Low Clouds and Cosmic Rays: Possible Reasons for Correlation Changes

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Abstract In this work we investigated the nature of correlations between low cloud cover anomalies (LCA) and galactic cosmic ray (GCR) variations detected on the decadal time scale, as well as possible reasons for the violation of these correlations in the early 2000s. It was shown that the link between cloud cover at middle latitudes and GCR fluxes is not direct, but it is realized through GCR influence on the development of extratropical baric systems (cyclones and troughs) which form cloud field. As the sign of GCR effects on the troposphere dynamics seems to depend on the strength of the stratospheric polar vortex, a possible reason for the violation of a positive correlation between LCA and GCR fluxes in the early 2000s may be the change of the vortex state which resulted in the reversal of GCR effects on extratropical cyclone development.

Key words: solar-atmospheric links, cosmic rays, extratropical cyclones, clouds.

Introduction

In the last two decades the hypothesis that cloud cover changes associated with galactic cosmic ray (GCR) variations is an important link in solar-climate connections has been widely discussed. This idea was first proposed by Dickinson (1975) who suggested that GCR may influence high-level clouds resulting in changes of the radiative and thermal budget of the atmosphere. Possible mechanisms for GCR influence on cloud formation were developed later in a number of works (Tinsley and Deen, 1991; Tinsley and Yu, 2004; Tinsley, 2008; Yu, 2002, 2004; etc.). Experimental data confirming a possibility of such links were obtained by Pudovkin and Veretenenko (1995). They detected cloud amount reduction at middle and high latitudes in the course of short-term decreases of GCR fluxes (Forbush decreases) using the data from ground-based actinometric stations. On the decadal time scale a prominent result was obtained by Svensmark and Friis-Christensen (1997) who showed a strong positive correlation of monthly values of global cloud amount and galactic cosmic rays, the data by satellite observations ISCCP (International Satellite Cloud Climatology Project) being used. These results gave rise to intensive discussion of GCR effects (Kernthaler et al., 1999; Gierens and Ponater, 1999; Jørgensen and Hansen, 2000; etc). The further research by March and Svensmark (2000) revealed that only low clouds correlate with GCR positively. According to their data, the correlation coefficient between globally averaged low cloud anomalies (LCA) and the neutron monitor counting rate (Huancayo) amounts to 0.63 increasing up to 0.92 for the 12-month running means in the period 1983-1994. However, in the second part of the 1990s the correlation between low clouds and GCR fluxes started decreasing and the sign reversal took place in the early 2000s (Gray et al., 2010, Ogurtsov et al., 2013). These data gave rise to doubt a possible influence of cosmic rays on cloudiness, as well as their role in solar-atmospheric links (Sloan and Wolfendale, 2008; Erlykin and Wolfendale, 2011; Gray et al., 2010).

Indeed, the GCR-cloud correlations remain a rather controversial question. Svensmark et al. (2009) found significant changes of cloud water and aerosol content associated with strong Forbush decreases of GCR, while Čalogović et al. (2010), Krissansen-Totton and Davies (2013) did not find any cloud response to similar events. Effects of short-term GCR variations on clouds were detected by Todd and Kniveton (2001, 2004), Laken et al. (2010). However, Kristjánsson et al. (2002, 2004) concluded that on the decadal time scale low clouds correlate better with solar irradiance than with GCR fluxes. On the other hand, regional and altitudinal dependences of correlations between clouds and variations of GCR, as well as UV radiation were reported by some authors (Voiculescu et al., 2006). In particular, Voiculescu and Usoskin (2012) detected a regional dependence of GCR effects on low clouds, with the regions of positive and negative correlations. Areas of significant correlations were detected between GCR/UV radiation and middle and high clouds. All mentioned above indicates a complexity of the influence of GCRs (and perhaps of other solar activity factors) on the state of clouds.

Thus, links between cloudiness variations and cosmic rays have not been well understood yet. The aim of this work is to study the nature of links between low cloud anomalies and cosmic rays observed at middle latitudes on the decadal time scale, as well as to consider possible reasons for the violation of positive LCA-GCR correlations in the early 2000s.

Cloud field at extratropical latitudes and its link to the atmosphere dynamics

It is well known that clouds form due to condensation and sublimation of water vapor in the atmosphere when air, warmed near the Earth's surface and containing water vapor, rises and cools (e.g., Vorobjev, 1991). So, the main reason for cloud formation is a vertical transport and cooling of water vapor. Let us consider what processes in the atmosphere contribute to a vertical air movement and cloud field formation.

Depending on horizontal dimensions vertical air movements in the atmosphere may be micro-, meso- or macro-scale (e.g., Matveev, 2000). Most large, macro-scale vertical movements, with the horizontal dimensions being from several hundred to several thousand kilometers, are closely related to baric systems (synoptic vortices). In low pressure areas (cyclones and troughs) a convergence of air flows takes place near the Earth's surface resulting in upward air movements. On the contrary, in high pressure areas (anticyclones and crests) there is a divergence of air flows and downward air movements.

