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Nature of Long-Term Correlations between Cloud State and Variations in Galactic Cosmic Ray Flux

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Abstract—The nature of long-term correlations between low cloud anomalies and galactic cosmic ray (GCR) intensity, as well as possible causes of variations in the character of these correlations in the early 2000s, were studied. It was shown that the influence of GCRs on a cloud state at midlatitudes is closely related to GCR effects on variations in extratropical cyclogenesis intensity. The high positive correlation coefficients between low clouds and GCR fluxes observed in 1983–2000 were caused by the fact that increases in GCR fluxes during this period were accompanied by an intensification of cyclonic activity at midlatitudes. The correlation between clouds and GCR fluxes in the early 2000s was possibly violated, because the sign of GCR effects on the development of extratropical baric systems reversed as a result of a change in the stratospheric polar vortex state.

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1. INTRODUCTION

Modulation of the solar energy that comes into the lower atmosphere as a result of cloud cover changes caused by GCR variations is considered as one of possible mechanisms of solar activity (SA) influence on the lower atmosphere circulation, weather, and climate. The hypothesis that GCRs affect cloud formation was proposed by Dickinson (1975) and was subsequently developed in (Tinsley and Deen, 1991; Tinsley and Yu, 2004; Yu, 2002, 2004; etc.). Experimental data indicating that these mechanisms are possible are presented in (Pudovkin and Veretenenko, 1995; Todd and Kniveton, 2001; Svensmark et al., 2009; Laken et al., 2010).

The detected correlations between a cloud state and GCR fluxes on a decadal scale are of especial significance in available experimental data. Based on an analysis of the ISCCP (International Satellite Cloud Climatology Project, http://isccp.giss.nasa.gov/) data, Svensmark and Friis-Christensen (1997) found that the total cloud cover undergoes an 11-year variation, developing in phase with GCR intensity. Further studies (Marsh and Svensmark, 2000) detected that most closely related to GCR variations are changes in low cloud cover area. These researchers presented rather high correlation coefficients between low cloud anomalies averaged over the globe (according to the ISCCP-D2 data) and the Huancayo neutron monitor count rate for 1983–1994 ($R = 0.63$ for unsmoothed values and $R = 0.92$ for running averages over 12 months). However, later works (e.g., (Gray et al., 2010; Erlykin and Wolfendale, 2011; Ogurtsov et al., 2013)) revealed a violation of the correlations between low cloud anomalies and GCR fluxes. The data cast doubt on the GCR effect on cloud formation as well as a possible physical mechanism of solar–atmospheric links, including cloud changes and the effect of these changes on the radiation–thermal balance of the atmosphere (Gray et al., 2010).

Nevertheless, reversals of the correlation sign between the lower atmosphere parameters and different SA characteristics represent a rather common phenomenon in the solar–atmospheric links (see, e.g., the review by Herman and Goldberg (1978); (Georgieva et al., 2007; Veretenenko and Ogurtsov, 2012a)). It was assumed (Veretenenko and Ogurtsov, 2012b, 2014) that a possible reason for temporal variability of SA/GCR effects on the lower atmosphere state is an alternation of large-scale circulation epochs depending on the evolution of the cyclonic vortex in the polar stratosphere (the polar or circumpolar vortex). Therefore, the question arises whether the observed violation of the correlation between low cloud anomalies and GCR fluxes results from a regular change in the character of solar–geophysical effects on the tropospheric circulation.

Thus, our goal was to study the nature of the correlation between a cloud state and GCR fluxes, as well as possible causes of the correlation violation after 2000.

2. RELATION BETWEEN CLOUDS AND DYNAMIC PROCESSES IN THE ATMOSPHERE

As it is known, the main reason for cloud formation is a vertical transport of water vapor and its cooling (see, e.g., (Vorob'ev, 1991)). Therefore, vertical air motions are decisive factors in the formation of a cloud field. At midlatitudes, the most large-scale ascending motions (with horizontal dimensions varying from several hundreds to several thousands of kilometers) are related to baric systems (synoptic objects): cyclones and troughs.

