
Galactic Cosmic Rays and Low Clouds: Possible Reasons for Correlation Reversal

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Abstract

Influence of galactic cosmic rays (GCRs) on cloud formation is suggested to be an important part of the mechanism of solar activity influence on weather and climate. A high positive correlation between low cloud amount and GCR fluxes was observed in the 1980s–1990s; however, in the early 2000s, it was violated. In this work, we consider a nature of long-term correlation links between cloud cover at middle latitudes and GCRs, as well as possible reasons for this correlation reversal. It was shown that the GCR-cloud links observed on the decadal time scale are indirect and caused by GCR effects on cyclonic activity which depend on epochs of the large-scale atmospheric circulation. The reversal of GCR-cloud correlation in the 2000s seems to be due to a sharp weakening of the Arctic and Antarctic stratospheric polar vortices, which results in the change of the troposphere-stratosphere coupling and, then, of GCR contribution to the development of extratropical cyclogenesis.

Keywords: solar-atmospheric links, space weather, galactic cosmic rays, low clouds, cyclonic activity, polar vortex

1. Introduction

Studying the influence of solar activity and related phenomena on the lower atmosphere state, weather and climate is one of most actual tasks of solar-terrestrial physics, which is due to an important part of climatic changes for different aspects of human activity. One of the possible mechanisms of this influence suggests an impact of galactic cosmic rays (GCRs) on the cloud cover allowing amplifying noticeably a weak signal of solar variability in the Earth's

atmosphere. Indeed, cloudiness changes can strongly modulate fluxes of both incoming short-wave solar radiation and outgoing long-wave radiation of the Earth and the atmosphere and, thus, influence significantly the radiative-thermal balance of the atmosphere. High-level clouds contribute to the warming of the atmosphere, whereas low-level clouds contribute, as a rule, to its cooling. A net influx of radiation coming to the Earth's surface under cloudy conditions depends on latitude, season and underlying surface. According to the data obtained from spaceborne experiments [Nimbus 7 Earth Radiation Budget experiment (N7ERB) and Earth Radiation Budget Experiment (ERBE)], when averaged over the globe, cloudiness reduces the input of solar radiation by $44.5\text{--}54.3\text{ W}\cdot\text{m}^{-2}$ (depending on the season) and the emission of long-wave radiation to space by $23.6\text{--}34.7\text{ W}\cdot\text{m}^{-2}$ [1, 2]. As a result, cloudiness decreases the global radiative heating of the atmosphere by $17.3\text{--}26.8\text{ W}\cdot\text{m}^{-2}$.

The hypothesis about GCR influence on the cloudiness state was first put forward in 1975 by Dickinson [3]. He suggested that ionization changes due to GCR variations affect the formation of stratospheric aerosols, the main component being a water solution of sulfuric acid H_2SO_4 . Such aerosol particles of $\sim 100\text{ nm}$ in size are effective cloud condensation nuclei (CCN) due to a high solubility of sulfuric acid in water which greatly lowers the saturated vapor pressure over these particles compared with homogenous water nuclei. According to Dickinson's suggestions, the formation of aerosol particles is more probable on positively charged water clusters $\text{H}_3\text{O}^+(\text{H}_2\text{O})_n$ ($n = 5\text{--}7$), the concentration of such clusters depending on ionization in the atmosphere. So, changes in ionization may influence the rate of nucleation processes and, thus, contribute to the formation of high-level (cirrus) clouds.

At present, we can note two possible ways of GCR influence on cloud formation: the ion-mediated (or induced) nucleation [3–7] and the mechanisms including changes in Global Electric Circuit (for example, see [8, 9]). Ion-mediated nucleation (IMN) is the nucleation of aerosol particles (which under certain conditions may later grow up to cloud condensation nuclei) taking place in the presence of ions. An important source of new aerosols in the atmosphere is molecular clusters forming from water and sulfuric acid. However, clusters of subcritical sizes ($<1\text{--}2\text{ nm}$) are unstable and easily destroyed by evaporation. When a cluster reaches a critical size of $\sim 1\text{--}2\text{ nm}$, surface tension forces start dominating and it gets stable. Such clusters represent aerosol nuclei which may grow due to condensation and coagulation up to $\sim 100\text{ nm}$ which allows turning into a cloud condensation nucleus and take part in the formation of cloud particles ($\sim 10\text{--}20\text{ }\mu\text{m}$). Charged molecular clusters forming around ions are more stable due to Coulomb attraction and can grow faster than neutral ones. Then, when ionization increases, a probability of the formation of charged, more stable clusters becomes higher and this results in the increase of the nucleation rate. According to model calculations by Yu and Turco [5], a 25% increase of the ionization rate in the lower atmosphere could lead to an increase of the concentration of aerosol particles capable for the further growth, with the diameter being >3 and $>10\text{ nm}$, by 16.5 and 9%, respectively, in several hours after the nucleation start.

Another way of GCR influence on clouds, which suggests changes in the Global Electric Circuit caused by variation of atmospheric conductivity and ionospheric potential, has been developed by Tinsley and colleagues [8–11]. It is suggested that changes of conductivity due to GCR variations, along with changes of ionospheric potential due to variations of interplanetary

magnetic fields influence a density J_z of downward ionosphere-Earth currents. In turn, these currents, when flowing through high gradients of conductivity at cloud boundaries, contribute to a separation of positive and negative ions which quickly attach to droplets and aerosol particles, including both cloud condensation nuclei and ice-forming nuclei. Electric charges on these particles influence microphysical processes in clouds, enhancing their collision rate and 'sticking' due to Coulomb attraction. In particular, this may result in more intensive freezing of thermodynamically unstable super-cooled water droplets in high-level clouds ('electrofreezing') [10]. An increase of charge on aerosol particles also enhances the rate of their scavenging by larger droplets due to the electric attraction between the charge on a particle and the image charge which it creates on a droplet ('electroscavenging') [11]. Thus, charging cloud particles associated with J_z variations results in a number of microphysical processes in clouds affecting particle concentration and their size distribution.