There are also vertical upward movements at atmospheric fronts (narrow bands separating cold and warm air masses) which are closely related with troughs (fronts are located at the axes of troughs). A front may be warm or cold depending on air mass movement. If a warm air mass moves toward a cold one and shifts it, a front is called 'warm', and vice versa. Atmospheric fronts are characterized by regular ascending movements of air along a frontal surface which results in the formation of strong systems of stratiform clouds Ns-As-Cs (nimbostratus Ns, altostratus As and cirrostratus Cs). In the case of a fast moving cold front warm air is displaced upward more intensively, so the additional formation of vertical development clouds (cumulonimbus Cb) takes place..

Considering the evolution of a frontal cyclone at middle latitudes, we can see that it involves atmospheric fronts at all the stages (e.g., Vorobjev, 1991). At the initial stage a cyclone is a wave at a cold front. The next stage (the stage of a young cyclone) is characterized by the existence of a warm sector between the cold and warm fronts. At the stage of a maximum development the cyclone occlusion starts, i.e. the cold and warm fronts start merging, with the occluded front being formed and a warm sector being displaced to the cyclone periphery. At the final stage the occlusion (the occluded front formation) continues accompanied by the filling of a cyclone. So, in addition to clouds associated with upward movements due to the convergence of air flows in the cyclone center, frontal stratiform cloudiness is observed at all the stages of the cyclone evolution. Cloud systems of a cold front and an extratropical cyclone in the Northern hemisphere as seen from satellites are shown in Figure 1 according to the data given by Vorobjev (1991). The cloud field of an atmospheric front represents a long band, the width being from one to several hundred kilometers and the

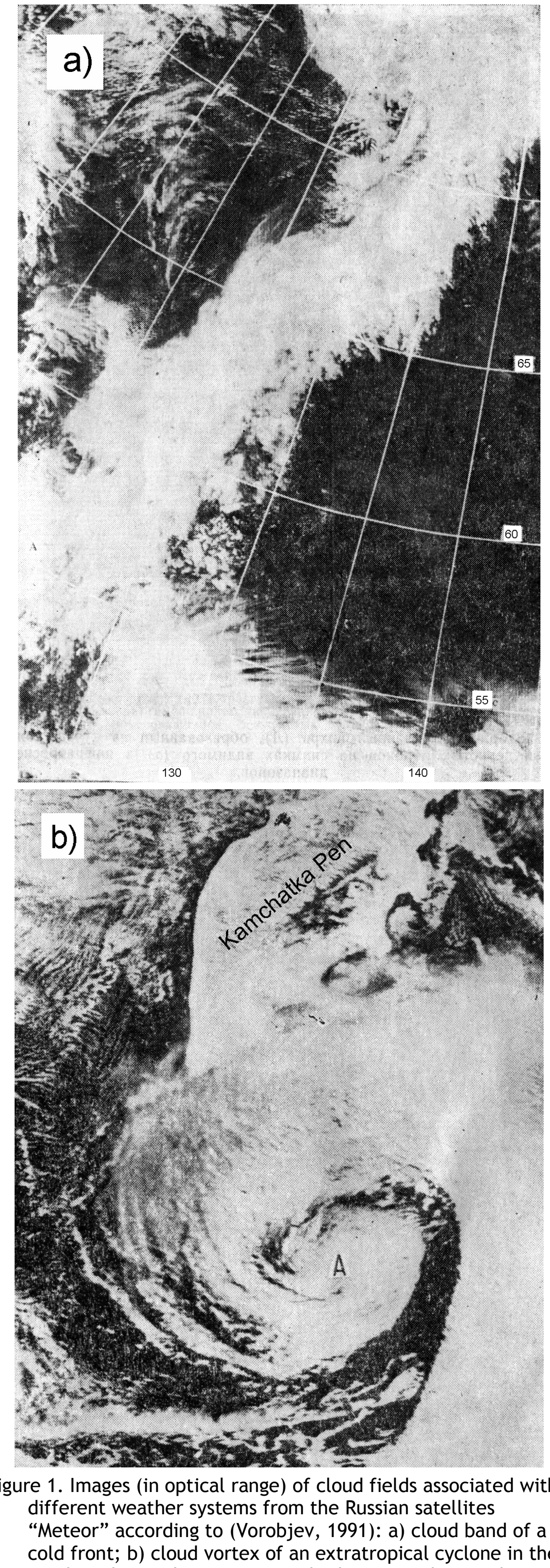

Figure 1. Images (in optical range) of cloud fields associated with different weather systems from the Russian satellites "Meteor" according to (Vorobjev, 1991): a) cloud band of a cold front; b) cloud vortex of an extratropical cyclone in the Northern hemisphere over Kamchatka peninsula (A indicates the center of the vortex).

length being up to several thousand kilometers. A well-developed cyclone is seen as a cloud vortex with a spiral structure and the horizontal dimensions comparable with the dimensions of a cyclone, i.e. up to several thousand kilometers.

