POSSIBLE REASONS FOR THE CORRELATION REVERSAL BETWEEN LOW CLOUDS AND GALACTIC COSMIC RAYS

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Abstract. The nature of correlation links detected between low cloud anomalies and galactic cosmic ray (GCR) variations in ~1983-2000 was investigated, with possible reasons for the correlation reversal after 2000 being discussed. It was shown that cloud field formation at middle latitudes is closely related to cyclonic activity, so GCR effects on low clouds observed on a decadal time scale are not direct, but they are realized through circulation changes associated with GCR variations. The character of GCR influence on the lower atmosphere dynamics was found to reveal a roughly 60-year periodicity related to the evolution of the stratospheric polar vortex. It was suggested that the reversal of correlation between cloud cover anomalies and GCR intensity detected after 2000 is due to the change of the vortex state which resulted in the sign reversal of GCR effects on the development of extratropical baric systems. The results obtained provide evidence for an important part of the stratospheric polar vortex in solar-atmospheric links.

1. Introduction

One of possible mechanisms of solar activity (SA) influence on the lower atmosphere, weather and climate suggests impact of galactic cosmic ray (GCR) variations on the cloud cover state which, in turn, affects the radiation and heat balance of the atmosphere, e.g. [Dickinson, 1975; Svensmark and Friis-Christensen, 1997]. Experimental data confirming a possibility of this mechanism were reported in a number of works [Pudovkin and Veretenenko, 1995; Todd and Kniveton, 2001, etc.]. On a decadal time scale a strong positive correlation between global cloud cover variations and GCR fluxes was revealed by Svensmark and Friis-Christensen [1997], with the satellite observations ISCCP (International Satellite Cloud Climatology Project) being used. Later it was found that namely low cloud anomalies (LCA) correlate well with changes in GCR flux [Marsh and Svensmark, 2000], the highest correlation being observed in the period 1983-1994. However, since the middle of the 1990s this correlation started decreasing and in the early 2000s its reversal took place [Gray et al., 2010]. This gave rise to doubts in a possible influence of cosmic ray variations on processes in clouds and their role in solar-atmospheric links. So, the aim of this work is to study the nature of LCA-GCR correlation observed in 1983-2000, as well as to consider reasons for the violation of this correlation after 2000.

2. Formation of cloud fields at extratropical latitudes

It is known that the main reason for cloud formation is vertical transport and cooling of water vapor, i.e. formation of cloud field is determined by vertical movement of air. Most large (macro-scale) vertical air movements, horizontal scales being from several hundred to several thousand kilometers, are closely related to extratropical baric systems. Upward movements take place in low pressure areas (cyclones and troughs). On the contrary, in high pressure areas (anticyclones and crests) downward movements are observed.

Upward air movements in an extratropical cyclone are due, first of all, to convergence of air flows near the Earth’s surface to the cyclone center. On the other hand, the evolution of these cyclones is closely related to atmospheric fronts which are characterized by regular ascending movements. At warm fronts warm air slides along a frontal surface resulting in the formation of a strong system of stratiform clouds Ns-As-Cs (nimbostratus Ns, altostratus As and cirrostratus Cs), so called ‘frontal’ cloudiness. In the case of fast moving cold fronts warm air is displaced upward more intensively, so the formation of vertical development clouds (cumulonimbus Cb) also takes place. Cloud field of an atmospheric front represents a long band, its width being from one to several hundred kilometers and its length reaching several thousand kilometers. Fig.1 (left panel) shows cloud systems of an extratropical frontal cyclone at different stages of its evolution. At the first stage it is a wave at a cold front. A characteristic feature of the second stage (‘young cyclone’) is a warm sector formed between the cold and warm fronts of a cyclone. At the next stage (‘maximum development’) the cyclone occlusion starts, i.e. the cold and warm fronts start merging. This results to the
formation of so called ‘occluded’ front and the displacement of a warm sector to the cyclone periphery. At the final stage the occlusion continues accompanied by the cyclone filling. So, cloudiness associated with fronts is observed at all stages of the cyclone evolution. The cloud field of a developed cyclone as seen from the satellite is shown in Fig.1 (right panel). It is a cloud vortex with a spiral structure and horizontal dimensions comparable with the cyclone dimensions, i.e. up to several thousand kilometers.

