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Sudden cosmic ray decreases: No change of global cloud cover

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[1] Currently a cosmic ray cloud connection (CRC) hypothesis is subject of an intense controversial debate. It postulates that galactic cosmic rays (GCR) intruding the Earth's atmosphere influence cloud cover. If correct it would have important consequences for our understanding of climate driving processes. Here we report on an alternative and stringent test of the CRC-hypothesis by searching for a possible influence of sudden GCR decreases (so-called Forbush decreases) on clouds. We find no response of global cloud cover to Forbush decreases at any altitude and latitude. **Citation:** Calogovic, J., C. Albert, F. Arnold, J. Beer, L. Desorgher, and E. O. Flueckiger (2010), Sudden cosmic ray decreases: No change of global cloud cover, *Geophys. Res. Lett.*, *37*, L03802, doi:10.1029/2009GL041327.

1. Introduction

[2] An influence of GCR on clouds [*Carslaw et al.*, 2002] has been reported by *Svensmark and Friis-Christensen* [1997] who analyzed one solar cycle and found that global cloud cover changed in phase with the GCR flux by 2–3% (Figure 1). They estimated that the radiative forcing of GCR during one solar cycle is comparable to the radiative forcing induced by the increase in greenhouse gases since 1750. This initiated a heated debate and heavy criticism [*Kernthaler et al.*, 1999; *Kristjánsson et al.*, 2002, 2004, 2008; *Laut*, 2003; *Sloan and Wolfendale*, 2008; *Sun and Bradley*, 2002; *Udelhofen and Cess*, 2001; *Wagner et al.*, 2001]. Later analyses made by *Marsh and Svensmark* [2000, 2003] indicated that the correlation holds only for low clouds (0–3.2 km) at low latitudes. Recently, *Svensmark et al.* [2009] claimed the finding of significant reductions in cloud water content (SSM/I), cloud cover (MODIS, ISCCP) and aerosol concentrations (AERONET) for low clouds during 26 Forbush decreases (hereafter briefly termed Fd). However, after reanalyzing the liquid water cloud fraction (LCF) data measured by MODIS and the corresponding Fd events *Laken et al.* [2009] concluded that LCF variations are unrelated to Fd events and thus do not support a relationship between GCR and clouds.

[3] The most often considered, but still uncertain, underlying physical mechanism involves GCR induced ion production followed by ion-induced cloud condensation nuclei formation [*Arnold*, 2008; *Eichkorn et al.*, 2002; *Kazil and Lovejoy*, 2004; *Lee et al.*, 2003; *Lovejoy et al.*, 2004; *Yu and Turco*, 2001].

[4] Galactic cosmic rays (GCR) reaching the troposphere, the cloud forming layer of the Earth's atmosphere, are variable in space and time. Systematic and stochastic temporal changes are induced by interplanetary magnetic field changes which in turn result from corresponding solar activity changes. During high solar activity, the strength and turbulence level of the interplanetary magnetic field are higher leading to an increased shielding of GCR and thereby a reduction of GCR reaching planet Earth. The best known systematic GCR variation is associated with the quasi-periodic 11-year solar activity (sunspot) cycle (Figure 1a). A common type of a stochastic short-term variation is the sudden GCR intensity decrease (called Forbush decrease), which lasts only about a week [*Cane*, 2000] (Figure 1b). While entirely different in duration, these two types of temporal GCR changes are very similar in amplitude.

2. Methods

[5] In order to test the CRC hypothesis which is based on the 11-year cycle (Figure 1a), we have chosen to investigate the response of clouds to Fd events (Figure 1b). Since the only difference between the CRC hypothesis and our approach is the duration of the GCR change, a necessary condition for our test to be applicable is that the time scales of the involved processes are short enough to follow the changes in cosmic rays. In other words, the cloud condensation nuclei (CCN) concentration must drop within 1–2 days and recover during about a week (Figure 1).