Thus, cloudiness at extratropical latitudes is closely related to the atmosphere dynamics. Upward movements associated with large-scale weather systems such as atmospheric fronts and cyclones contribute significantly to the formation of a cloud field. As a result, a rather strong correlation may be observed between the income of total solar radiation to the Earth's surface which is influenced by cloud cover (the total solar radiation Q is the sum of direct and scattered radiation and decreases significantly with the increase of cloud amount) and pressure variations arising due to baric system development. In the earlier work Veretenenko and Pudovkin (1999) showed that there is a negative correlation between half-yearly sums of total radiation ΣQ at high-latitudinal stations and galactic cosmic ray variations. It was suggested that this link is realized through GCR influence on atmospheric circulation which in turn influences the cloud cover and, consequently, the solar radiation input. Let us consider if it is really so. In Figure 2 the solar radiation input at the stations at high latitudes 65-68°N, the data being taken from (Veretenenko and Pudovkin, 1999), is compared with pressure variations characterized by geopotential heights of the 1000 hPa isobaric level (GPH1000) according to NCEP/NCAR reanalysis data (Kalany et al., 1996). The stations under study (Arkhangelsk, Turukhansk, Olenek, Verkhoyansk) are located in the regions characterized by a rather high frequency of occurrence of extratropical cyclones (Vorobjev, 1991). Indeed, the data in Figure 2 show a positive correlation between total radiation sums ΣQ at these stations, both in warm and cold periods, and pressure variations. This means that more solar radiation (less cloudiness) is detected when pressure is higher (fewer cyclones pass over these stations). So, the link between total radiation sums (cloud cover) and GCR detected by Veretenenko and Pudovkin (1999) is realized through GCR influence on extratropical cyclones. Similarly, we can suggest that correlations observed between cloud cover anomalies and cosmic rays on the decadal time scale (Svensmark and Friis-Christensen, 1997; March and Svensmark, 2000) involve correlations between the weather system development and cosmic rays.

ISCCP cloud data and cyclonic processes at middle latitudes

As experimental base for this study we used the cloud cover data from ISCCP-D2 project (International Satellite Cloud Cover Project, D2 analysis) based on infrared (11 mkm) radiance measurements (Rossow et al., 1996) available for the period 1984-2009. Depending on the pressure on the cloud top (CP) clouds are divided into three types, low (CP >680 hPa), middle (440 hPa <CP<680 hPa) and high clouds

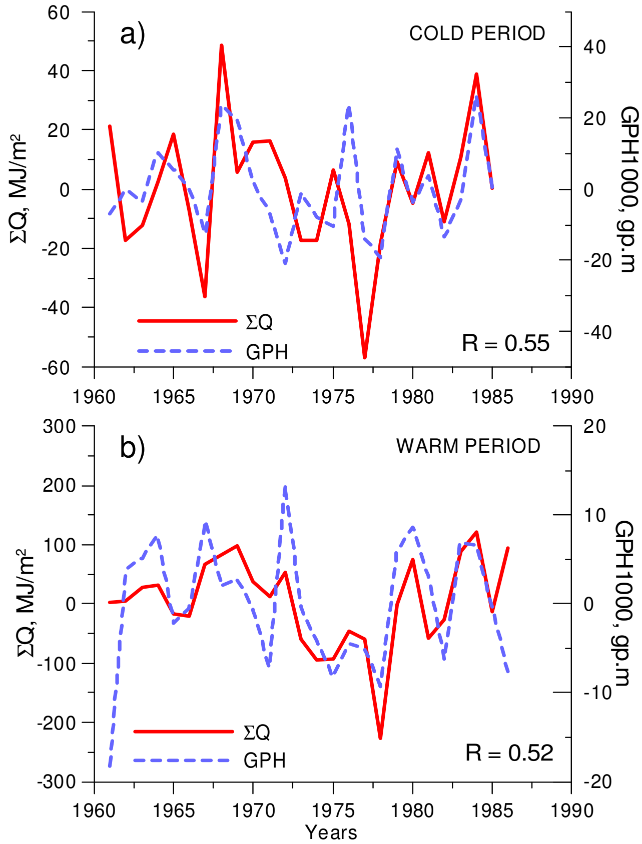

Figure 2. Variations of half-yearly sums of total radiation ΣQ (Veretenenko and Pudovkin, 1999) and geopotential heights of the 1000 hPa isobaric level at the stations in the latitudinal belt 65-68^{0}N for cold (October-March) and warm (April-September) periods.

(CP<440 hPa). Cloud amount (the fraction of the area covered by clouds of a definite type) is expressed as a percentage of the total area. Cloud amount anomalies are determined as the difference between mean monthly values of cloud amount of a definite type and the climatic mean (cloud amount averaged over the whole period of observation).