Fig.1. Left panel: Cloud systems of a frontal cyclone at different stages of its evolution: 1 – the cyclone center near the Earth’s surface; 2 – the axis of a jet stream; 3 and 4 – the direction of the movement of cold and warm air, respectively [Vorobjev, 1991]. Right panel: Cloud vortex (A is the vortex center) associated with an extratropical cyclone in the Northern hemisphere [Vorobjev, 1991].

Thus, cloudiness at extratropical latitudes is closely related to dynamic processes in the atmosphere. Upward movements associated with macro-scale systems such as atmospheric fronts and cyclones contribute significantly to the formation of cloud fields. This allows suggesting that correlations observed between cloud cover anomalies and cosmic rays [Svensmark and Friis-Christensen, 1997; March and Svensmark, 2000] are caused by cosmic ray influence on the development of weather systems.

3. ISCCP data and troposphere dynamics

Let us consider variations of low cloudiness and cyclonic processes at middle latitudes 30-60°N which is the region of intensive cyclogenesis. As experimental base we used cloud cover anomalies from ISCCP-D2 archive (http://isccp.giss.nasa.gov/pub/data/D2CLOUDTYPES) available for the period 1983-2009. Low clouds are defined as clouds with pressure on the cloud top CP > 680 hPa. These clouds involve stratus (St), nimbostratus (Ns) and stratocumulus (Sc) and their formation is closely related to atmospheric fronts and frontal cyclones. Low cloud amount (the fraction of the area covered by these clouds) is given as a percentage of the total area. Low cloud anomalies (LCA) are determined as the difference between monthly values and the climatic mean over the whole period of observations. To estimate intensity of cyclonic processes we used monthly values of tropospheric pressure characterized by geopotential (gp) heights of the isobaric level 700 hPa (GPH700) according to NCEP/NCAR reanalysis data [Kalany et al., 1996].

Anomalies of low clouds at mid-latitudes 30-60°N are presented in Fig.2a. We can see a gradual decrease of LCA since the early 1980s. The time variations of pressure (GPH700) values area-averaged over the same belt are shown in Fig.2b. One can see long-term variations in troposphere pressure in this belt, with the minimum taking place in the 1960s. During the period since ~1970 till ~2010 pressure was gradually increasing which indicates a weakening of cyclonic processes on average over the mid-latitudes. Anomalies of GPH700 calculated similarly to LCA anomalies are presented in Fig.2c. One can see a positive linear trend in pressure anomalies for all the period of cloud cover observations, i.e. the trend in pressure variations is opposite to the trend in low cloud anomalies. Detrended values of LCA and GPH700 anomalies (Fig.2d) are also opposite. Thus, low clouds and pressure at middle latitudes, both the trends and the 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. Dynamical nature of low cloud anomalies is also confirmed by their seasonal variations. Indeed, the
data in Fig.3a show that highest variations of LCA are observed in cold months (winter and spring) when extratropical cyclogenesis is most intensive due to enhanced temperature contrasts in the troposphere. The link ‘low cloud – troposphere dynamics’ manifests itself most distinctly in yearly values of LCA and pressure anomalies (Fig.3b), since averaging over a year decreases noises caused by micro- and meso-scale processes. One can see a rather strong negative correlation LCA-GPH700, the correlation coefficient amounts to \(-0.63\) and reaches \(-0.8\) for 3-year running means.

Thus, the above results show that low cloud anomalies at middle latitudes are closely related to the development of cyclonic processes; the decrease of cyclonic activity is accompanied by the corresponding decrease of cloud cover. The detected pressure growth may be due to cyclone weakening and/or the decrease of their areas on the average over the belt under study, as well as to the shift of cyclone tracks to higher latitudes. Indeed, the intensification of C-type meridional processes according to Vangengeim-Girs classification [Girs, 1974] was observed since the early 1980s till the early 2000s [Veretenenko and Ogurtsov, 2013]. This type of circulation is characterized by the formation of a crest over the eastern part of
the North Atlantic and Europe which blocks the cyclone movement to the Eurasian continent and shifts their tracks to the north. So, pressure changes at latitudes 30-60°N observed in 1983-2009 seem to agree with long-term variations of the large-scale circulation.