[6] The minimum diameter required for an aerosol particle to act as a CCN decreases with increasing particle hygroscopicity and increasing atmospheric relative humidity. For an aerosol particle containing H_2SO_4, which is highly hygroscopic, and a relative humidity of say 100.05%, easily reached in adiabatically cooling convective updrafts, a diameter of only about 30 nm is sufficient for a sulphate particle to act as a CCN. The time span required for a newly formed aerosol particle to grow to this diameter (growth time) depends on the concentration of condensing gas molecules. For example for H_2SO_4, the only condensing gas (at relative humidity $< 100\%$) presently known to exist in the free troposphere, the growth time is about 3–6 days [*Arnold*, 2007]. After the onset of an Fd event GCR induced ion formation is markedly lowered for about 1–2 days. Therefore GCR mediated CCN reformation in an air mass, which has experienced convective ascent accompanied by CCN depletion, does not take place after the above growth time, but after the growth time incremented by a lag time of 1–2 days. Hence, one may expect less than usual cloud cover about 4–8 days after a Fd event. A detailed description of CCN formation and growth is given by *Arnold* [2007, 2008].

[7] To test the CRC hypothesis we have made a detailed correlation analysis of the cloud cover and the corresponding GCR induced ion production for the six largest Fd events

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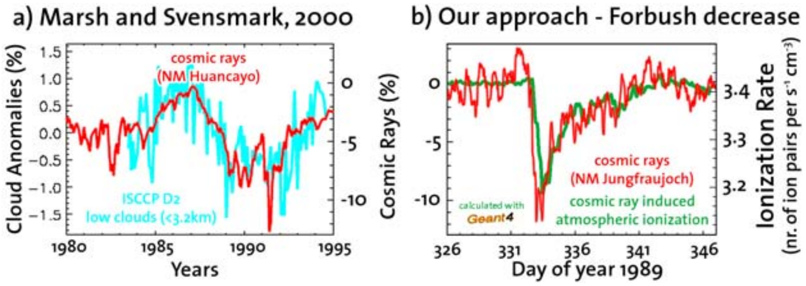

Figure 1. Comparison between (a) *Marsh and Svensmark* [2000] and (b) our approach. Relative change in cosmic rays (Huancayo neutron monitor - red curve) and ISCCP D2 low clouds (light blue curve) over roughly one solar cycle (11-year) are used to analyze possible connection between CR and clouds (Figure 1a). In our approach, relative changes in CR during Fd (Jungfraujoch NM - red curve) are associated by the same amplitude as during 11-y solar cycle (Figure 1b). Calculated cosmic ray induced ionization (green curve) is compared with the same clouds dataset like in Figure 1a (ISCCP D1 - not shown). The shown example corresponds to Fd event 1.

which occurred in the period 1989 to 2001 (see Table 1). These Fds have been selected based on the following three criteria: i) Before the onset of the Fd the CR intensity is constant to be used as a reference level ii) The Fd has a smooth recovery iii) during the Fd additional ionization due to solar proton events can be excluded.

[8] Periods of 20 days with up to 10 days of lag as used in our study offer much better statistics than one single period of 11 years as used in previous analyses [e.g., *Marsh and Svensmark*, 2000]. Our analysis uses the 3 hourly infrared (IR) ISCCP (International Satellite Cloud Climatology Project) D1 cloud cover data [*Rossow*, 1996], which are equivalent to the ISCCP D2 monthly data used by *Marsh and Svensmark* [2000, 2003] and *Svensmark and Friis-Christensen* [1997] and other studies [*Kernthaler et al.*, 1999; *Kristjánsson et al.*, 2002, 2004; *Palle et al.*, 2004; *Sun and Bradley*, 2002; *Usoskin et al.*, 2004].

[9] For each event neutron monitor data was used to determine the changes in the differential energy spectrum of the primary galactic cosmic rays for a period of 20 days starting about five days prior to the onset of the Fd. Using this spectral information the Monte Carlo PLANETOCOSMICS [*Bütikofer et al.*, 2008; *Desorgher et al.*, 2005] code based on Geant4 [*Agostinelli et al.*, 2003] was applied to calculate the ion production rate in the atmosphere during each event as a function of latitude, longitude, and altitude, taking into account the geomagnetic field prevailing at that time.