Let us consider time variations of low-level cloudiness and cyclonic processes at middle latitudes which is the region of intensive extratropical cyclogenesis. Low clouds involve stratus (St), nimbostratus (Ns) and stratocumulus (Sc) clouds and their formation is closely related to atmospheric fronts which in turn are involved in the cyclone development. Anomalies of low clouds (LCA) over the latitudinal belt 30-60^{0}N taken from ISCCP-D2 archive (http://isccp.giss.nasa.gov/pub/data/D2CLOUDTYPES) are presented in Figure 3a. We can see a gradual decrease of low cloud cover from the early 1980s to 2009. To estimate the intensity of cyclonic processes we used mean monthly values of tropospheric pressure characterized by geopotential heights of the 700 hPa level (GPH700) according to NCEP/NCAR reanalysis data (Kalany et al., 1996). The time variations of GPH700 values area-averaged over the belt 30-60°N and smoothed by 12-month running means are shown in Figure 3b. One can see long-term variations in

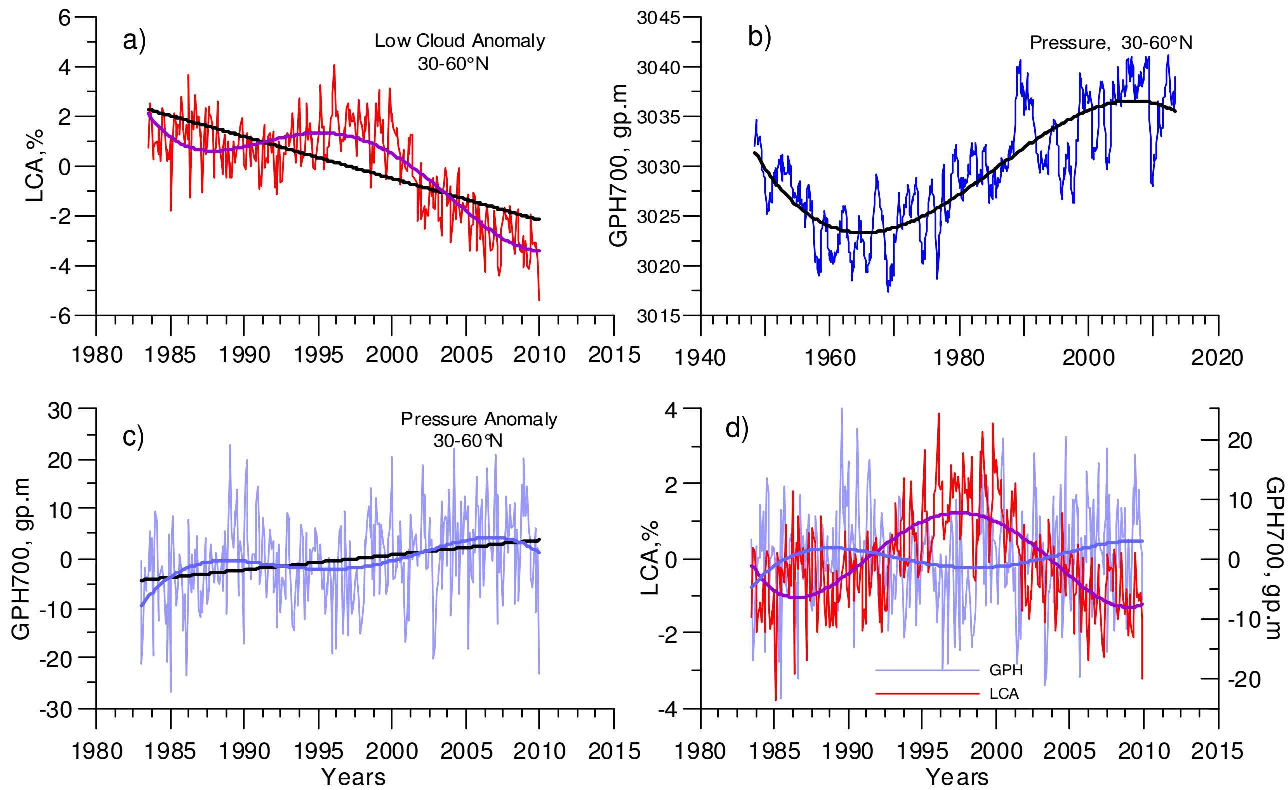

Figure 3. Time variations of low cloudiness and pressure at middle latitudes:
a) mean monthly values of LCA;
b) geopotential heights of the 700 hPa isobaric level (12-month running means);
c) mean monthly values of pressure (GPH700) anomalies;
d) detrended monthly values of low cloud and pressure anomalies.
Thick lines show linear trends and polynomial smoothing of LCA and GPH700.

troposphere pressure in the belt under study with the minimum in the 1950-1960s. During the period from the 1970s to ~2010 pressure was gradually increasing. This seems to indicate a weakening of cyclonic processes on the average over the latitudinal belt. In Figure 3c we can see anomalies of mean monthly values of GPH700 at middle latitudes calculated similarly to LCA. The data in Figure 3c reveal a positive linear trend in pressure anomalies for the period of cloud cover observations, this trend being opposite to that in low cloud anomalies. Detrended monthly values of LCA and GPH700 anomalies presented in Figure 3d are also opposite. Thus, we can see that low cloud and pressure anomalies at middle latitudes, both the trends and deviations from these trends, vary in opposite ways. This indicates a close connection between cloud cover and atmosphere dynamics, with the increase of pressure (decrease of cyclonic activity) resulting in the decrease of low cloud cover.

