with variations in pressure characterized by geopotential heights of the isobaric level 700 hPa (GPH700) according to the reanalysis data by the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996). In Fig. 2, temporal variations of GPH700 values are shown; the values were area-averaged over the latitude belts 30° N–60° N and 30° S–60° S for the whole period of the reanalysis data (1948–2013). It is seen that the long-term pressure variations in the latitudinal belts under study somewhat differ. This shows that dynamic processes in the Northern and Southern Hemispheres are independent to a great extent. Nevertheless, for the period from 1983 to 2009, when the cloud amount in the considered regions was decreasing, the pressure was increasing (Fig. 2), which indicates a weakening of cyclonic processes and a strengthening of anticyclonic ones at midlatitudes of both hemispheres. Since a cloud field at midlatitudes is formed by large-scale ascending air motions connected with baric systems—cyclones and troughs—the decrease of LCA observed in the belts 30° N–60° N and 30° S–60° S agrees well with the character of cyclonic activity variations.

2.2. Influence of GCR Variations on the Development of Extratropical Cyclogenesis and LCA in the Northern and Southern Hemispheres

Let us consider links between pressure variations at midlatitudes and GCR fluxes. In Fig. 3 and 4, the temporal behavior of annual averages of pressure anomalies (GPH700) calculated similarly to cloud anomalies in the latitude belts 30° N–60° N and 30° S–60° S is shown for the period from 1983 to 2013. The GPH700 anomalies are compared with GCR intensity characterized by fluxes of charged particles F_{CR} at the maximum of the transition curve (the height is 15–25 km) at the midlatitude station Dolgoprudny (the geomagnetic cutoff rigidity R_C = 2.35 GV) according to the data by Stozhkov et al. (2009). The detrended values of GPH700 anomalies and F_{CR} are shown. In the figures there are also presented temporal variations of the correlation coefficients between pressure anomalies and fluxes of charged particles (solid curves) for sliding 11-year intervals for the period 1958–2013, as well as between LCA and fluxes of charged particles (dashed curves).

As is seen from Fig. 3a, from the early 1980s to the late 1990s, pressure at midlatitudes of the Northern Hemisphere and GCR variations developed in antiphase; i.e., an increase of GCR fluxes was accompanied by a strengthening of cyclonic processes (i.e., a decrease of pressure) at midlatitudes. The character of the link between GPH700 and F_{CR} sharply changed near 2000, which is confirmed by the temporal behavior of sliding correlation coefficients between the studied values. According to the data shown in Fig. 3b, from the mid-1980s to the mid-1990s, the highest negative correlation between pressure at midlatitudes and GCR fluxes ($R \sim -0.8$) was observed. According to the estimates by the Monte Carlo method, these coefficients are statistically significant at the level $P = 0.98$ (to estimate the significance, time variations of sliding correlation coefficients were simulated for 1000 pairs of surrogate series obtained by randomization of the initial series of pressure and GCR fluxes). Since the