First experimental data providing evidence for a possible influence of GCRs on the cloudiness formation were obtained by Pudovkin and Veretenenko [12]. They detected a decrease in cloud cover and an increase in the frequency of occurrence of clear-sky days at middle and high latitudes in the course of short-term decreases of GCR intensity (Forbush decreases), with the data at the network of actinometric stations of the U.S.S.R. being used. The decrease of cloud cover associated with Forbush decreases at the stations under study was also confirmed by an increase of the input of total radiation which includes both direct and scattered solar radiation [13]. Later a remarkable result showing cloud-GCR links on the decadal time scale was obtained by Svensmark and Friis-Christensen [14] basing on the satellite data ISCCP (International Satellite Cloud Climatology Project). The authors detected a variation of 3–4% in global cloud amount which was strongly correlated with GCR intensity (the correlation coefficient ~ 0.9) for the period 1984–1991. As a change of global cloud cover by 1% corresponds to a net radiation change by 0.5 W.m^{-2} according to the estimates by Rossow and Cairns [15], Svensmark [16] concluded that the radiative forcing of the detected decrease of global cloud cover by $\sim 3\%$ from 1987 to 1990 (i.e. from a minimum to a maximum of solar activity) may amount to $\sim 1.5 \text{ W.m}^{-2}$. He suggested that cloud forcing associated with long-term GCR variations might explain most part of the temperature changes in the period 1975–1989. The results gave rise to a lively discussion of GCR effects on the formation of clouds, as well as their role in the mechanism of solar-atmospheric links (for example, see [17–19]).

The further studies by Marsh and Svensmark [20, 21] revealed that only low-level cloud amount correlates significantly with GCR intensity. The correlation coefficients between globally averaged values of low cloud anomalies (LCA) according to the ISCCP-D2 satellite data and the counting rate of the Huancayo neutron monitor amount to 0.63 and 0.92 for unsmoothed values and 12-month running averages, respectively, for the period 1984–1994. However, in the second part of the 1990s the positive correlation LCA-GCR started weakening and broke down completely near 2000 [22, 23]. The observed violation of LCA-GCR correlation caused doubts in a possible influence of cosmic rays on cloud formation, as well as their important role in the physical mechanism of solar-atmospheric links [22, 24, 25].

Thus, at the moment cloud-GCR relationship remains a rather controversial question. In different studies, we can find the data both confirming and rebutting a possibility of GCR

influence on cloud formation. Svensmark et al. [26] found a significant decrease of liquid water in low clouds, as well as in fine aerosol concentration associated with strong GCR Forbush decreases. A decrease of high-level clouds over the Antarctic in the course of Forbush decreases of GCR intensity was revealed by Todd and Kniveton [27, 28] as well as Laken and Kniveton [29] on the base of the ISCCP cloud data. Laken et al. [30] detected changes in cloud cover over middle latitudes ($30\text{--}60^\circ$) of both hemispheres associated with short-term changes in GCR intensity, using also the ISCCP data. However, no responses of cloudiness to Forbush decreases were revealed by Čalogović et al. [31], Krissansen-Totton and Davies [32].

As to the decadal time scale, the problem of GCR-cloud relations is complicated because of a number of other solar activity phenomena affecting the atmosphere and conditions for cloudiness formation simultaneously with cosmic rays. Kristjánsson et al. [33, 34] concluded that low cloud cover correlates better with total solar irradiance (TSI) variations than with those of GCRs, the suggested mechanism involving variations in sea surface temperature and their impact on low clouds. In the works by Voiculescu and colleagues [35–37], variations of ultraviolet radiation and solar wind disturbances are considered as possible factors influencing cloudiness state. In particular, it was noted that the effects of GCR and UV variations on cloudiness state are characterized by regional and altitudinal dependencies [36]. In this work the areas of positive and negative correlations were revealed for low cloud amount and GCRs. For middle and high clouds the areas of statistically significant correlations with GCRs and UV radiation were also detected. The data in [37] provide evidence for a possible influence of interplanetary electric fields (IEE) modulated by solar wind speed and interplanetary magnetic fields on cloud formation. The detected cloud-IEE correlations seem to indicate an important part of downward atmospheric currents in the Global Electric Circuit for cloud particle formation, as described in [8–11].

For an experimental verification of a possible influence of cosmic rays on the rate of nucleation and subsequent growth of clusters an experiment CLOUD (Cosmics Leaving OUtdoor Droplets) was carried out at CERN (the European Organization for Nuclear Research) [38]. In this experiment there were investigated processes of cluster formation on the base of sulfuric acid, ammonia and water vapor, as well as ionization influence on these processes. The results of the experiment CLOUD confirmed that in the presence of ions the nucleation rate does really increase by a factor of ~ 10 under conditions typical for the middle troposphere (~ 5 km), the sulfuric acid and water being involved in nucleation. However, under conditions in the lower part of the atmosphere the rate of the formation of clusters with the diameter ~ 1.4 nm was found to be less by a factor of $10\text{--}10,000$ than in the real atmosphere [38]. To reach nucleation rates corresponding to those measured in the lower atmosphere, the content of ammonia had to be substantially increased and the temperature had to be lowered to $\sim 250^\circ\text{C}$ [38, 39]. Another way to enhance nucleation was to add biogenic amines (dimethylamine), as it was reported by Almeida et al. [40]. The results of this study carried out on the base of the CLOUD chamber at CERN showed that dimethylamine can influence significantly nucleation rates and account for the rates observed in the real atmosphere. These results indicate that in the lower atmosphere a ternary nucleation seems to take place, with sulfuric acid, water and bioorganic compounds being involved. However, the rate of the ternary nucleation was found to depend weakly on ionization [40]. On the other hand, the experiments by Svensmark

et al. [41] revealed a noticeable link between the formation of CCN particles ~50 nm and ionization. Thus, the question of GCR influence on the intensity of nucleation and subsequent growth of clusters to CCN sizes remains open and further experiments are needed.