The link between low clouds and troposphere dynamics manifests itself most distinctly in yearly values of LCA and pressure anomalies (Figure 4), since averaging over a year decreases noises caused by micro- and meso-scale processes. Time variations of LCA and GPH700 values averaged over a year are presented in Figure 4a. Figure 4b shows a relationship between mean yearly values of LCA and GPH700. One can see that a rather high negative correlation between LCA and GPH700, with the correlation coefficient amounting to –0.63 (the statistical significance is 0.97 according to the random phase test (Ebisuzaki, 1997)), is observed for the whole period of the cloud cover record. For the values of LCA and GPH700 smoothed by 3-year running means the negative correlation reaches –0.8. Dynamical nature of low cloud anomalies is also confirmed by their seasonal variations. Indeed, the data in Figure 5 show that the amplitude of LCA variations is greater for cold months (winter and spring) when extratropical cyclogenesis is most intensive due to enhanced temperature contrasts in the troposphere.

The results obtained show a close relationship between low clouds and dynamic processes at middle latitudes. The decrease of cyclonic activity (the increase of pressure on the average over the belt 30-60°N) is accompanied by the decrease of the cloud cover. This confirms the suggestion that the observed low cloud anomalies are closely related to the development of cyclonic processes. The increase of pressure at middle latitudes may be due to the weakening of cyclones and/or the decrease of their areas as well as to the shift of their tracks to higher latitudes. Indeed, the analysis of long-term variations of the large-scale atmospheric circulation according to

Vangengeim-Girs classification (Vangengeim, 1952; Girs, 1974) revealed the intensification of meridional processes of the C-type starting in the early 1980s (Veretenenko and Ogurtsov, 2012). The C-type meridional processes are characterized by the formation of a crest over the eastern part of the North Atlantic and Europe which blocks the cyclone movement to Eurasian continent, so tracks of cyclones from the North Atlantic are shifted to polar latitudes. Thus, changes of pressure at latitudes 30-60°N observed during the period 1983-2009 seem to agree with long-term changes of the large-scale circulation.

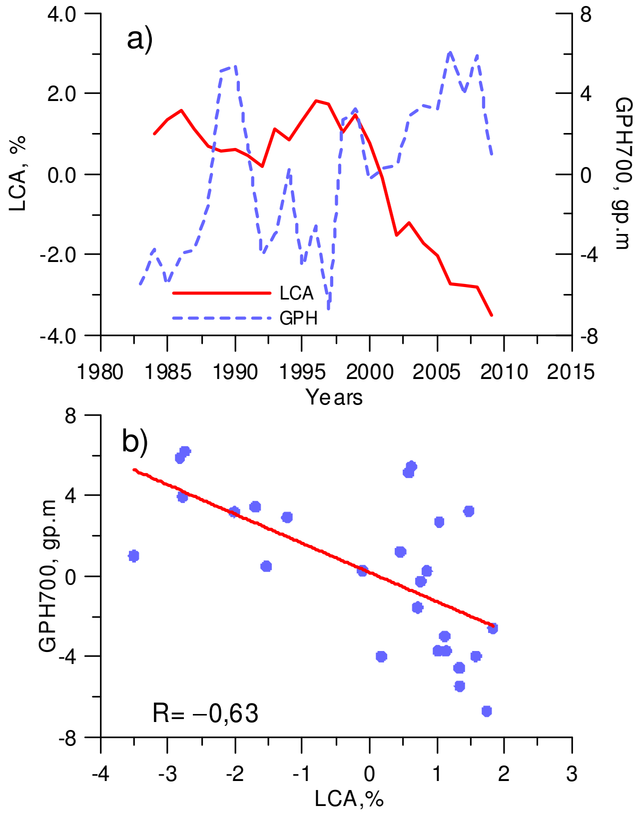

Figure 4. a) Time variations of mean yearly values of low cloud (LCA) and pressure (GPH700) anomalies at middle latitudes; b) LCA versus GPH700 anomalies at middle latitudes (mean yearly values).

Temporal variability of cosmic ray effects on the troposphere dynamics and low cloud cover

As the cloud field at mid-latitudes is influenced significantly by macro-scale weather systems (cyclones and troughs) one can suggest that the correlations between anomalies of cloud cover and cosmic rays observed in the 11-year solar cycle (Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000) may be due to GCR effects on the weather system development. Indeed, there are a number of studies showing correlations between cosmic ray variations and the troposphere dynamics both on long-term and short-term time scales. In particular, it was shown that increases of energetic solar cosmic ray fluxes in the Earth's atmosphere contribute to the intensification of cyclone development at extratropical latitudes (Veretenenko and Thejll, 2004, 2013), whereas Forbush decreases of galactic cosmic rays contribute to weakening of cyclones and intensification of anticyclones (Tinsley and Deen, 1991; Artamonova and Veretenenko, 2011, 2014). Increases of GCR intensity in the minima of the 11-year solar cycle were found to be accompanied by the shift of cyclone tracks to the north (Tinsley, 1988). A pronounced intensification of cyclones at polar fronts of middle latitudes associated with GCR increase on the decadal scale (Veretenenko and Ogurtsov, 2012) was detected for the period 1983-2000 when the LCA-GCR correlations were the highest (Marsh and Svensmark, 2000). The data above confirm a possibility of indirect influence of GCR variations on cloud cover, i.e., through the changes in baric systems forming the cloud field.