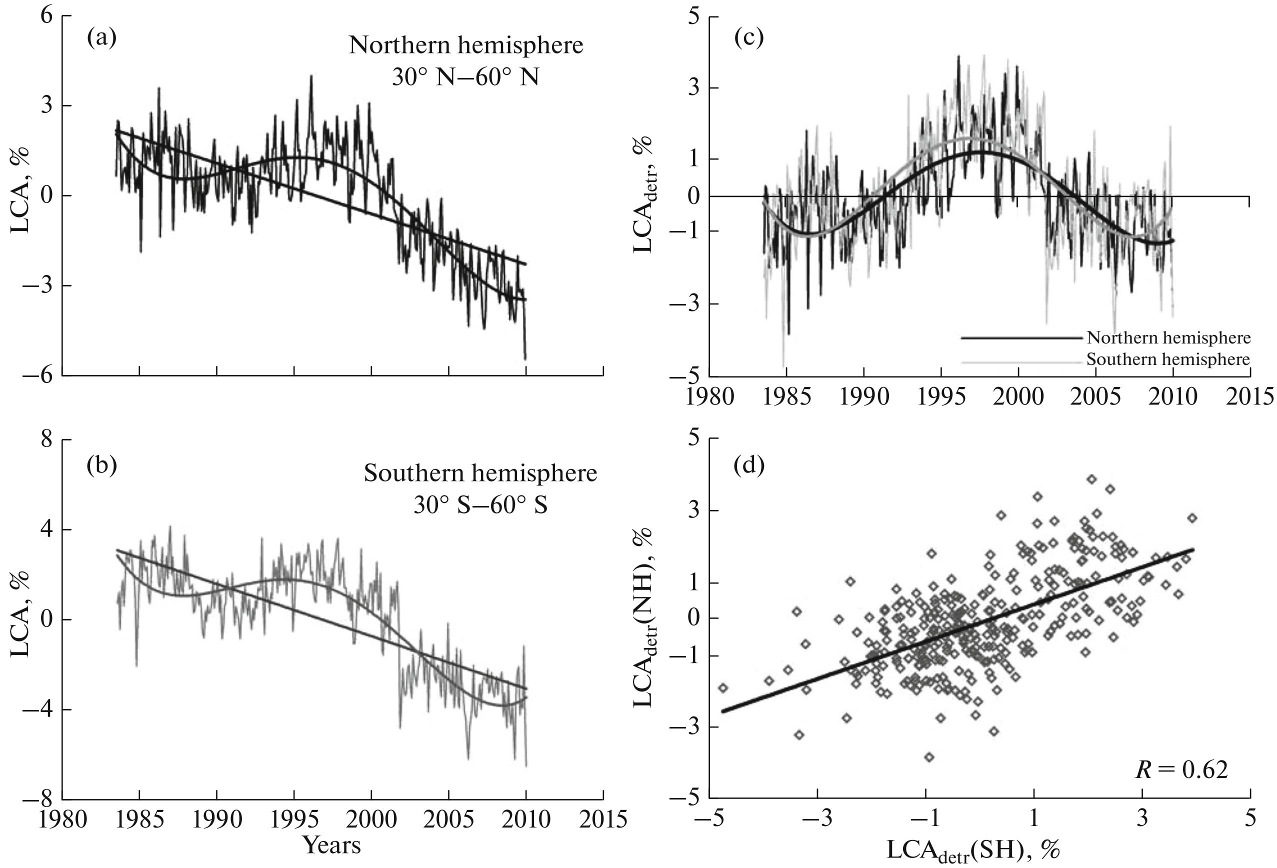

Fig. 1. (a, b) Time variations of monthly average values of low cloud anomalies (LCA) at midlatitudes of the Northern and Southern Hemispheres; (c) the same values after the removal of linear trends; (d) detrended values of low cloud anomalies in the Northern hemisphere versus those in the Southern hemisphere. The linear trends and polynomial smoothing of LCA are shown with thick curves.