Let us consider vertical motions in an extratropical frontal cyclone. A cyclone is a low pressure area with closed isobars. In the free atmosphere, where friction forces are absent, the forces affecting an air mass (the pressure gradient force, the deflecting Coriolis force, and the centrifugal force) are mutually balanced, and air moves along isobars (the gradient wind). Near the Earth's surface, the wind will acquire the component directed toward the cyclone center due to the friction force action. The convergence of air flows near the Earth's surface results in the origination of ascending motions in the cyclone center (e.g., (Khromov and Petrosyants, 1994)).

At the same time, midlatitude cyclones are as a rule frontal formations. They originate at cold fronts and go through several stages anyhow related to fronts during their evolution (Vorob'ev, 1991). At the first stage of its evolution, a cyclone is a wave at a cold front. The next stage is that of a young cyclone, when a warm sector between warm and cold fronts is formed. As the cyclone develops, the cold and warm fronts start merging, forming an occlusion front. By the beginning of occlusion process, the cyclone reaches the stage of a maximal development. As a result of a further evolution, the cyclone moves into the final stage, which is characterized by a pronounced occlusion front and a warm sector location on the periphery, and starts gradually filling.

We should note that intense vertical air motions are a characteristic feature of atmospheric fronts. At warm fronts, the warm air motion presents ascending sliding along the frontal surface, which results in the formation of powerful systems of Ns–As–Cs stratiform clouds (nimbostratus, altostratus, and cirrostratus), the so-called frontal clouds. In the case of fast moving cold fronts, warm air is more intensively displaced upward, which promotes the development of convection before the surface frontal line and the formation of convective cloud forms (cumulus and cumulonimbus clouds). Atmospheric fronts are closely related to baric troughs (the front lies in a baric trough on its axis).

Thus, a midlatitude cyclone is characterized by cloud systems related to regular vertical motions along frontal surfaces as well as to ascending motions in the cyclone center. On satellite photographs, a well-developed cyclone is observed as a vortex with a clear spiral structure; the cloud field dimensions being comparable with the cyclone dimensions. Clouds of individual atmospheric fronts look like bands, their width and length varying from one to several hundred kilometers and from several hundred to several thousand kilometers, respectively (Vorob'ev, 1991).

The facts presented above indicate that the fields of clouds and pressure are closely interrelated. This relation is also confirmed by the latitudinal and seasonal dependences of cloud fields (Khromov and Petrosyants, 1994). The average annual cloud amount reaches its maximum at 50°–70° latitudes in the Northern and Southern hemispheres, which is related to the maximal development of cyclonic activity at these latitudes. The cloud minimum is observed at 20°–30° latitudes, where subtropical anticyclones are formed. In the regions affected by cyclones, the cloud maximum is observed in winter months, when cyclonic activity is most developed (e.g., in Europe).

3. EXPERIMENTAL DATA AND THEIR ANALYSIS

3.1. Low Cloud Anomalies according to ISCCP Data and Pressure at Midlatitudes

As mentioned above, a cloud field observed from satellites at extratropical latitudes is mainly formed by synoptic objects (cyclones and troughs) and by the systems of their fronts. This makes it possible to assume that the correlation between the variations in clouds and GCR fluxes, detected in the 11-year cycle (Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000), at these latitudes is explained by an indirect influence of cosmic particles, i.e., through variations in the extratropical cyclogenesis intensity, rather than by their direct influence on microphysical processes in clouds. Indeed, several works indicated that variations in solar and galactic cosmic ray fluxes can affect dynamic processes in the lower atmosphere on the timescales from several hours and days to the 11-year cycle. Bursts of solar protons with energies sufficient to penetrate into the stratosphere contribute to a more intense regeneration of cyclones at Arctic and Antarctic fronts (Veretenenko and Thejll, 2013). Decreases in GCR intensity (Forbush decreases) are accompanied by cyclogenesis weakening at midlatitudes and by the intensification of anticyclonic processes (Tinsley and Deen, 1991; Artamonova and Veretenenko, 2011). When GCR fluxes increase at the 11-year cycle minimum, cyclone tracks shift northward (Tinsley, 1988), and cyclonic processes intensify at polar fronts during the period of a strong polar vortex (Veretenenko and Ogurtsov, 2014). All these data indirectly confirm that low cloud anomalies are related to GCR variations in the 11-year solar cycle (Marsh and Svensmark, 2000) through variations of dynamic processes in the lower atmosphere.