4. Cosmic ray effects on troposphere dynamics/cloud cover and their temporal variability

As cloud fields at middle latitudes are influenced significantly by macro-scale weather systems (cyclones and troughs), we should consider, first of all, GCR effects on the development of cyclonic processes. Indeed, a number of studies show correlations between cosmic ray variations and troposphere dynamics on different time scales. In particular, increases of energetic solar cosmic ray fluxes in the Earth’s atmosphere were found to contribute to cyclone regeneration near the Greenland coasts [Veretenenko and Thell, 2004]. On the contrary, Forbush decreases of GCR fluxes contribute to weakening of cyclones and intensification of anticyclones at middle latitudes [Artamonova and Veretenko, 2011]. It should be noted that a pronounced intensification of cyclones at Polar fronts associated with GCR increases on a decadal time scale was detected for the period 1983-2000 [Veretenenko and Ogurtsov, 2012] which is the period of highest correlation between LCA and GCR intensity [Marsh and Svensmark, 2000]. The above data suggest a possibility of indirect influence of GCR variations on cloud cover, i.e., through changes in the evolution of baric systems which, in turn, influence cloud fields at extratropical latitudes.

However, solar-atmospheric links are often characterized by temporal variability, with correlation changes and reversals being observed. A roughly 60-year periodicity was found in correlation coefficients between troposphere pressure at middle and high latitudes and sunspot numbers [Veretenenko and Ogurtsov, 2012]. This periodicity seems to be caused by the epochs of the large-scale circulation which, in turn, depend on the evolution of the stratospheric polar vortex (a large-scale cyclonic circulation in the polar stratosphere which is an important factor of climate variability).

Let us consider temporal behavior of SA/GCR effects on troposphere dynamics. The data in Fig.4 (left panel) show time variations of sliding correlation coefficients between troposphere pressure at high latitudes and SA/GCR characteristics (a) compared with long-term changes of the vortex intensity (b, c) and the evolution of the main forms of the large-scale circulation according to Vangengeim-Girs classification (d). We can see that since the end of the 19th century several reversals of the correlation sign took place coinciding with the changes in the evolution of the C-type meridional circulation. The vortex strength was estimated using NCEP/NCAR reanalysis data (available since 1948). The data in Fig.4b and 4c indicate that the vortex was weak in the period ~1950-1980. This was manifested in a decrease of pressure gradients between middle and high latitudes and an increase of stratospheric temperature in the vortex area. In ~1980-2000 the vortex was strong, with the pressure gradients being enhanced and stratospheric temperature being low. So, the reversals of correlations between troposphere pressure and SA/GCR characteristics near 1950 and in the early 1980s coincided with the vortex transitions between its different states and the corresponding changes in the evolution of meridional circulation. As the vortex intensity reveals a roughly 60-year variability, one can expect the subsequent change of the vortex state in 2000-2010. This change may result in the reversal of the correlations between lower troposphere dynamics and SA/GCR characteristics which were observed in the period ~1980-2000.

Indeed, the data in Fig.4 (right panel) show that the response of cyclonic activity to GCR variations on a decadal time scale strongly depends on the vortex conditions. Increases of GCR intensity in minima of the 11-year solar cycle contribute noticeably to the strengthening of cyclonic activity (decrease of pressure) at climatic Polar fronts only under the strong vortex conditions. Under the weak vortex conditions there is no cyclone intensification associated with GCR variations. A possible reason for the detected change of the response of cyclonic activity to GCR variations may be changes in the troposphere-stratosphere coupling caused by different conditions for planetary wave propagation in the periods of a strong and weak vortex. According to [Perlwitz and Graf, 2001], the stratosphere may influence the troposphere only under the strong vortex conditions when planetary waves are reflected back to the troposphere. Under the weak vortex conditions planetary waves propagate upward and only the troposphere influences the stratosphere. This may explain why GCR variations contribute to cyclonic processes only under a strong polar vortex.