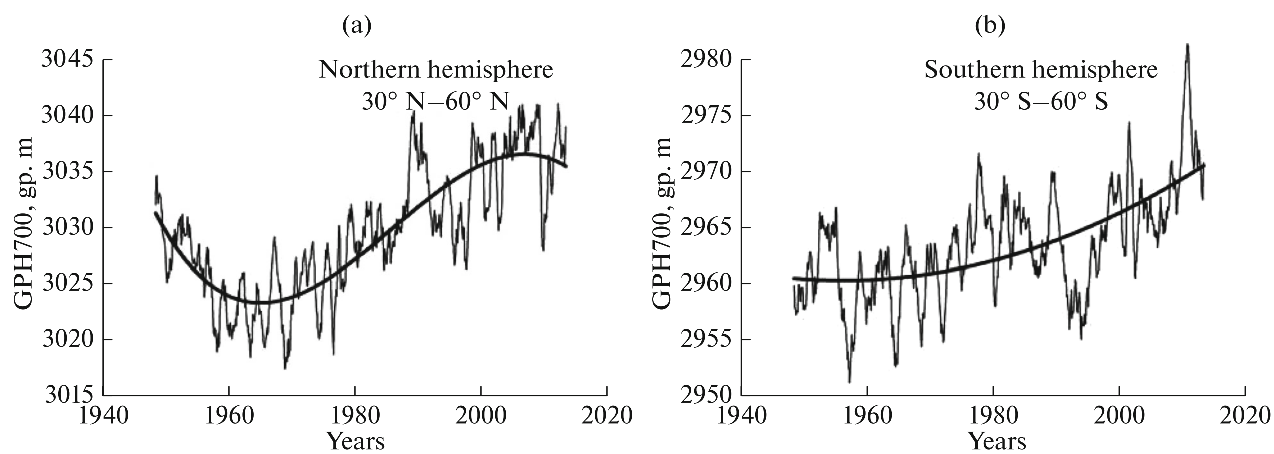

Fig. 2. Time variations of pressure (GPH700) at midlatitudes of the Northern (a) and Southern (b) Hemispheres for the period 1948–2013 (12-month running averages). The polynomial smoothing of GPH700 is shown with thick curves.

late 1990s, the negative correlation between pressure and GCR fluxes started weakening; and a sharp change of the correlation sign took place in the early 2000s. The correlation coefficients between cloud anomalies and GCR fluxes in the Northern Hemisphere reached maximum values ($R \sim 0.6–0.8$ with the confidence level $P = 0.95–0.98$) in the 1990s, when the highest negative correlation between pressure and