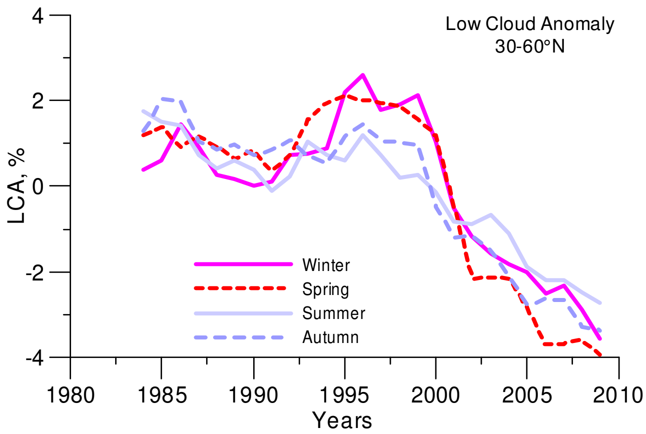

Figure 5. Time variations of low cloud anomalies for different seasons.

However, links between the lower atmosphere parameters and phenomena related to solar activity are often characterized by temporal instability, with changes and reversals of correlations being observed (Herman and Goldberg, 1978; Georgieva et al., 2007; etc.). In particular, a roughly 60-year periodicity was found in the correlation coefficients between troposphere pressure at extratropical latitudes and sunspot numbers (Veretenenko and Ogurtsov, 2012). It was suggested that this periodicity is due to the changes of large-scale circulation epochs. Indeed, the reversals of the correlation sign coincided well with the climatic regime shifts associated with a roughly 60-year variability over the North Pacific and North America (Minobe, 1997) and the transitions between the warm and cold epochs in the Arctic region (Gudkovich et al., 2009; Frolov et al., 2009). In the last two works the authors showed that these epochs are closely related to the state of the polar vortex (cyclonic circulation forming in the polar stratosphere), with the warm and cold periods being associated with the vortex strengthening and weakening, respectively. Veretenenko and Ogurtsov (2014) using the Arctic Oscillation in sea-level pressure and temperature as a proxy of the vortex state confirmed that the reversals of correlations between troposphere pressure and SA/GCR characteristics do really correspond to the vortex transitions between its different regimes. It was also shown that GCR increases contribute noticeably to the intensification of mid-latitudinal cyclones only under the strong vortex conditions; these effects weaken or even change the sign under the weak vortex conditions. As the vortex evolution seems to reveal a roughly 60-year variability (Gudkovich et al., 2009; Frolov et al., 2009; Veretenenko and Ogurtsov, 2014) and the change of the vortex (its transition to a strong state) apparently took place near 1980, we can suggest the subsequent change of the vortex state in 2000-2010. This may result in the reversal of correlations between the lower atmosphere characteristics and GCR intensity (as well as other phenomena related to solar activity) observed in the period ~1980-2000.

Let us consider a relationship between troposphere pressure at middle latitudes and GCR variations. To characterize GCR intensity we used fluxes of charged cosmic particles F_{CR} in the maximum of the transition curve (i.e. at the heights ~15-25 km) at the mid-latitudinal station Dolgoprudny (geomagnetic cut-off rigidity 2.35 GV) according to balloon measurements (Stozhkov et al., 2009). Figure 6a shows time variations of mean yearly values of pressure (GPH700) anomalies in the belt 30-60^{0}N compared with cosmic ray fluxes F_{CR} for the period 1983-2013, with the linear trends being subtracted. One can see that pressure and GCR fluxes varied in opposite phases till ~2000. This implies the decrease of pressure, i.e., cyclone intensification (and, consequently, increase of cloud cover), associated with GCR increases in the 11-year solar cycle. This result agrees well with the previous data showing intensification of cyclonic activity at polar fronts of middle latitudes with GCR increases in the epoch of a strong vortex (Veretenenko and Ogurtsov, 2014). The character of the links between troposphere pressure and GCR intensity changed sharply in the early 2000s. In 2000-2009 we can see that pressure and GCR fluxes vary in the same phase. The time variation of the correlation coefficients between mean yearly values of troposphere pressure in the belt 30-60°N and GCR fluxes for sliding 11-year intervals is shown in Figure 5b (solid line). It is seen that the strongest negative correlation between the values under study, with the correlation coefficients reaching –0.8, was observed from the middle 1980s till the middle 1990s. Then the negative correlation started weakening. A sharp increase of correlation coefficients up to high positive values (~0.8) took place after 2000 followed by the correlation decrease. So, the data in Figure 6b show a strong fluctuation of the correlation coefficients between troposphere pressure at mid-latitudes and GCR intensity in the early 2000s. This may indicate a beginning of the vortex transition to its weak state after the period of a strong vortex in ~1980-2000. Indeed, such fluctuations are observed in the periods of correlation reversals between troposphere pressure and solar activity/cosmic ray characteristics (Veretenenko and Ogurtsov, 2012). The suggestion about the change of the vortex state seems to be confirmed by the data by Ivy et al. (2014) showing that major sudden stratospheric warmings got much more frequent in the period 2000-2009 (these events were observed every year except for 2005) indicating a weaker and unstable vortex, while in the 1990s (when the correlations between GCRs and cyclonic activity were strongest) no such events were observed (i.e., the vortex was stable and strong).