[10] Temporal changes in the ion production rate resulting from changes in the CR flux were obtained for a global grid with a spatial resolution of 5° x 5° and a temporal resolution of 3 hours. As an example Figure 2 shows the model calculated distribution of the atmospheric ion production rate for March 19,1991, which was 5 days before the Fd event number 1 (Table 1). The variation with atmospheric depth and latitude are very pronounced while the variation with longitude (inset picture Figure 2) is weak.

[11] For each grid cell the ion production rate change was then compared with the corresponding ISCCP D1 cloud data change allowing for time lags ranging from 0 to 10 days. This approach led to important improvements compared to the majority of previous studies [*Marsh and Svensmark*, 2000, 2003; *Palle et al.*, 2004; *Sun and Bradley*, 2002; *Svensmark and Friis-Christensen*, 1997; *Todd and Kniveton*, 2004] which were mostly restricted to neutron monitor measurements at a few specific sites.

[12] Furthermore, the vast number of data processed in this work (in total more than one hundred thousand effectively used grid cells in six independent Fds events) allowed much better statistics and sensitivity compared to *Marsh and Svensmark* [2000, 2003] and *Svensmark and Friis-Christensen* [1997] and other studies [*Palle et al.*, 2004; *Sun and Bradley*, 2002] where only one period (event) was investigated.

[13] Since only relative values of cloud cover for short periods were considered in the correlation analysis, the effects of other important factors which could influence cloud cover over longer time periods such as the El Niño-Southern Oscillation [*Farrar*, 2000], explosive volcanic eruptions, instrument calibration, and detection uncertainties were avoided. However, large scale atmospheric transport of CCNs as well as other factors beside CR could reduce the correlation. A more detailed description of the correlation analysis and statistics is given in the auxiliary material.[1]

3. Results and Discussion

[14] For each Fd event, cloud layer and lag between 0 and 10 days in time steps of 3 hours the correlation coefficients between ionization and cloud cover were calculated for each grid cell on a global grid of about 1700 to 6000 cells depending on the cloud layer. Correlation coefficients were then averaged leading to the global average correlation (P_{avg}) for each event, cloud layer and lag.

[15] Figure 3 summarizes the results of our analysis. In Figure 3a the global average correlation (P_{avg}) averaged over all available grid cells and all 6 Fds events is plotted versus lag time for 3 altitude layers (high >6.5 km, middle 3.2–6.5 km and low 0–3.2 km).

[16] The absence of a significant maximum for all three cloud layers is an indication that tropospheric clouds do not respond to an Fd on a global scale. Support for the negative results comes from the correlation analysis for control events (details in the auxiliary material). Despite a nearly constant CR flux (changes < 2%) during the control events compared to the Fd events (up to 25%), the obtained P_{avg} dependences on the lag are very similar (see Figure S2).

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[1] Auxillary materials are available in the HTML. doi:10.1029/2009GL041327.

Table 1. List of Selected 6 Fds Used in the Analysis[a]

Event Number	Date	Time UT	Fd Strength (%)	Analyzed Period
1	24.03.91	03:41	21.3	19.03–07.04.91
2	28.10.91	15:37	17.4	23.10–11.11.91
3	13.03.89	01:27	16.6	08.03–27.03.89
4	27.11.89	21:39	15.4	22.11–11.12.89
5	26.02.92	16:57	9.7	21.02–11.03.92
6	24.09.98	23:45	9.2	19.09–08.10.98

[a] This list was obtained by selection from altogether 14 strongest Fds in period from 1989–2001 using the data from 18 different neutron monitor stations covering all latitudes and longitudes. Date and time refer to arrival of storm sudden commencement, which is considered as the beginning of Fd. All listed times are in UT and analyzed period begins on the first day at 00:00 h and ends on the last day at 23:59h. Fd strength describes the 10 GeV CR density variation outside the Earth's magnetosphere [*Belov et al.*, 1995].