Concerning observations in the real atmosphere, one should stress that direct effects of GCRs and corresponding changes of ionization on microphysical processes in clouds seem to be detectable only on rather short time scales (about several hours or days). On longer time scales dynamic processes developing as a response to GCR variations (or to some other solar activity phenomena) should be taken into account. Indeed, cloud enhancement according to any suggested mechanism (ion-mediated nucleation or mechanisms including atmosphere electricity changes) results in changing radiative-thermal balance in the lower atmosphere and, consequently, in some changes in the structure of thermo-baric fields of the troposphere which, in turn, influence atmospheric circulation and the evolution of baric systems. If changes of the thermo-baric field contribute to the deepening of low-pressure systems (cyclones and troughs), cloud fields of these systems will be enhanced. Thus, monthly averaged cloud amount will include not only direct (microphysical) effects of GCR variations on cloud particle formation, but also indirect effects due to the circulation changes influencing cloudiness. So, when considering cloud data on longer time scales, we cannot distinguish between primary (microphysical) GCR effects on clouds and secondary ones, resulting from circulation changes associated with GCRs. Moreover, direct effects of GCRs on cloud characteristics seem to be weaker than those associated with long-term circulation disturbances. This point seems to be of importance to understand the nature of cloud-GCR correlation on longer time scales.

An important point to be understood concerns the violation of correlations between cloudiness and GCR intensity occurred near 2000. As it was said above, this violation gave rise to doubt the role of GCRs in the mechanism of solar-atmospheric links. However, temporal variability of correlation links between the lower atmosphere characteristics and solar activity characteristics is a rather typical feature of these links. The observed correlations may enhance, weaken or even change the sign depending on time period. Veretenenko and Ogurtsov [42, 43] suggested that this variability may be due to changes of the epochs of the large-scale atmospheric circulation associated, in turn, with changes in the strength of the stratospheric polar vortex. So, the question arises whether the observed violation of cloud-GCR links is a result of a change in the character of helio-geophysical effects on tropospheric circulation. The aim of this study is to consider the nature of correlation links detected between low clouds and GCRs on the decadal time scale, as well as possible reasons for the violation of these links near 2000.

2. CGR effects on atmosphere dynamics and cloud fields

It is well known that the main reason for cloud formation is a vertical transport of water vapor which results in its cooling and condensation (for example, see [44]). So, the formation of cloud fields in the troposphere is determined by upward air movements which, in turn, are closely related to atmospheric circulation.

At extratropical latitudes most large-scale upward movements, with the horizontal extent being from several hundred to several thousand kilometers, are associated with low-pressure systems,

cyclones and troughs. They result from a convergence of air flows near the Earth's surface to the cyclone center or to the trough axis. Upward movements in the atmosphere are also associated with atmospheric fronts which are narrow transition zones between cold and warm air masses. A front is called 'warm', if a warm air mass moves toward a cold one shifting it. Warm fronts are characterized by regular ascending movements of air sliding slowly along a frontal surface. These movements produce strong systems of frontal stratiform clouds Ns-As-Cs (nimbostratus Ns, altostratus As and cirrostratus Cs) with continuous precipitation. Cold fronts arise when a cold air mass moves toward a warm one. Cloud systems of slowly moving cold fronts are similar to those of warm ones. If a cold front is fast moving, vertical velocity of air movements before this front is higher than before a warm one; this contributes to the development of convective clouds, such as cumulonimbus (Cb) with storm precipitation and lightening (for example, [44]). A merging of the cold and warm fronts (so-called 'occlusion') in the process of cyclone evolution results in the formation of an occluded front with the most complex cloud systems. A cloud field of an atmospheric front is seen from satellites as a long band, with the width being usually less than 1000 km and the length reaching several thousand kilometers.

An extratropical cyclone is usually a frontal one, all its evolution being closely related to fronts. First, a cyclone arises as a wave at cold front; then, it passes to the stage of a young cyclone characterized by an existence of a warm sector, i.e. the area of warm air between its cold and warm fronts. At the stage of the maximum development of a cyclone the occlusion starts and an occluded front is formed. At the final stage of cyclone evolution the occlusion continues, a cyclone gets cold and slow and starts filling. A well-developed cyclone can be seen from a satellite as a cloud vortex with a spiral structure, the cloud field dimensions being comparable with those of a cyclone (see **Figure 1**). Thus, frontal cloudiness develops at all the stages of cyclone evolution. This results in a close connection between cloud fields and baric fields of the atmosphere, with baric field changes being accompanied by the evolution of cloud systems.

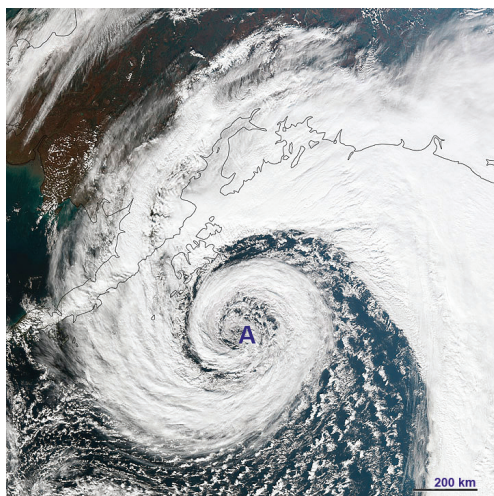


Figure 1. Cloud system of an extratropical cyclone over Alaska gulf (NASA Earth Observatory, photo by Jessy Allen and Robert Simon [45]). The center of the vortex is marked by A.