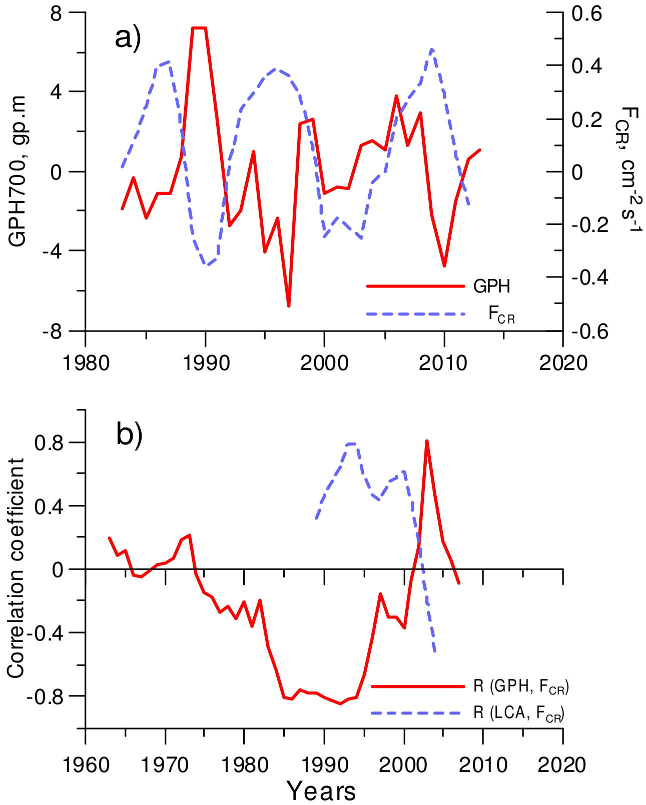

Figure 6. a) Mean yearly values of pressure (GPH700) anomalies at middle latitudes and charged particle fluxes (F_{CR}) in the maximum of the transition curve at Dolgoprudny station (Stozhkov et al., 2009); b) time variations of correlation coefficients for sliding 11-year intervals: solid line - between pressure anomalies at middle latitudes and charged particle fluxes R(GPH, F_{CR}); dashed line - between low cloud anomalies and charged particle fluxes R(LCA, F_{CR}).

Thus, the data above confirm the conclusions about the subsequent change of the character of solar-atmospheric links near 2010 due to the change of the polar vortex state made by Veretenenko and Ogurtsov (2014). Let us consider how this change may influence the correlations between low clouds at middle latitudes and GCR intensity. The correlation coefficients between low cloud anomalies and charged particle fluxes for sliding 11-year intervals are presented in Figure 6b (dashed line). We can see that the time variations of GPH700-GCR and LCA-GCR correlation coefficients are opposite. The highest positive correlation between LCA and GCR intensity (~0.8) took place in the middle 1990s when the highest negative correlation between pressure at middle latitudes and GCR intensity (–0.8) was observed. To estimate the statistical significance of the detected correlations we used Monte–Carlo simulations of sliding correlation coefficients for the surrogate data sets which were obtained by a randomization of the initial time series. The results of the estimates are given in Figure 7. One can see that the most statistically significant correlations (both GHP700-GCR and LCA-GCR) were observed from the middle 1980s to the middle 1990s, with the correlations reaching the absolute values up to 0.8 and their significances reaching 0.98. The correlation reversal in the early 2000s seems also to be significant at the 0.95 significance level. Let us note that the sign reversals of GPH700-GCR and LCA-GCR correlations occurred simultaneously in the early 2000s. This confirms the suggestion that the violation of positive correlation between low cloud anomalies and GCR fluxes is caused by the sign reversal of GCR effects on the development of extratropical cyclones.