The small positive bias of about 0.02 is present for all events, cloud layers and lags. Since the control events show a similar deviation from 0, this deviation is likely to be the bias of the correlation estimate, which is expected for a relatively short time series of 20 days with high autocorrelation. Tests with artificial data (details in the auxiliary material) prove that our approach is sufficiently sensitive (Figure S2) to detect a 2% change in cloud cover as reported by *Marsh and Svensmark* [2000] for the 11-year solar cycle. Consequently - if the correlation between CR and cloud cover postulated by Svensmark exists - an increase in P_{avg} for Fds compared to control events should be observable in the given lag range.

[17] Furthermore, the geographical correlation coefficient distributions for the three altitude layers and all time lags are highly inhomogeneous and with no larger areas consisting of positive and negative correlations. Figure 3b shows an example for the low cloud layer assuming a lag between 5 and 6 days.

[18] The correlation histograms for all cloud layers and time lags show normal distributions of correlation coefficients indicating no correlation between cloud cover and CR. An example of such a histogram is shown in Figure 3c.

[19] In a recent study *Svensmark et al.* [2009] analyzed 26 Forbush decreases and, contrary to us, found a significant response in cloud cover and aerosol content. However, a closer inspection of Svensmark et al.'s list of used Fd events revealed 5 Fd events which did not fulfill our selection criteria. For example, the third strongest Fd event in Svensmark et al.'s list which occurred on January 20, 2005 was accompanied by one of the strongest solar proton events. *Mironova et al.* [2008] analyzed this event and found a significant increase in the aerosol content for the Antartic region. Without further discussion we would like to state that a study as the one by *Svensmark et al.* [2009] including Fd events which are associated with the solar proton events leads easily to questionable or even contradictory results [see also *Laken et al.*, 2009].

4. Conclusions

[20] All our tests did not provide any evidence for a response of the cloud cover to Fd events:

[21] 1. No significant global average correlation (P_{avg}) nor median maxima were found in the independent analysis of every Fd event for all cloud layers (not shown). The geographical locations where the cloud cover correlates more positively with the CR intensity are different for each single Fd event, an indication of stochastic correlations.

[22] 2. Median values calculated for the frequency distributions of the correlation coefficients are all almost zero and independent of the lag time (not shown).

[23] 3. There are no indications of regional effects of CR changes on cloud cover. P_{avg} and median values obtained in the analysis of grid cells corresponding to particular geographical regions (high and low latitudes, grid cells over oceans and land, see details in the auxiliary material) show no considerable difference in significance.

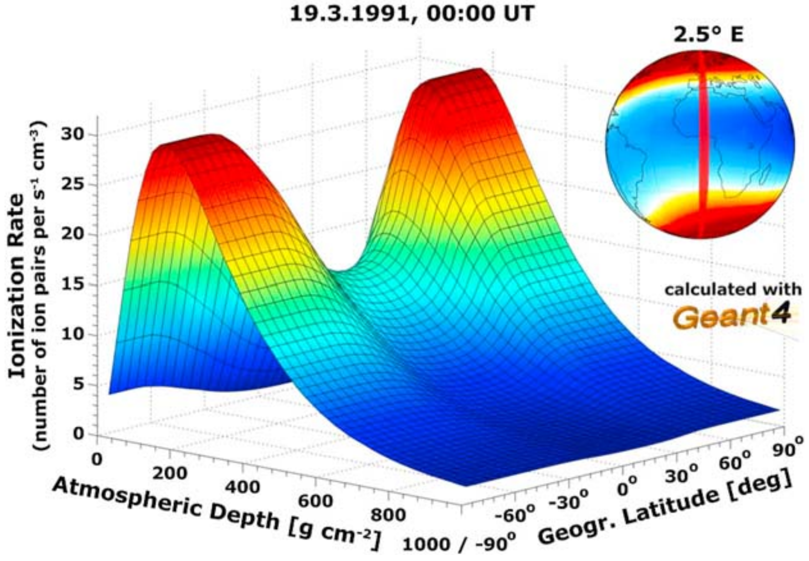

Figure 2. Example of calculated cosmic ray induced ionization rate for 19.3.1991 at 00:00h UT (Fd event 1). The ionization rate is shown for 2.5° East longitude as a function of geographic latitude and atmospheric depth. The inset picture on the right shows the ionization rate at an atmospheric depth of 180 g/cm^2 (13.2 km) as a function of the geographical position.