Let us consider variations of cloud cover at middle latitudes where the intensive cyclonic activity takes place and compare them with pressure variations. As experimental base for this study the cloud data from ISCCP (International Satellite Cloud Climatology Project) [46] available for the period from July 1983 to December 2009 were used. At present it is the most comprehensive and the longest archive of different cloud characteristics. According to ISCCP classification clouds are divided into three types depending on pressure at cloud top (CP): low (CP > 680 hPa), middle (440 hPa < CP < 680 hPa) and high (CP < 440 hPa) clouds. Cloud amount is defined as a fraction of the area covered by clouds of a definite type and is expressed as a percentage of the total area. Anomalies of cloud amount are determined as the difference between monthly values of cloud amount of the studied type and the climatic mean, i.e. cloud amount for a given month averaged over the whole period of observation.

In this study we consider monthly values of low cloud anomalies (LCA) from the ISCCP-D2 archive based on infrared (11 μm) radiance measurements [47]. Low-level cloudiness involves stratus (St), nimbostratus (Ns) and stratocumulus (Sc), it may also involve convective cumulus (Cu). The data were taken for the mid-latitudinal belts 30–60° of both hemispheres which are regions of intensive extratropical cyclogenesis. At these latitudes the ISCCP data are in a rather good agreement with other satellite data (MODIS, UW HIRS), unlike polar ones [48].

In **Figure 2a** and **b**, temporal variations of LCA for the Northern and Southern hemispheres are presented. One can see a gradual decrease of low cloudiness from the early 1980s to 2009,

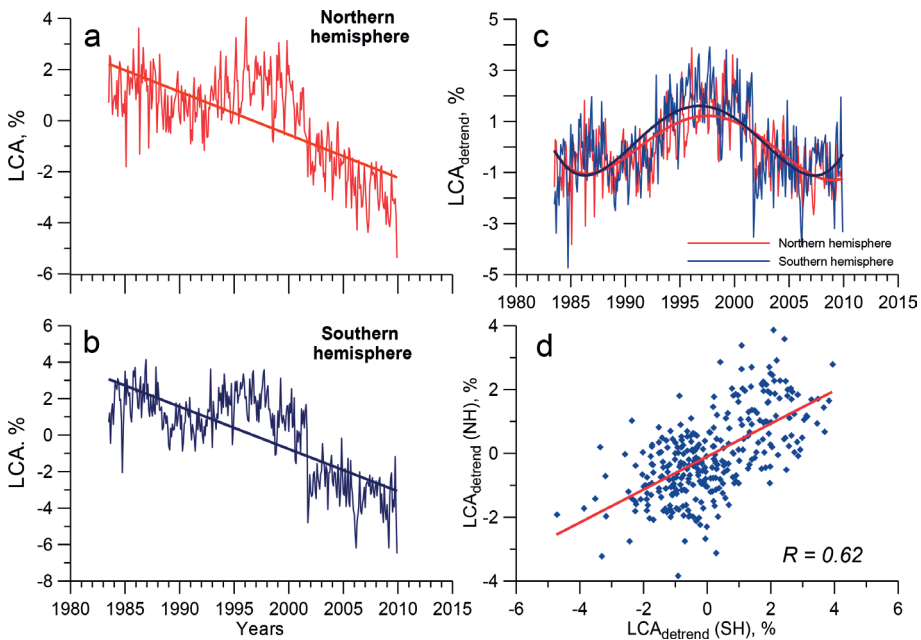


Figure 2. Left: Temporal variations of LCA (monthly values) at the latitudes 30–60° in the Northern (a) and Southern (b) hemispheres. Right: Temporal variations of detrended values of LCA in the Northern and Southern hemispheres (c) and detrended values of LCA in the Northern hemisphere versus those in the Southern one. Thick lines show linear (a, b) and polynomial (c) trends in LCA variations.

a reason for this decrease being not quite clear. According to [49], the trends may be due to some changes in the satellite view angles. However, as it will be shown later, this decrease of cloudiness may be also associated with long-term weakening of cyclonic activity in the belts under study. In any case, for our analysis of cloud-GCR links, we detrend values of LCA and GCR intensity.

Removal of linear trend in LCA reveals (**Figure 2c**) that low cloud anomalies in the Northern and Southern hemispheres have a rather high similarity. The correlation coefficient between these values amounts to 0.62 (**Figure 2d**), the statistical significance being 0.95 according to the random-phase test [50]. LCA variations in both hemispheres seem to be also characterized by a roughly 20-year periodicity. This periodicity, which is close to the magnetic Hale cycle on the Sun, was detected in many climatic parameters (for example, see [51, 52]), including the intensity of extratropical cyclogenesis in the North Atlantic [53]. Thus, the ~20-year periodicity indicates a link between cloudiness and the evolution of dynamic processes in the lower atmosphere.

Let us now compare temporal variations of LCA and GCR intensity. To characterize GCR intensity we used monthly values of charged particle fluxes F_{CR} measured in the stratosphere at ~15–20 km (in the maximum of the transition curve) at the mid-latitudinal station Dolgoprudny (geomagnetic cutoff rigidity $R_c = 2.35$ GV) near Moscow [54]. Variations of LCA and F_{CR} monthly values, the linear trends being subtracted, are presented in **Figure 3**. We can see that till ~2000 LCA and GCR intensity varied in a similar way, but then this similarity was violated. Indeed, the correlation coefficients between yearly values of LCA and GCR fluxes for sliding 11-year intervals (**Figure 4**) show that cloud-GCR links were the closest in both hemispheres from the middle 1980s to the middle 1990s, the correlation coefficients amounting to ~0.6–0.8. The statistical significance levels (dotted lines in **Figure 4**) for the correlation coefficients were estimated on the base of Monte-Carlo simulations of sliding coefficients for surrogate time series obtained by a randomization of initial ones. In the indicated period the cloud-GCR correlations were most significant (the significance level 0.95–0.99), but since ~2000 they started to decrease sharply and in the early 2000s correlation became negative in both hemispheres.