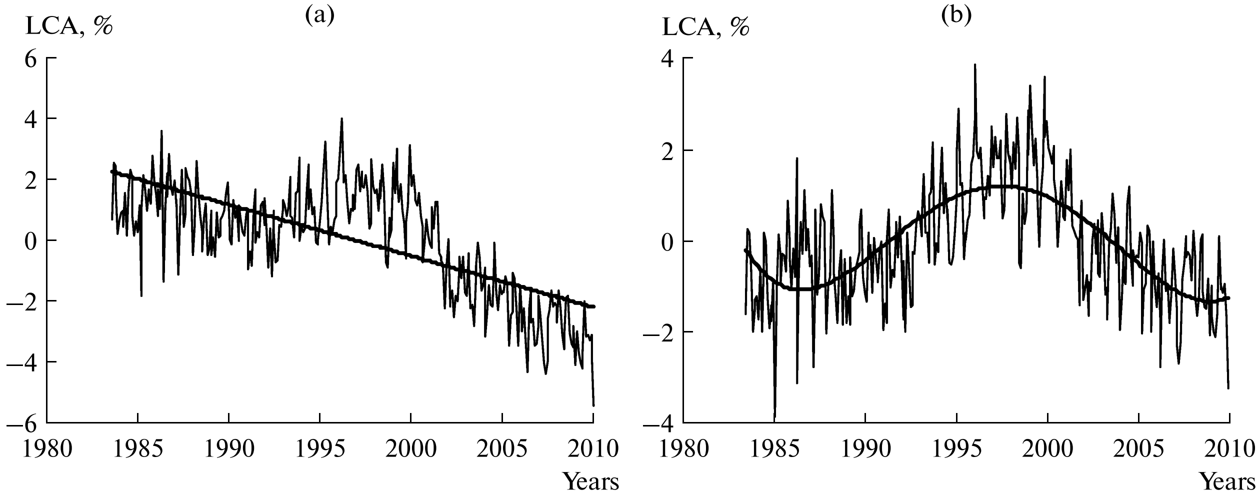

Fig. 1. (a) Time variations in LCAs at midlatitudes (30°–60° N) according to the ISCCP-D2 data (monthly mean values); (b) LCAs after elimination of the linear trend.

Let us consider the ISCCP-D2 data presented in ISCCP archives for the period from July 1983 to December 2009 (ftp://isccp.giss.nasa.gov/pub/data/D2CLOUDTYPES). Depending on the pressure at the cloud top (CP), the ISCCP data correspond to low (CP > 680 hPa), middle (440 hPa < CP < 680 hPa), or high (CP < 440 hPa) clouds. The amount of clouds is determined as an area occupied by clouds during a satellite observation (as a percentage of the total area). Cloud cover anomalies represent the difference between the monthly average amount of a given cloud type and the climatic value (the average cloud amount for a given month during the entire observation period).

Figure 1a presents time variations of low cloud anomalies (LCAs) at midlatitudes (30°–60° N) according to the ISCCP-D2 data. The data presented in Fig. 1a indicate that anomalies in the low cloud amount noticeably decreased from the beginning of the observations to 2009. We should note that LCAs show a rather pronounced variation with the period of about 20 years after elimination of the linear trend (Fig. 1b). The cycles with a period of about 20 years, which is close to the Hale cycle on the Sun, are observed in many climatic parameters (Ohl, 1969; Mitchel et al., 1979; Peristykh and Damon, 1998; Raspopov et al., 2004; etc.) and, in particular, in variations of extratropical cyclogenesis in the North Atlantic (Veretenenko et al., 2007).

Since a cloud field formation at extratropical latitudes is closely related to the development of cyclonic processes, let us consider how the intensity of these processes changed during the time interval under study. The monthly average values of geopotential (gp) heights of the 700 hPa isobaric level (GPH700) from the NCEP/NCAR reanalysis archives (Kalnay et al., 1996), characterizing pressure in the lower troposphere, were used as experimental data. Figure 2a presents time variations of GPH700 values (in gp meters), averaged with area-weighting over the 30°–60° N latitudinal belt, for the entire reanalysis period (from 1948 to 2013). It is evident that the atmospheric pressure at midlatitudes undergoes long-term variations. Pressure was minimal in the 1950s–1960s and increased from the 1970s to ~2010, which indicates that cyclonic activity on average weakened at midlatitudes during that period.