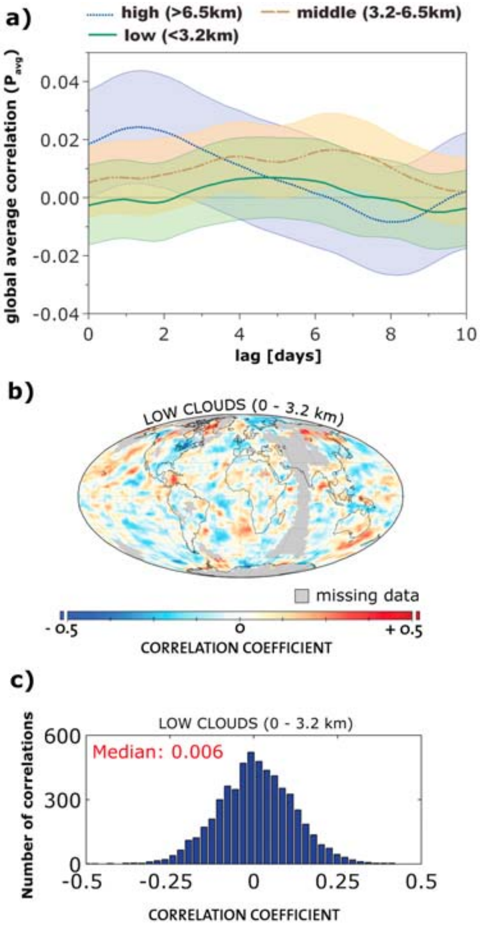

Figure 3. (a) Global average correlation (P_{avg}) for all available grid cells as a function of lag time for all 6 Fd events. High (blue), middle (brown) and low (green) cloud layers are shown. For every lag in steps of 3 hours 11466 (29%) correlation coefficients for high, 27445 (69%) for middle and 32623 (90%) for low clouds were averaged. The standard deviation (σ) was calculated separately for every P_{avg} (see details in the auxiliary material). The colored shaded areas (light blue for high, light yellow for middle and light green for low clouds) represent the 95% confidence intervals ($\pm 1.96\ \sigma$). Due to the small amount of available data (29%) the high clouds (>6.5 km) show a bigger variability than the other cloud layers. The control events show similar variability for high clouds. (b) Correlation coefficients (negative: blue; positive: red) for the low cloud layer (0–3.2 km). Correlation coefficients for all 6 Fd events were averaged for every single grid cell and the lag time between 5 and 6 days. Grid cells with coefficients averaged over less than 4 Fd events were excluded from further analysis. Grey color corresponds to missing data. (c) Correlation histogram with the same coefficients as plotted in Figure 3b for a lag time between 5 and 6 days. y axis: number of correlations in specific correlation coefficient class; x axis: correlation coefficient value. The median value depicted above the histogram is calculated from all correlation coefficients and indicates the displacement from the normal random distribution.

[24] In conclusion, our global and regional analysis does not indicate any significant response of the cloud cover to undisturbed Forbush decreases.

[25] **Acknowledgments.** The ISCCP D1 data were obtained from the International Satellite Cloud Climatology Project web site http://isccp.giss.nasa.gov maintained by the ISCCP research group at the NASA Goddard Institute for Space Studies, New York [*Rossow and Schiffer*, 1999]. We are indebted to Reinhard Furrer and Peter Reichert for helpful comments regarding the statistical analysis.

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