Now let us consider temporal variability of the links between troposphere pressure in the belt 30-60°N and GCR fluxes and compare them with temporal variability of the LCA-GCR links. To characterize GCR intensity we used fluxes of charged particles FCR in the maximum of the absorption curve (the heights ~15-25 km) at the station Dolgoprudny (geomagnetic cut-off rigidity 2.35 GV) according to balloon measurements [Stozhkov et al., 2009]. In Fig.5a there are presented time variations of yearly values of troposphere pressure (GPH700) anomalies at middle latitudes and cosmic ray fluxes for the period 1983-2013, the linear trends being subtracted. It is seen that before 2000 pressure and GCR fluxes varied in
**Fig. 4.** Left panel: a) Time variations of correlation coefficients between troposphere pressure at high latitudes (60-85°N) and SA/GCR characteristics for 15-year sliding intervals; b) anomalies of yearly pressure difference between the latitudes 40 and 65°N in the middle troposphere; c) anomalies of yearly stratospheric temperature at high latitudes 60-90°N; d) annual frequencies of occurrence of the large-scale circulation forms according to Vangengeim-Girs classification (15-year running means). The vertical dashed lines show the years of the correlation reversals [Veretenenko and Ogurtsov, 2013].

Right panel: Correlation coefficients between yearly values of troposphere pressure (GPH700) and GCR intensity for the periods of a strong (a) and weak (b) polar vortex. Curves 1 and 2 indicate climatic Arctic fronts in January and July, respectively. Similarly, curves 3 and 4 indicate climatic Polar fronts.

**Fig. 5.** a) Time variations of yearly values of pressure (GPH700) anomalies at middle latitudes and charged particle fluxes ($F_{CR}$) in the maximum of the absorption curve at the station Dolgoprudny [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; dashed line – between low cloud anomalies and charged particle fluxes.
opposite phases indicating the strengthening of cyclonic processes (and, therefore, increase of cloud cover) associated with GCR increases. This agrees well with cyclone intensification at Polar fronts due to GCR increases in the epoch of a strong vortex (Fig.4). However, the character of the correlation GPH700-GCR changed sharply in the early 2000s. The time behavior of sliding correlation coefficients between GPH700 and GCR intensity (Fig.5b, solid line) show that the strongest negative correlation (about $-0.8$) was observed in $\sim 1985$-$1995$, then it started weakening and its sharp increase took place after 2000. This may indicate the beginning of the polar vortex transition to its weak state after the period of a strong state in $\sim 1980$-$2000$.

Thus, the data in Fig.5b confirm the suggestion that the character of solar-atmospheric links may change in 2000-2010 due to the change of the polar vortex state. Let us consider the evolution of the LCA-GCR link. Sliding correlation coefficients between low cloud anomalies and charged particle fluxes are presented in Fig.5b (dashed line). We can see that the time variations of GPH700-GCR and LCA-GCR correlation coefficients are opposite. The strongest positive correlation between LCA and GCR intensity took place in $\sim 1985$-$1995$, i.e. in the period of the strongest negative correlation between troposphere pressure and GCR intensity. The sign reversals of GPH700-GCR and LCA-GCR correlations occurred simultaneously in the early 2000s. This provides evidence that the violation of a positive correlation between low clouds and GCR fluxes is caused by the reversal of GCR effects on the development of extratropical cyclones.

5. Conclusions

The link between low cloudiness at middle latitudes and GCR fluxes observed on a decadal time scale is not direct, but realized through GCR effects on the development of baric system (cyclones and troughs) which form cloud fields. A high positive correlation between low cloud anomalies and GCR variations in the period 1983-2000 resulted from intensification of cyclonic activity associated with GCR increases under a strong stratospheric polar vortex. The violation of a positive correlation LCA-GCR in the early 2000s is likely to be caused by the beginning of the vortex transition to its weak state which resulted in the reversal of GCR effects on troposphere dynamics at extratropical latitudes.

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References