Let us consider the variations of GPH700 anomalies from 1983 to the present. Pressure anomalies were calculated similarly to LCAs; i.e., the climatic average for the period 1983–2013 was subtracted from the GPH700 monthly mean value for the midlatitude belt. Time variations of pressure anomalies are presented in Fig. 2b. It is clear that pressure variations at 30°–60° N during the time interval under study show a positive trend close to linear.

A comparison of LCA (Fig. 1a) and pressure (Fig. 2) time variations at 30°–60° N indicates that the long-term variations (trends) in the studied values are opposite. From 1983 to 2009 pressure at midlatitudes was gradually increasing, and amount of low clouds was decreasing. This can be explained by the fact that weakening of cyclonic processes (on average over the studied latitudinal belt), which is observed as a pressure rise, results in a corresponding decrease of the cloud amount. We should note that anomalies in the pressure and low cloud amount at midlatitudes also change in the opposite phase after elimination of the trends. This is observed in Fig. 3, which presents deviations of the studied values from the linear trends. Thus, the above data indicate that the time variations (both the trends and deviations from the trends) in LCAs and pressure anomalies at 30°–60° N are opposite, which shows close connections between the

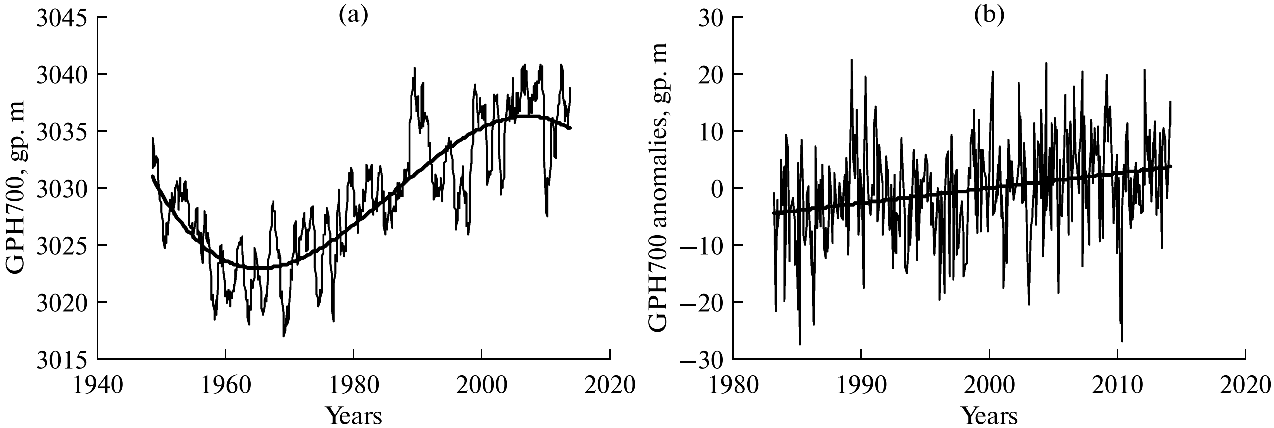

Fig. 2. Time variations (a) of geopotential height of the 700 hPa isobaric level (GPH700) (running averages over 12 months) at 30°–60° N in 1948–2013 (a thick line shows GPH700 smoothing by a polynom of degree 3) and (b) of monthly mean GPH700 anomalies at 30°–60° N in 1983–2013 (the linear trend is shown by a thick line).