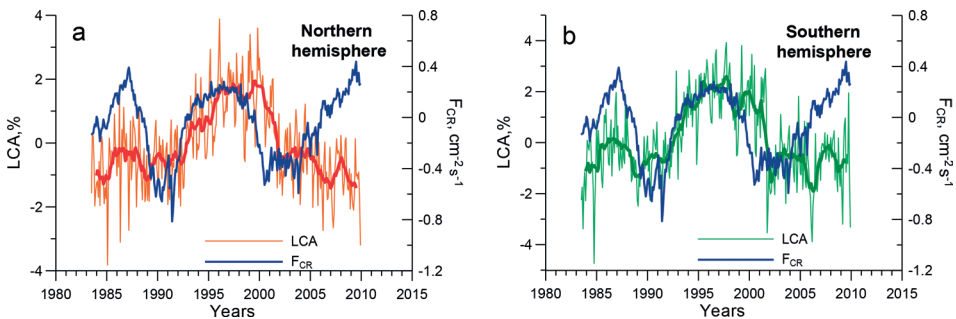


Figure 3. Temporal variations of detrended monthly values of LCA and GCR fluxes in the Northern (a) and Southern (b) hemispheres. Thick lines show 12-month running averages of LCA.

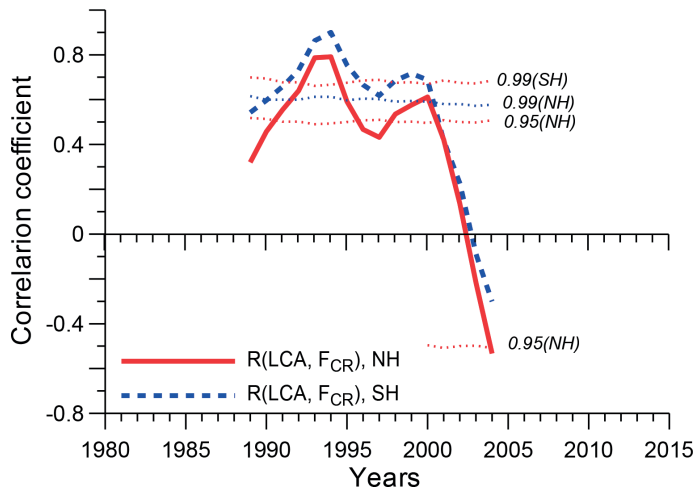


Figure 4. Correlation coefficients between yearly values of LCA and GCR fluxes for sliding 11-year intervals in the Northern (solid red line) and Southern (dashed blue line) hemispheres. Dotted lines show the significance levels of the correlation coefficients.

Taking into account a close link between cloudiness and dynamic processes in the atmosphere, let us consider pressure variations at middle latitudes. As a characteristic of pressure we used geopotential heights of the pressure level 700 hPa (GPH700), taken from NCEP/NCAR reanalysis archive [55]. The indicated level is related to the free atmosphere where effects of Earth's surface friction on air motion are negligible, and its heights correlate well with surface pressure. Temporal variations of 12-month running averages of GPH700 values area-averaged over the belts 30–60° in both hemispheres are shown in **Figure 5** for the period 1948–2013. One can see that long-term variations of pressure differ noticeably in these belts, which implies that cyclonic processes at middle latitudes of the Northern and Southern hemispheres develop to a great extent independently. However, during the period of ISCCP observations (1983–2009) pressure in the studied belts was gradually increasing, i.e. cyclonic processes were weakening. As cloud fields are produced by upward air movements closely associated with large-scale low-pressure areas, a weakening of cyclonic processes had to result in a decrease of cloud cover. Thus, LCA decrease during the period 1983–2009 is consistent with observed pressure changes.

In **Figure 6a** and **b**, pressure (GPH700) anomalies in the belts 30–60°N (S), calculated similarly to low cloud anomalies, are compared with GCR variations, with the data being averaged over a year and the linear trends being removed. From the early 1980s to ~2000 pressure at middle latitudes of the Northern hemisphere and GCR variations developed in the opposite phases, i.e. GCR increases were accompanied by cyclone intensification and pressure decrease, which agrees well with the effects detected in [42]. However, this link was destroyed near 2000. A similar situation took place in the Southern hemisphere. However, unlike the Northern one, where GCR effects are pronounced in almost all the belt 30–60°, GCR effects on cyclone evolution in the Southern hemisphere are restricted by the areas of climatic lows near

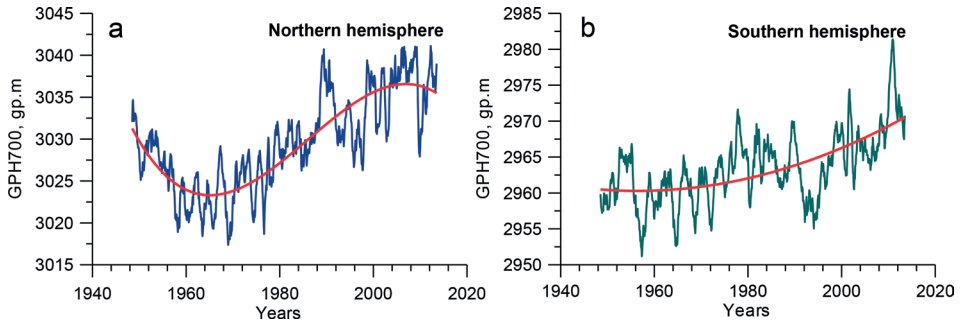


Figure 5. Long-term variations of tropospheric pressure (12-month running averages of GPH700) in the belts 30–60° of the Northern (a) and Southern (b) hemispheres. Red lines show polynomial trends.