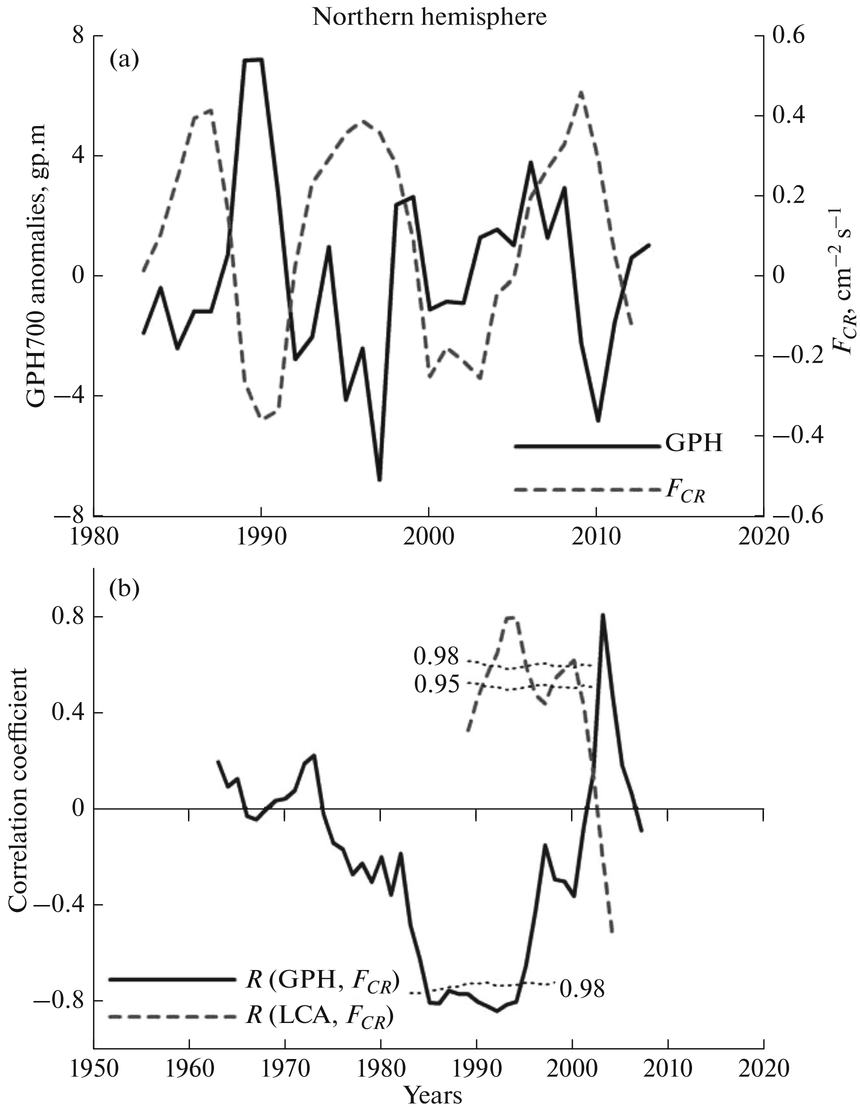

Fig. 3. (a) Temporal variations of pressure (GPH700) anomalies at midlatitudes (30°–60°) of the Northern Hemisphere and GCR intensity; (b) correlation coefficients for sliding 11-year intervals between LCA and GCR fluxes (dashed curve) and between pressure anomalies and GCR fluxes (solid curves) at midlatitudes of the Northern Hemisphere. The significance levels of the correlation coefficients are shown with dotted curves.

GCR fluxes was observed. Later the correlation between the clouds and GCRs started weakening; in the early 2000s the correlation sign reversed, which coincided with the sign reversal for the correlation between pressure and GCR fluxes.

At midlatitudes of the Southern Hemisphere, it was detected that the correlations between the studied atmospheric characteristics (pressure and low cloud anomalies) and GCR variations change in a similar way (Fig. 4). However, unlike the Northern Hemisphere, where the regions of negative correlation between pressure and GCR fluxes cover almost all the belt 30°–60°, in the Southern Hemisphere the regions of negative correlation are less extended (Veretenenko and Ogurtsov, 2012a). These regions coincide with the climatic depressions (the regions of an increased frequency of cyclones) observed in the western part of the South Atlantic and the southern part of the Indian Ocean, as well as the region of Polar fronts over the Pacific Ocean. Thus, for the Southern Hemisphere, GPH700 anomalies were calculated over these cyclonic areas. According to the data presented in Fig. 4, the link between pressure changes and GCR fluxes is similar to that in the Northern Hemisphere. The most significant correlation coefficients between the investigated values ($R \sim -0.8$, $P = 0.98$) were observed in the 1980s–1990s, and the correlation sign reversed in the early 2000s. The correlation coefficients between LCA in the Southern Hemisphere and GCR fluxes also reached a maximum in the 1990s ($R \sim 0.6$–0.8,