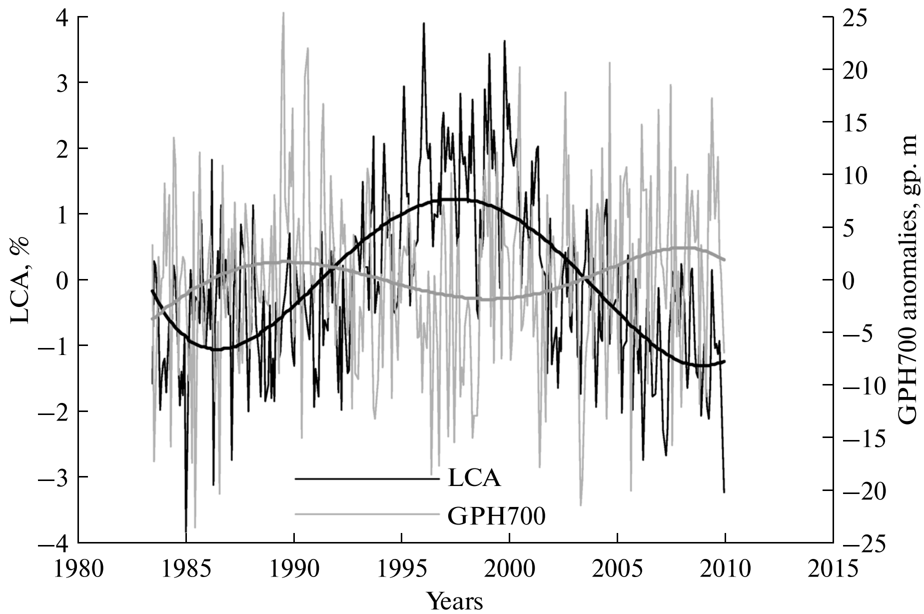

Fig. 3. LCAs and GPH700 anomalies at midlatitudes (30°–60° N) after elimination of linear trends. Polynomial smoothing of anomalies is shown by thick lines.

observed variations of the cloud state and the dynamics of the lower atmosphere.

Now let us consider variations of the average annual low cloud and pressure anomalies at midlatitudes in order to eliminate the seasonal variation from the studied data and decrease noises caused by small-scale processes. Time variations of the studied values for the period 1983–2009 are shown in Fig. 4a. Figure 4a indicates that a pronounced negative correlation between low cloud and pressure anomalies in the troposphere was observed during the entire studied period; i.e., the variations of these parameters develop in opposite phases. The correlation coefficient between LCA and GPH700 average annual values (Fig. 4b) is –0.63 with a statistical significance 0.97, estimated using the phase randomization method (Ebisuzaki, 1997). The correlation coefficient between LCA and GPH700 anomaly values, smoothed over three years, reaches –0.8.

Thus, a comparison of the time variations of low clouds and pressure in the midlatitude troposphere, which characterizes the intensity of cyclonic activity, shows that these variations are closely interrelated. This makes it possible to conclude that the decrease in cloud anomalies observed during the period 1983–2009 can be interpreted first of all as a result of weak-

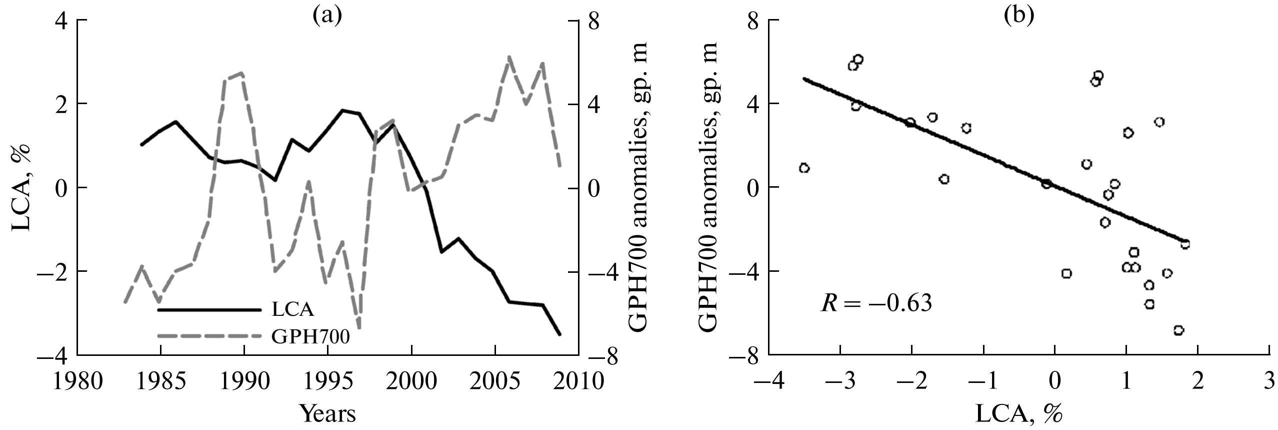

Fig. 4. (a) Time variations of the average monthly values of LCAs and GPH700 anomalies at 30°–60° N; (b) the relationship between the average annual values of LCAs and GPH700 anomalies at 30°–60° N.