Antarctic coasts in the South Atlantic and the Indian ocean, as well at climatic Polar fronts over the South Pacific [42]. So, GPH700 anomalies for the Southern hemisphere (**Figure 6b**) were calculated for these cyclonic areas.

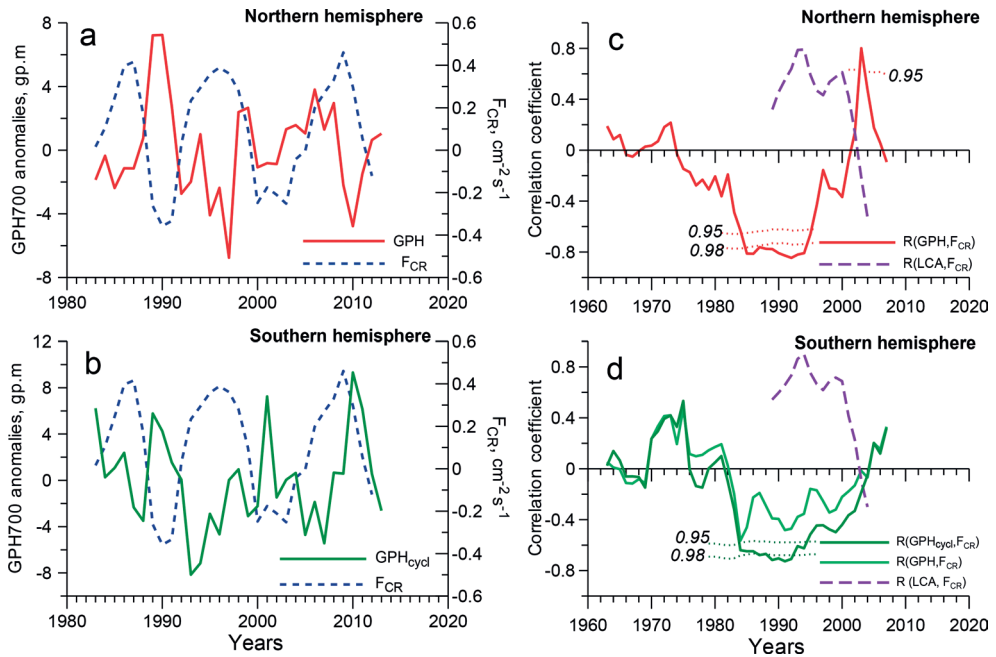


Figure 6. Left: Temporal variations of GPH700 anomalies in the belts 30–60° and GCR fluxes (detrended yearly values) in the Northern (a) and Southern (b) hemispheres. Right: Correlation coefficients for sliding 11-year intervals between LCA and GCR fluxes (dashed lines), GPH700 anomalies and GCR fluxes (solid lines) in the Northern (c) and Southern (d) hemispheres. In the Southern hemisphere, the correlation coefficients are shown for the whole belt 30–60°S (light green line) and for the cyclonic areas (dark green line). Dotted lines show the significance levels of the correlations coefficients between GPH700 and GCR fluxes.

Thus, the data presented in **Figure 6** (left) show that before ~2000 GCR increases in the solar minima contributed to extratropical cyclone intensification at middle latitudes of both hemispheres, but near 2000 the character of the pressure-GCR link was abruptly changed. This is confirmed by the temporal behavior of correlation coefficients for sliding 11-year intervals between detrended yearly values of GPH700 anomalies and GCR fluxes shown in **Figure 6** (right). From the middle 1980s to the middle 1990s, the strongest negative correlation, with $R(\text{GPH}, F_{\text{CR}})$ reaching approximately -0.8 and statistically significant at the level 0.98 according to Monte-Carlo estimates, was observed throughout the mid-latitudinal belt of the Northern hemisphere and in the cyclonic areas of the Southern one. In this period we can see the most pronounced positive correlation between low clouds and GCR fluxes which is consistent with GCR effects on cyclone development. Then, a negative correlation between pressure and GCR fluxes started weakening and its sign reversal took place in the early 2000s. Simultaneously with the weakening of the pressure-GCR correlation, we observe the corresponding weakening of a positive correlation between low clouds and GCR variations, as well as this correlation turning negative in the early 2000s. Thus, the obtained results suggest that cloud-GCR correlation links at middle latitudes observed on the decadal time scale are closely related to GCR effects on the development of cyclonic processes.

3. Polar vortex as a possible reason for the variability of GCR effects on the lower atmosphere

It is well known that temporal variability is a characteristic feature of solar-atmospheric links (see, for example, [56]). Correlation links observed between lower atmosphere characteristics and phenomena related to solar activity may weaken, disappear and even change sign depending on time period. So, a violation of the cloud-GCR link in the 2000s is not an extraordinary event. Herman and Goldberg [56] suggested that a reason for temporal variability of solar-atmospheric links may be long-term processes of the Sun which do not influence sunspot numbers and/or some changes of atmospheric conditions. Veretenenko and Ogurtsov [42, 43] showed that temporal behavior of correlation links between surface pressure at extratropical latitudes and sunspot numbers is characterized by a roughly 60-year periodicity caused by changes in the epochs of the large-scale atmospheric circulation. The reversals of the correlation signs were found in the end of the nineteenth century, in the early 1920s, the 1950s and the early 1980s coinciding with climatic regime shifts at middle latitudes [57], as well as with the transitions between cold and warm epochs in the Arctic [58]. So, a violation of the cloud-GCR link in the 2000s seems not to be unexpected and may be associated with the next change of the circulation epochs resulting in the change of GCR contribution to extratropical cyclonic activity and, then, to cloud field formation.