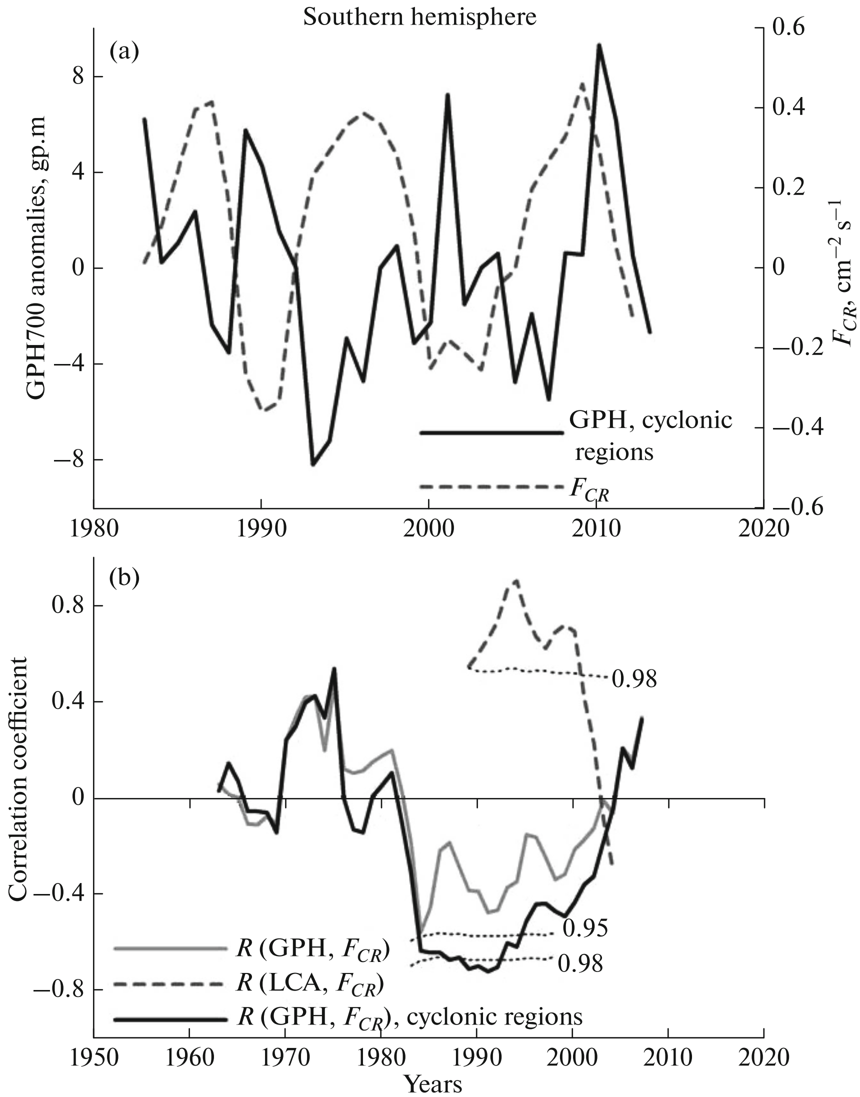

Fig. 4. Same as in Fig. 3, but for the Southern Hemisphere. The sliding correlation coefficients between pressure and GCR fluxes are shown for the whole latitude belt 30° S–60° S (solid gray curve) and for the cyclonic regions (solid black curve).

$P = 0.98$) and changed the sign in the early 2000s, simultaneously with the correlation coefficients between pressure and GCRs. The obtained results suggest that GCR effects on low cloud variations of both the Northern and Southern Hemispheres are caused by changes in cyclonic activity.

2.3. Change in the State of the Arctic and Antarctic Polar Vortices in the Early 2000s

Let us consider possible reasons for the violation of the correlation between pressure at midlatitudes and GCR intensity after 2000. It was earlier shown that the character of GCR effects on tropospheric circulation depends on the epoch of the large-scale atmospheric circulation which, in turn, depends on the state of the stratospheric polar vortex (Veretenenko and Ogurtsov, 2012a, 2012b). The polar vortex is a cyclonic circulation formed in the high-latitude atmosphere above the level 500 hPa. A decrease in pressure at midlatitudes (a strengthening of cyclonic processes) with an increase of GCR flux was detected only under a strong vortex (Veretenenko and Ogurtsov, 2012b). Since cyclonic circulation in the vortex is strongest at the heights 20–30 km (the isobaric levels 50–10 hPa), we will characterize the vortex strength by zonally averaged values of the U-component (directed from west to east) of wind velocity at the level 50 hPa. In Figs. 5 and 6 we show variations (deviations from the linear trends) of wind velocity in the latitude belts 60° N(S)–80° N(S) and temperature of the stratosphere in the region 65° N(S)–90° N(S) (according to the data of the NCEP/NCAR reanalysis (Kalnay et al., 1996)) for cold months (October–March and April–September in the North-