ening of cyclonic processes on average in the 30°–60° N latitudinal belt. Weakening of cyclonic activity can be due to a decrease in cyclone areas and intensity as well as to a more intense displacement of cyclones to high latitudes. These assumptions are confirmed by the variations of the large-scale circulation evolution that took place in the late 1970s–early 1980s. Indeed, it was shown (Veretenenko and Ogurtsov, 2014) that in this period the western (zonal) circulation (the W form) started intensifying and the intensity of meridional processes of the E-form started decreasing, these forms being determined by Vangengeim and Girs (Vangengeim, 1952; Girs, 1974). The frequency of occurrence of the C-form meridional processes also started increasing from the early 1980s. C-type processes are characterized by the formation of a crest over the eastern North Atlantic and Europe, which blocks the western transfer over the Atlantic, i.e., it hinders cyclone movement to Eurasian continent. Passing around the crest, North Atlantic cyclones shift northeastward to the polar regions, which can also contribute to a pressure rise at midlatitudes and a decrease of cloud amount. Thus, the pressure (cyclonic activity) variations at 30°–60° N, observed in 1983–2009, are in good agreement with the character of the evolution of the large-scale atmospheric circulation and, in turn, they affect the cloud state.

3.2. Time Variations of GCR Effects on Atmospheric Circulation and Cloud State at Midlatitudes

Having obtained the evidence that the cloud state is closely related to the intensity of dynamic processes at extratropical latitudes, let us now consider the violation of the correlation between clouds and GCR fluxes in the early 21st century. Sign reversals of correlations between parameters of the lower atmosphere and solar–geophysical factors represent a rather common phenomenon for solar–atmospheric links (Herman and Goldberg, 1978; Georgieva et al., 2007, etc.). In the work (Veretenenko and Ogurtsov, 2012a) a ~60-year periodicity was found in the correlation coefficients between pressure at middle and high latitudes and Wolf numbers. It was assumed that this periodicity is caused by the evolution of the large-scale atmospheric circulation, which is in turn related to variations of the state of the stratospheric cyclonic vortex at polar latitudes (the polar or circumpolar vortex). The last sign reversal of the correlation between tropospheric pressure and SA/GCR characteristics was observed in the early 1980s and coincided with a period of sharp changes in the evolution of the main macrocirculation forms (W, E, and C) according to Vangengeim–Girs classification and with the polar vortex transition from a weak state to a stronger one (Veretenenko and Ogurtsov, 2014). Since the vortex evolution is characterized by a ~50–60 year periodicity (Gudkovich et al., 2009; Frolov et al., 2009; Veretenenko and Ogurtsov, 2014), we can assume that a regular change of the vortex state should occur after 2000 accompanied by a change of correlations observed between the lower atmosphere parameters and solar–geophysical indices in ~1980–2000.

Let us consider the relation between pressure variations at midlatitudes and GCR intensity. We used the fluxes of charged cosmic particles (F_{CR}) at the maximum of the transition curve (height 15–25 km) at midlatitude Dolgoprudny station (geomagnetic cutoff rigidity R_c = 2.35 GV) according to the LPI balloon measurements (Stozhkov et al., 2009) in order to characterize GCR intensity. Figure 5a shows time variations of the values of GPH700 average annual anomalies at 30°–60° N and of cosmic particle fluxes in 1983–2013. The values of pressure and particle flux anomalies are presented after removal of linear trends.

Figure 5a indicates that pressure anomalies at midlatitudes and GCR intensity variations changed in opposite phases till 2000; i.e., a pronounced negative correlation was observed between these parameters.