According to the suggestions in [58], the changes of the circulation epochs are closely related to the state of the polar vortex. The polar vortex is a cyclonic circulation forming in a cold air mass in the polar region of the Northern and Southern hemispheres and spreading from the middle troposphere to the upper stratosphere. A circular air motion in the vortex results

in a decrease of heat exchange between polar and middle latitudes and this contributes to a temperature drop inside the vortex and an increase of temperature gradients at its edges (see **Figure 7**). The vortex can also be seen as a region of enhanced velocity of zonal winds in the stratosphere during cold months for the given hemisphere, the highest values being observed at latitudes 50–80° at the pressure levels above 50 hPa.

The polar vortex is an important factor of the large-scale atmospheric circulation and climate variability. Gudkovich et al. [58] showed that the rotation of cold and warm epochs in the Arctic are caused by changes of the vortex intensity, warm and cold epochs being associated with a strong and weak vortex, respectively. Indeed, under strong vortex conditions cyclone tracks are shifted to the north [59] and more North-Atlantic cyclones arrive in the polar region bringing warm air. An important feature of the polar vortex is its influence on the troposphere-stratosphere coupling via planetary waves. Propagation of planetary waves upward depends on stratospheric circulation (for example, [60, 61]). If the vortex is strong and a velocity of western winds in the stratosphere exceeds some critical value, these waves are reflected back to the troposphere. If the vortex is weak, planetary waves propagate freely upward. So, the stratosphere may influence the troposphere under a strong vortex regime. Under a weak vortex, only the troposphere may influence the stratosphere. This point seems to be of importance to understand the observed temporal variability of solar activity/GCR effects on tropospheric circulation.

Let us consider variations of the polar vortex intensity and compare them with temporal behavior of GCR effects on cyclonic activity and clouds. To characterize the vortex strength, we used zonally averaged velocity of western winds (i.e. the U-component of wind velocity directed from west to east from [55]) at the level 50 hPa (~20 km). In **Figure 8** (top panel) there are presented variations (detrended values) of mean zonal wind velocity in the belts 60–80° in both hemispheres averaged for six cold months (October–March in the Northern hemisphere and April–September in the Southern one). The correlation coefficients $R(\text{GPH}, F_{\text{CR}})$ and $R(\text{LCA}, F_{\text{CR}})$ for sliding 11-year intervals are shown in **Figure 8** (bottom panel).

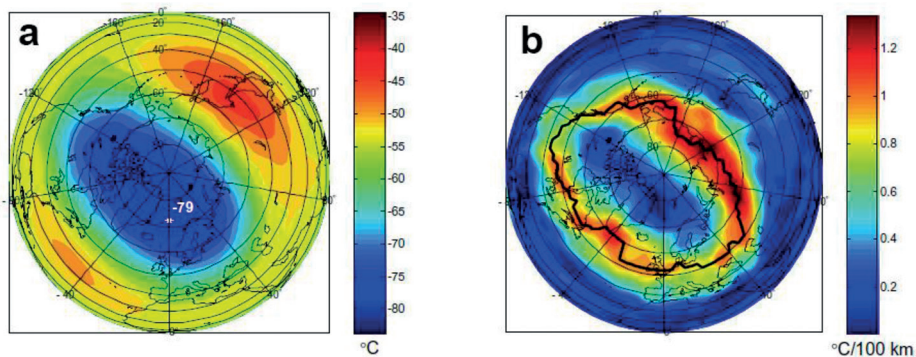


Figure 7. Distribution of mean monthly temperature at the pressure level 20 hPa (a) and of magnitude of horizontal temperature gradients (b) in the Northern hemisphere in January 2005. White asterisk indicates a minimum of temperature in the vortex; thick black line connects the points of maximal values of the temperature gradient at given latitude.

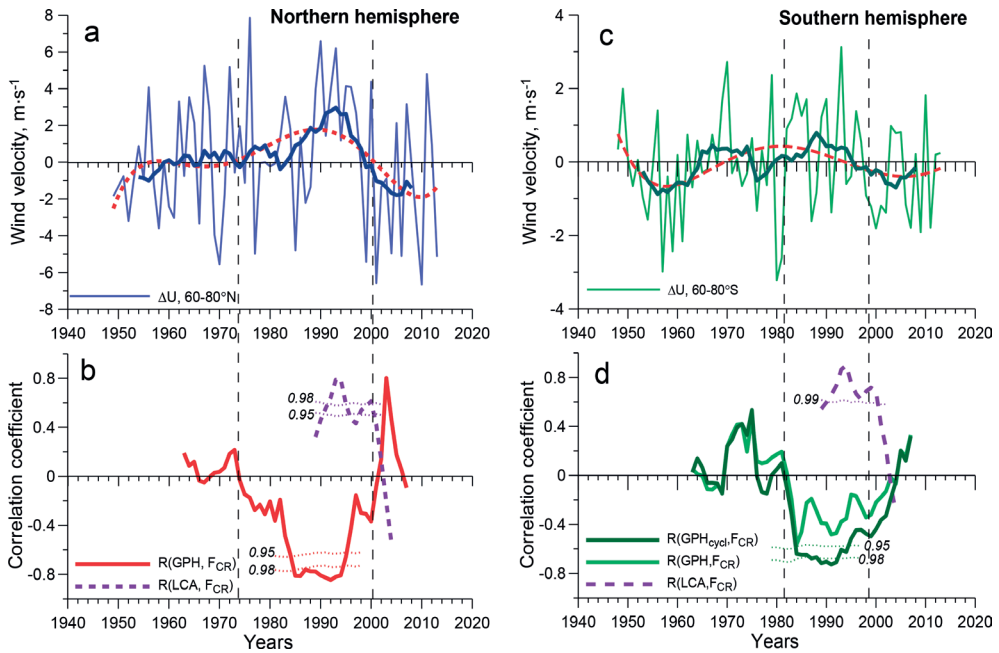


Figure 8. Top: Variations of mean zonal velocity of western winds (the U-component) at the stratospheric level 50 hPa in the belt 60–80° for cold months in the Northern (a) and Southern (c) hemispheres. Thick lines show 11-year running averages and polynomial fits. Bottom: Correlation coefficients for sliding 11-year intervals between LCA and GCR fluxes (dashed lines), GPH700 anomalies and GCR fluxes (solid lines) in the Northern (b) and Southern (d) hemispheres. Dotted lines show the significance levels of the correlation coefficients. The period of an enhanced vortex is marked by vertical dashed lines.