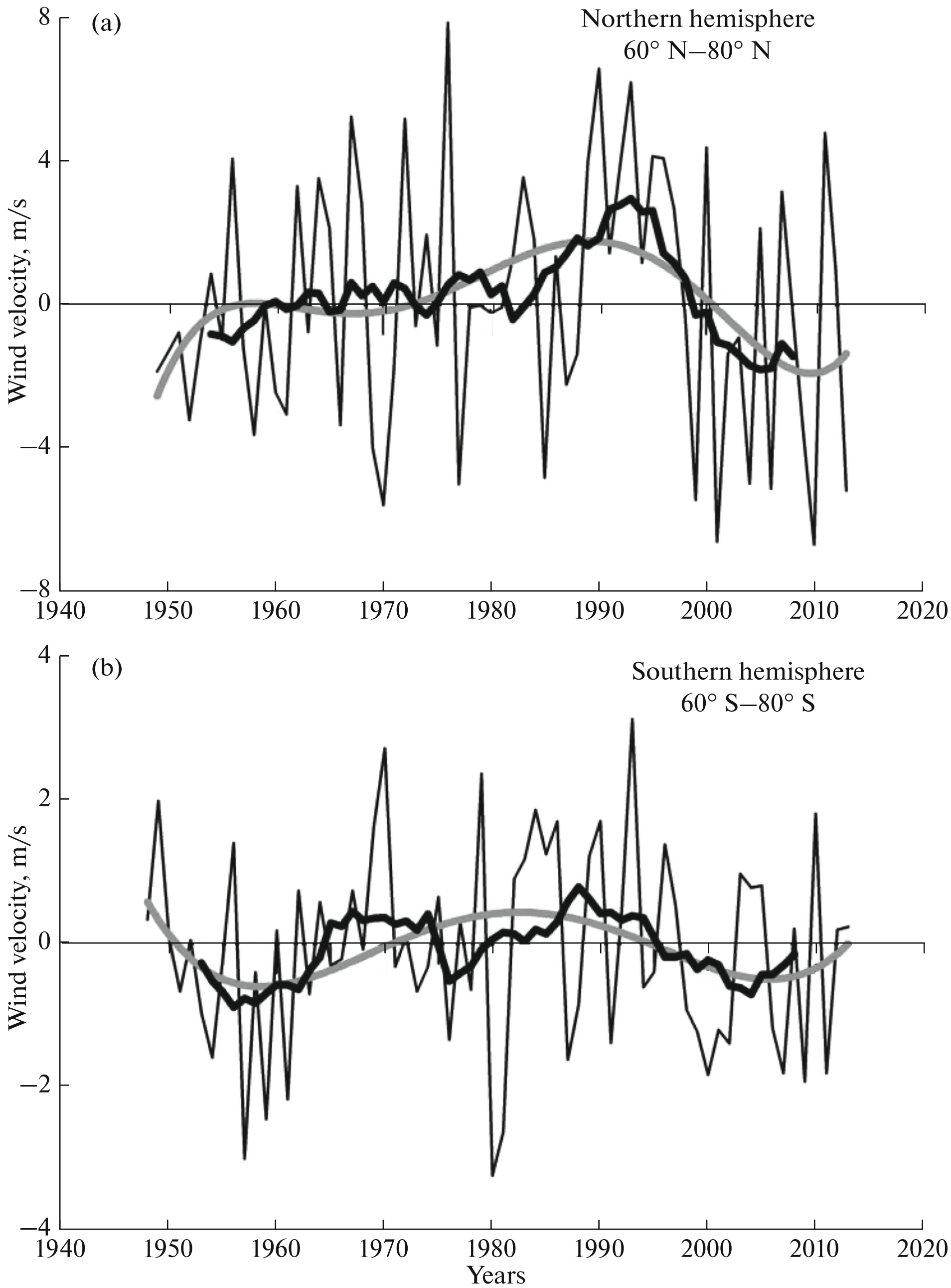

Fig. 5. Variations of zonal wind velocity at the level 50 hPa in the high-latitude stratosphere at 60°–80° in the Northern (a) and Southern (b) Hemispheres for cold months. Black and gray thick curves show the 11-year running averages and the polynomial smoothing of velocity variations, respectively.

ern and Southern Hemispheres respectively) when the vortex is strongest.