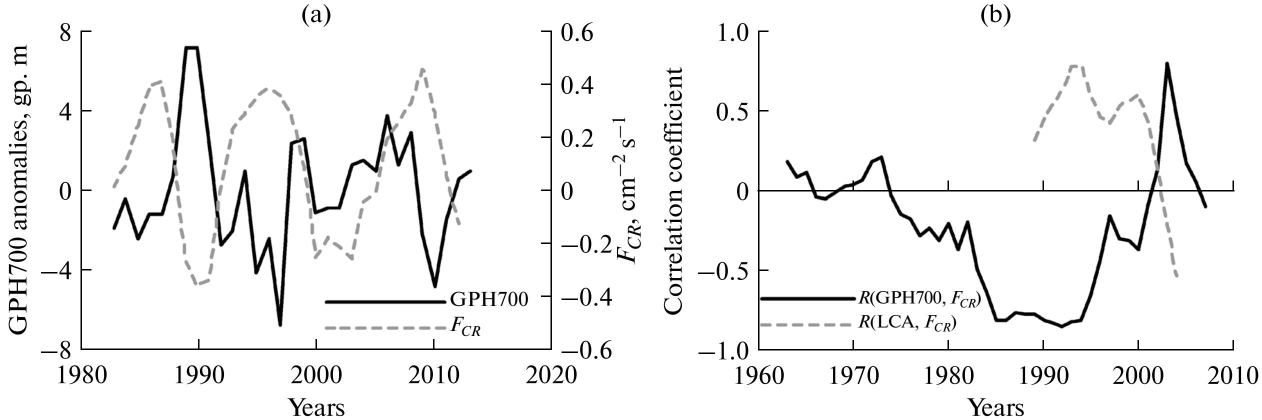

Fig. 5. (a) Average annual values of GPH700 anomalies at 30°–60° N and particle fluxes F_{CR} at the maximum of the transition curve (Dolgoprudny station) (Stozhkov et al., 2009) in 1983–2013; (b) time variations of the correlation coefficients for sliding 11-year intervals R(GPH700, F_{CR}) and R(LCA, F_{CR}).

This result is in good agreement with the data, providing evidence for cyclonic intensification (pressure decrease) at polar fronts with GCR flux increasing during the period 1980–the early 2000s, when the polar vortex was strong (Veretenenko and Ogurtsov, 2012b, 2014). Nevertheless, this correlation was violated in the early 2000s. Pressure and GCR flux anomalies developed in the same phase from 2003 to 2008, but a negative correlation between these parameters appeared again after 2009. Time variations of the correlation coefficients between pressure anomalies at 30°–60° N and particle fluxes for sliding 11-year intervals R(GPH700, F_{CR}) are shown in Fig. 5b (solid line). It is evident that the period from the early 1980s to the mid-1990s was characterized by a rather high negative correlation between pressure and GCR intensity (the correlation coefficients reached –0.8); then a negative correlation started weakening, and the correlation sign abruptly reversed after 2000. The statistical significance of the correlation coefficients was estimated using the Monte Carlo method (sliding correlation coefficients were calculated for 1000 surrogate series obtained by randomization of initial pressure and GCR flux series). According to these estimates, the significance of the correlation coefficients observed from the mid-1980s to the mid-1990s (R varied from approximately –0.7 to –0.8) is 0.97–0.98. An abrupt increase in the correlation coefficient after 2000 is significant at the 0.95 confidence level.

Time variations of the correlation coefficients presented in Fig. 5b suggest long-term (with a period of ~60 years) variations of the amplitude and sign of GCR effects on the midlatitude atmospheric circulation, which agrees with the results obtained in (Veretenenko and Ogurtsov, 2012b, 2014). The correlation sign reversal after 2000 can be caused by the polar vortex transition from a strong state, which was observed from ~1980 to 2000, to a weaker state. The correlation coefficients became negative again after an abrupt increase in the early 2000s, apparently because of fluctuations in the correlation coefficients, which can be observed when the vortex changes its state (Veretenenko and Ogurtsov, 2012a). The assumption of the vortex state changing is confirmed by the data presented in (Ivy et al., 2014), where it was shown that the frequency of sudden stratospheric warmings (SSWs), which result in a vortex decay, has sharply increased since 2000 (in 2000–2010 these events occurred each winter except 2005). In the 1990s, when the highest negative correlation between the pressure and GCR fluxes took place, powerful SSWs were not observed, which indicates that the vortex was stable and strong. We should note that a change in the vortex state and the correlation sign reversal occurred against the background of a decrease in SA to an unusually low level (comparable with the minimum in 1913–1914 according to the number of sunspots), which resulted in the maximal GCR flux intensification during the entire period of instrumental GCR observations (Bazilevskaya et al., 2012).