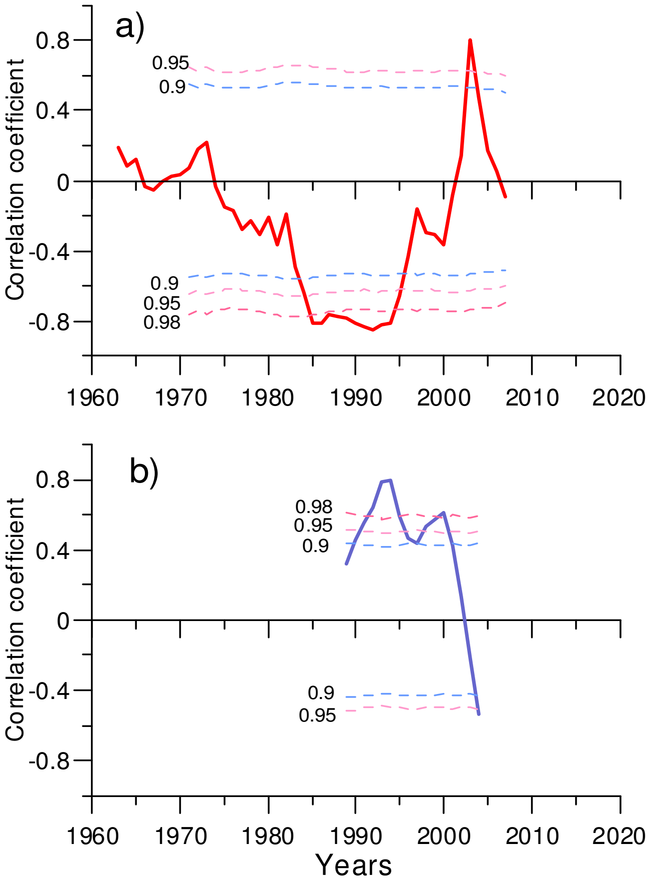

Figure 7. Time variations of correlation coefficients for sliding 11-year intervals and their significance levels: a) between pressure anomalies at middle latitudes and charged particle fluxes R(GPH, F_{CR}) ; b) between low cloud anomalies and charged particle fluxes R(LCA, F_{CR}).

Taking into account the data above, we can state that the reversal of the correlation sign between cloud cover anomalies and GCR fluxes occurring after 2000 does not imply the lack of cosmic ray influence on atmospheric processes. The correlation reversal suggests that GCR effects on cloud cover observed on the decadal time scale are not direct, but realized through circulation changes. In turn, GCR effects on troposphere dynamics are not straightforward and seem to be modified by atmosphere conditions involving the epoch of the large-scale circulation and the state of the stratospheric polar vortex. So, the mechanism of GCR influence on troposphere dynamics and cloud cover turns out to be more complicated than it was suggested earlier and, perhaps, it may differ depending on the time scale under study. In particular, on the decadal time scale a possible mechanism may involve the troposphere-stratosphere coupling through planetary wave propagation (e.g., Avdushin and Danilov, 2000). When the vortex is strong and zonal circulation velocity in the stratosphere exceeds some critical value, planetary waves propagating upward reflect back to the troposphere and their interference may cause changes in temperature and pressure resulting in intensification of baric systems at middle latitudes. Then, under the strong vortex conditions changes produced in the polar stratosphere by helio/geophysical agents may influence tropospheric processes. When the vortex is weak, planetary waves propagate upward and only the troposphere influences the stratosphere (Perlwitz and Graf, 2001). In turn, the polar vortex intensity may be affected by different helio/geophysical factors including GCRs owing to its favorable latitudinal and altitudinal location (Veretenenko and Ogurtsov, 2014). Indeed, the vortex was found to be stronger for high geomagnetic activity levels (Seppälä et al., 2013). Thus, if GCR variations contribute to the intensification of the vortex when it is already strong, the above dynamical mechanism might explain changes in tropospheric baric systems and corresponding changes in cloud cover. If the vortex is weak, GCR influence may be insufficient to intensify the vortex enough to cause changes in the development of extratropical cyclones. It should also be noted that other factors of solar activity may influence troposphere dynamics and clouds simultaneously with GCR variations intensifying or weakening GCR effects. However, the problem of the mechanism of SA/CGR variability on the lower atmosphere parameters needs further researches.

Let us also stress that the above does not exclude direct influence of GCR on microphysical processes intensifying the formation of clouds through some mechanisms involving changes in atmospheric electricity (Tinsley and Deen, 1991; Tinsley, 2008) and ion-mediated nucleation of aerosols (Yu, 2002, 2004) contributing to the formation of cloud condensation nuclei. Probably, the direct effects may be seen only on short time scales (several hours or days). However, on longer time scales direct (microphysical) effects of GCR on cloud formation may be masked by indirect ones resulting from GCR effects on circulation changes.

Thus, the data above provide evidence for indirect influence of GCR variations on cloud cover observed on the decadal time scale. The results obtained agree well with the previous data showing changes in correlations between GCR and troposphere pressure (Veretenenko and Ogurtsov, 2012, 2014), as well as demonstrate how these changes may influence correlations between GCR and other atmospheric characteristics (in this case, cloud cover anomalies). This means that we need to take into account circulation changes when interpreting peculiarities of GCR effects on atmospheric characteristics. A modulating effect of the polar vortex seems to be also of significant importance for solar-atmospheric links.

Conclusions

The results of this study allow to make the following conclusions:

1) The links between cloud cover anomalies and GCR fluxes observed on the decadal time scale are not direct. At middle latitudes they are realized through GCR effects on the development of extratropical baric systems (cyclones and troughs) which form cloud fields.
2) A high positive correlation between low cloud anomalies and GCRs in the period 1983-2000 results from a high positive correlation between cyclonic activity and GCRs which takes place under the conditions of a strong stratospheric polar vortex.
3) The violation of a positive correlation LCA-GCR in the early 2000s seems to be due to the transition of the polar vortex to its weak state which resulted in the reversal of GCR effects on the troposphere dynamics.
4) The polar vortex evolution is of significant importance for solar-atmospheric links. Its modulating effect should be taken into account when interpreting correlations between lower atmosphere characteristics and solar activity phenomena.

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