The data in Fig. 5 show that, from the 1980s to the late 1990s, the polar vortices in the Arctic and Antarctic were actually strong. This was manifested in the increase of western wind velocity in the stratosphere, which was mostly prominent in the Northern Hemisphere. In the Southern Hemisphere, where the vortex is more stable, the variations in wind velocity are smaller in amplitude. A sharp weakening of both vortices occurred near 2000. Variations in the strength of the vortices are also confirmed by temperature changes in the high-latitude stratosphere. A strengthening of cyclonic circulation in the vortex is accompanied by a weakening of heat exchange between middle and high latitudes, which results in a temperature decrease in the vortex region. The data in Fig. 6 show that the temperature in the high-latitude stratosphere was lowered in the 1990s and it sharply increased near 2000. Moreover, according to the results by Ivy et al.

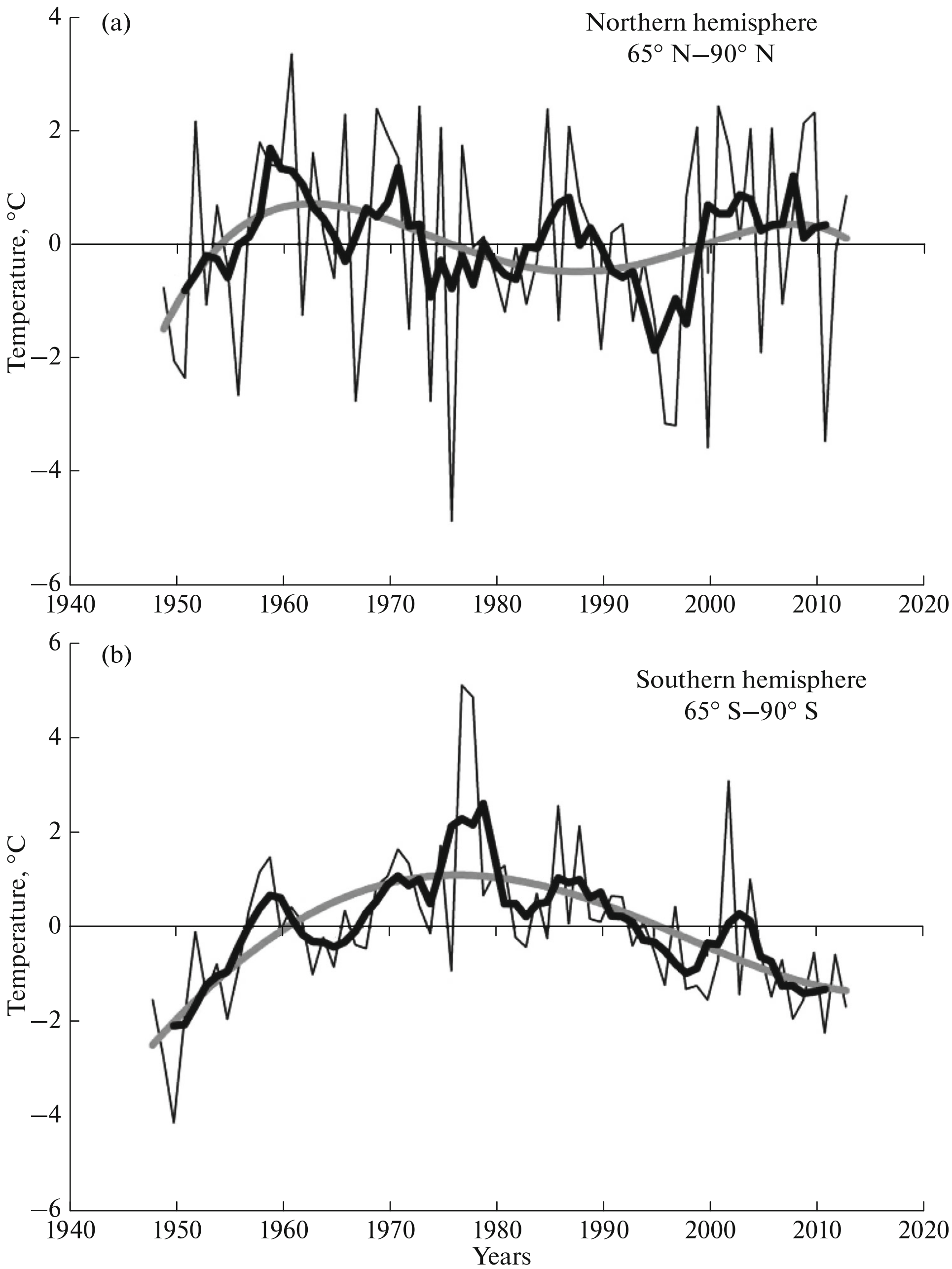

Fig. 6. Variations of temperature at the level 50 hPa in the high-latitude stratosphere at 65°–90° in the Northern (a) and Southern (b) Hemispheres for cold months. Black and gray thick curves show the 5-year running averages and the polynomial smoothing of temperature variations, respectively.

(2014), in the Northern Hemisphere, strong sudden stratospheric warmings (SSWs), which break the vortex, were absent in the period from the late 1980s to the late 1990s, whereas since 2000 such events started occuring partically every year. Thus, the variations in wind velocity and temperature in the stratosphere at high latitudes, as well as the occurrence of strong SSWs indicate a strengthening of the polar vortex in the period from the 1980s to the 1990s and its sharp weakening after 2000.

3. DISCUSSION OF THE RESULTS

The considered data show that, on the decadal temporal scale, the character of correlations between the state of clouds and GCR variations is the same for midlatitudes of both the Northern and Southern Hemispheres and depends on GCR effects on the intensity of cyclonic processes. It was found that the violation of the correlation links under study took place when the vortices sharply weakened in both hemispheres. Thus, the state of the stratospheric polar vortex may considerably influence the development of dynamic response of the atmosphere to phenomena of solar activity and GCR variations and be a possible reason for temporal variability of solar–climatic connections.