The data presented above (Fig. 5) make it possible to conclude that a regular variation in the character of solar–atmospheric links after 2000 is caused by a change in the state of the polar vortex. According to the data obtained in (Veretenenko and Ogurtsov, 2012b, 2014), the GCR flux intensification is accompanied by an enhancement of extratropical cyclones only when the vortex is strong, and GCR effects weaken and reverse the sign when the vortex gets weak. Apparently, this effect is caused by different conditions for planetary wave propagation during the periods of a strong and weak vortices, which results in the changes of the stratosphere–troposphere coupling. According to the data obtained in (Perlwitz and Graf, 2001), the stratosphere affects the troposphere only when the vortex is strong, i.e., when upward propagating planetary waves reflect back to the troposphere. When the vortex is weak, planetary waves can freely propagate upward, and only the troposphere affects the stratosphere. Thus, the state of the vortex can affect the transfer of a disturbance, generated by GCRs, from the stratosphere into the troposphere. We should also note that the GCR effect on the intensity of water vapor condensation in the troposphere is important and can contribute to the release of latent heat and the intensification of cyclogenesis (Krymsky, 2002).

Since a cloud field at midlatitudes is closely related to cyclonic processes, the sign reversal of the correlation between cyclogenesis intensity and GCR fluxes, caused by the vortex transition into a weak stage, can be followed by the violation of the correlation between clouds and GCR fluxes, which was observed in the 1980s–1990s (when the vortex was strong). Indeed, time variations of the correlation coefficients between LCAs and particle fluxes R(LCA, F_{CR}) for sliding 11-year intervals (Fig. 5b, dashed line) show that the correlation sign reversed in the early 2000s, which coincided with the sign reversal of the correlation between pressure and particle fluxes. The period when a positive correlation between cloud anomalies and GCR fluxes in the 1990s was maximal ($R \sim 0.6$–0.8, and the statistical significance was 0.97–0.98 according to Monte Carlo estimations) coincided with the period when a negative correlation between pressure and GCR fluxes was most statistically significant. This also confirms the assumption that GCRs affect a cloud state through changes in cyclonic activity.

Thus, we can assume that the change of the correlation between LCAs and GCR fluxes detected after 2000 does not prove the absence of GCR influence on atmospheric processes. This change of the correlation sign only confirms that long-period GCR effects on cloud state variations are indirect, i.e., caused primarily by GCR effects on tropospheric circulation. It does not mean that cosmic rays cannot affect microphysical processes in clouds directly, which might lead to a more intense cloud formation (e.g., according to the mechanisms proposed in (Tinsley and Deen, 1991; Tinsley, 2008; Yu, 2002, 2004)). However, such a direct influence seems to be substantially smaller than the effect of GCRs on clouds through a change of circulation. In the contrary case, the sign of GCR effects on the cloud state variations would remain constant; i.e., the correlation between cloud anomalies and cosmic ray fluxes would not be violated.

Thus, the data presented above indicate that we should take into account the circulation when interpreting the relations observed on long time scales between a cloud state and variations in GCR flux as well as other phenomena related to solar activity (e.g., variations in the total and UV solar radiation). We should also take into account the state of the polar vortex, which apparently modulates SA/GCR effects on the development of extratropical baric formations.

4. CONCLUSIONS

The results of this study showed that the relation between a cloud state at midlatitudes and GCR fluxes on long time scales is indirect, i.e., caused by GCR effects on extratropical cyclogenesis variations. A positive correlation between the cloud amount and GCR intensity, which was observed from 1983 to the early 2000s, is due to the intensification of cyclonic activity when GCR fluxes intensify during the period of a strong polar vortex. Since the GCR effects on the development of extratropical cyclones weaken and reverse the sign when the vortex gets weak, the violation of the indicated correlation in the early 2000s can be related to a change of the polar vortex state. The obtained results give evidence for a rather important role of cosmic ray variations as well as for a modulating effect of the stratospheric polar vortex in solar–atmospheric links.

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