From the middle 1980s to the middle 1990s the polar vortices in both hemispheres were enhanced. The vortex enhancement was the most prominent in the Northern hemisphere, the wind velocity increasing up to 4–7 $\text{m}\cdot\text{s}^{-1}$ relative to the trend values. This agrees well with the data [62] showing no strong sudden stratospheric warming destroying the vortex in the indicated period. The vortex in the Southern hemisphere is more stable than that in the Northern one; however, we can also see a noticeable increase in wind velocity. The data in **Figure 8** show that in the period of the vortex enhancement most statistically significant correlations between pressure (cyclonic intensity) and GCR fluxes, as well as between low clouds and GCR fluxes take place. In the late 1990s both the vortices and the correlations GPH–GCR and LCA–GCR in both hemispheres started weakening. A sharp decrease of the wind velocities resulting in the vortex transition to its weak state occurred near 2000 in both hemispheres. The reversal of correlation coefficients under study coincided well with the transition of the vortices to a weak state. Thus, the presented data allow suggesting that the violation of the correlation between low cloudiness and GCR intensity detected on the decadal scale is closely related to the change of the polar vortex strength.

The results of this study confirm that the changes of the atmosphere state, in particular, of the intensity of the stratospheric polar vortex, may be a real reason for the observed temporal variability of solar-atmospheric links. Indeed, sign reversals of correlation links between

troposphere pressure in the Northern hemisphere and sunspot numbers during the twentieth century coincided with the changes in the evolution of the large-scale circulation, which, in turn, were associated with the polar vortex transitions from one state to another [42, 43]. A roughly 60-year periodicity was revealed in the vortex strength, the phases of the Arctic Oscillation being used as a proxy of the vortex intensity [43], which is consistent with a similar periodicity found earlier in correlation links between pressure at extratropical latitudes and sunspot numbers [42]. Thus, the data presented in this study revealed the next change of the vortex state, which resulted in the reversal of correlation links between atmosphere characteristics and phenomena associated with solar activity.

The detected modulation of long-term solar activity/GCR effects on troposphere dynamics by the polar vortex state seems to be due to its role in troposphere-stratosphere coupling via planetary waves. As it was said above, the stratosphere may influence the troposphere only under a strong vortex regime when planetary waves are reflected back to the troposphere. Hence, a strong vortex regime seems to be more favorable to transfer a signal produced in the polar stratosphere by GCRs (or other solar activity phenomena) to the troposphere, as changes in the vortex formation region may influence its intensity and, then, conditions for propagation of planetary waves. Indeed, we can see that GCR effects on cyclonic activity are most pronounced under a strong vortex (see **Figures 6 and 8**) that agrees well with the previous data [42]. Thus, the results of this study provide new evidence for an important part of the polar vortex in the mechanism of solar activity/GCR influence on the troposphere dynamics on the decadal and longer time scales.

Let us note a favorable location of the vortex for GCR effects on the lower atmosphere. The vortex is formed in the region of low geomagnetic cutoff rigidities ($R_c < 2\text{--}3$ GV) that allows particles with a broad energy range to precipitate, including low-energy GCR component which is strongly modulated by solar activity. Wind velocities in the vortex reach maximal values at the heights $\sim 20\text{--}30$ km where the maximum of the transition curve is observed [63]. This height range also involves the layer of stratospheric aerosols consisting mainly of water solution of sulfuric acid (the Junge layer) (for example, [64]). This creates conditions for influence of ionization changes on aerosol formation which, in turn, may influence the radiative-thermal balance and temperature in the stratosphere and, as a result, the vortex characteristics.

We should also stress that the data presented above do not imply a lack of GCR influence on microphysical processes in clouds. However, they suggest that the formation of cloud-GCR correlation links differs depending on the time scale. GCR variations may influence nucleation rates and growth of particles in clouds according to IMN and/or electric mechanisms [3–11], but this influence may be detected only on rather short time scales (from hours to several days) until the response of atmosphere dynamics to radiative forcing of cloud changes enhances or weakens initial microphysical effects. On longer time scale direct effects of GCRs on cloud formation are masked by more powerful indirect effects through circulation changes associated with GCR variations, these indirect effects depending on the polar vortex state. Taking into account this suggestion, the violation of cloud-GCR correlation links detected near 2000 may be explained.

4. Conclusion

The question of cloud-GCR links remains controversial and requires new studies, both experimental and theoretical, to evaluate a real contribution of galactic cosmic rays to solar activity influence on the Earth's climate. The data presented in this chapter show that possible links between clouds and GCR variations on the decadal and longer time scales could involve not only direct (microphysical) effects, but mostly indirect ones mediated by circulation changes. This should be taken into account when considering long-term GCR effects on the cloudiness state.

An important part in the formation of long-term GCR effects on cloud cover at extratropical latitudes seems to be played by the stratospheric polar vortex. The state of the vortex controls the stratosphere-troposphere coupling creating more favorable conditions for GCR influence on extratropical cyclonic activity and, consequently, on cloud cover under a strong vortex regime. In this connection, a high positive correlation of low cloudiness and GCR variations in the 1980s–1990s, which was the period of a strong vortex, may be explained by a pronounced intensification of extratropical cyclones associated with GCR increases in the minima of the 11-year solar cycle. A sharp change of the vortex state near 2000 both in the Northern and Southern hemispheres altered the character of GCR effects on cyclone evolution and, thus, resulted in a violation of cloud-GCR correlation links observed earlier under strong vortex conditions.

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