Indeed, the state of the vortex plays an important role in the troposphere-stratosphere coupling via planetary waves (e.g., Avdyushin and Danilov, 2000). When the vortex is strong, planetary waves propagating upward are reflected back to the troposphere, which allows the stratosphere to influence the troposphere. When the vortex is weak, these waves freely propagate upward and only the troposphere influences the stratosphere. A strengthening of extratropical cyclogenesis with an increase of GCR fluxes is observed only under a strong vortex; if the vortex is weak, GCR effects become weaker and change the sign (Veretenenko and Ogurtsov, 2012b). The correlation reversal between the intensity of cyclonic processes (and the corresponding changes in clouds) and GCR variations detected under the change of the vortex state seems to provide evidence for an appreciable contribution of the dynamic mechanism to the formation of solar–atmospheric links.

4. CONCLUSIONS

The results of the performed analysis allow us to conclude the following.

(1) The links observed between low clouds and GCR fluxes at midlatitudes of the Northern and Southern Hemispheres in the 11-year solar cycle are caused by the changes in intensity of cyclonic activity.

(2) The positive correlation between LCA at midlatitudes of the Northern and Southern Hemispheres and GCR fluxes was observed in the period from1983 to 2000, when the Arctic and Antarctic polar vortices were strengthened and an increase in GCR fluxes was accompanied by an intensification of cyclonic processes.

(3) The correlation between cloudiness and GCR fluxes was violated in the early 2000s probably due to a sharp weakening of the stratospheric polar vortices of the Northern and Southern Hemispheres, which resulted in the change of GCR contribution to the development of extratropical cyclogenesis.

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