GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L15101, doi:10.1029/2009GL038429, 2009

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Cosmic ray decreases affect atmospheric aerosols and clouds

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Received 31 March 2009; revised 1 June 2009; accepted 17 June 2009; published 1 August 2009.

[1] Close passages of coronal mass ejections from the sun are signaled at the Earth's surface by Forbush decreases in cosmic ray counts. We find that low clouds contain less liquid water following Forbush decreases, and for the most influential events the liquid water in the oceanic atmosphere can diminish by as much as 7%. Cloud water content as gauged by the Special Sensor Microwave/Imager (SSM/I) reaches a minimum ≈7 days after the Forbush minimum in cosmic rays, and so does the fraction of low clouds seen by the Moderate Resolution Imaging Spectroradiometer (MODIS) and in the International Satellite Cloud Climate Project (ISCCP). Parallel observations by the aerosol robotic network AERONET reveal falls in the relative abundance of fine aerosol particles which, in normal circumstances, could have evolved into cloud condensation nuclei. Thus a link between the sun, cosmic rays, aerosols, and liquid-water clouds appears to exist on a global scale.
Citation: Svensmark, H., T. Bondo, and J. Svensmark (2009), Cosmic ray decreases affect atmospheric aerosols and clouds, *Geophys. Res. Lett.*, *36*, L15101, doi:10.1029/2009GL038429.

1. Introduction

[2] Explosive events on the sun provide natural experiments for testing hypotheses about solar influences on the Earth. A conspicuous effect is the sudden reduction, over hours to days, in the influx of galactic cosmic rays (GCRs), first noticed by Scott E. Forbush in 1937. Such Forbush decreases (FDs) are now understood to be the result of magnetic plasma clouds from solar coronal mass ejections that pass near the Earth and provide a temporary shield against GCRs [*Hilary*, 2000]. Whether or not any consequences of these events are perceptible in the weather has been a subject of debate for 50 years [*Ney*, 1959; *Dickinson*, 1975; *Tinsley*, 2008]. Recent attention has focused on the question of whether an effect on clouds due to changes in atmospheric ionization by GCRs is observable [*Svensmark and Friis-Christensen*, 1997; *Marsh and Svensmark*, 2000; *Kniveton*, 2004; *Todd and Kniveton*, 2004; *Harrison and Stephenson*, 2006], or is not observable [*Kristjánsson and Kristiansen*, 2000; *Sloan and Wolfendale*, 2008; *Kristjánsson et al.*, 2008]. Here we report clear signals of changes in both the liquid water content of the Earth's low clouds and the relative abundance of fine atmospheric aerosols, during the days that follow the FDs.

2. Ranking Forbush Decreases by Their Low-Altitude Effects

[3] An important preliminary step in the present work is to distinguish quantitatively between "strong" and "weak" FDs, by calculating changes in ionization in the atmosphere due to each FD. Because we are concerned with clouds in the lower atmosphere, we choose as the reference the average ionization below 3 km altitude during the period for which cloud water data are available, 1987–2007. From responses to an FD in about 130 neutron monitors world-wide and the Nagoya muon detector, the changes in the primary cosmic ray spectrum at 1 AU are derived. This procedure, and the subsequent Monte Carlo simulations of ionization by cosmic ray showers, are explained in the auxiliary material.[2] Table 1 lists the strongest FDs, 1987–2007. The first and second columns give the numerical order and the dates of the Forbush minima in the daily averaged GCRs. The third column is the strength of the FD, defined by the change in the ionization at the minimum, relative to a base period 14 days before the minimum. The value of the ionization decrease is normalized to be relative to the variation in ionization during the solar cycle at a latitude of 45 deg. On average the solar cycle variation in GCR ionization is 10–15% below 6 km altitude [*Bazilevskaya et al.*, 2008].

3. Responses to FDs in Liquid Water Clouds and Aerosols

[4] Three independent sources of satellite data on liquid water clouds are used to explore responses to FD events. The Special Sounder Microwave Imager (SSM/I) [*Wentz*, 1997; *Weng et al.*, 1997] observes changes in the cloud liquid water content (CWC) over the world's oceans. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites (land and oceans) gives the liquid water cloud fraction (LWCF). The International Satellite Cloud Climate Project (ISCCP) [*Rossow and Schiffer*, 1991] provides data on IR detection of low clouds (<3.2 km) over the oceans. Substantial declines in liquid water clouds, apparently tracking the declining cosmic rays and reaching minima some days after the GCR minima, were readily detectable for the strongest events in Table 1, whether considered individually or in superpositions of several events.

[5] To investigate a possible mechanism, we use observational data on aerosols in the atmosphere as monitored by the solar photometers of the AERONET program, with

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0094-8276/09/2009GL038429$05.00

[2]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038429.

Table 1. Twenty-Six Solar Events in the Period 1987–2007 are Here Ranked According to Their Depression of Ionization in the Earth's Lower Atmosphere, Gauged as a Percentage of the Normal Overall Variation in Ionization During the Course of a Solar Cycle[a]

Order	Date	Decrease (%)
1	**31/10/2003**	119
2	13/6/1991	87
3	**19/1/2005**	83
4	**13/9/2005**	75
5	15/3/1989	70
6	**16/7/2000**	70
7	**12/4/2001**	64
8	29/10/1991	56
9	9/7/1991	54
10	29/11/1989	54
11	**10/11/2004**	53
12	**26/9/2001**	50
13	25/3/1991	48
14	**17/7/2005**	47
15	**25/9/1998**	45
16	**27/7/2004**	45
17	10/9/1992	44
18	**31/5/2003**	44
19	**25/11/2001**	39
20	**15/5/2005**	38
21	**28/8/2001**	37
22	**27/8/1998**	36
23	10/5/1992	35
24	27/2/1992	33
25	**18/2/1999**	33
26	**2/5/1998**	28

[a]Variations are set to 100%. The dates given are those of the minima of the Forbush decreases (FD) reported from neutron monitors. The bold dates are the FD for which AERONET data are available, with the earliest occurring in 1998. In general, the FD were chosen for their strength, so only FD with reduction larger than 7% in the South Pole neutron monitor (cutoff rigidity 0.06 GV) were selected. Three events 13–27 October 1989 were omitted because they were so close in time that they interfered with one another and were also interspersed with large ground level events.

many stations well distributed over the globe. The relative blocking of sunlight of different wavelengths is given by the Angstrom exponent α in the aerosol extinction law, $\tau(\lambda_i) = \tau_1 \lambda_i^{-\alpha}$, where $\tau(\lambda_i)$ is the aerosol optical thickness at a given wavelength λ_i and τ_1 is the approximate optical thickness at a wavelength of 1 micron. In the case of measurements at two wavelengths λ_1 and λ_2 the fitted exponent $\alpha_{1,2}$ provides information about the relative abundance of fine aerosols. Long wavelengths respond to their volume fraction, whilst short wavelengths are sensitive to the effective radius of the fine mode (<250 nm) aerosol [*Schuster et al.*, 2006]. Figure 1a averages the AERONET data and GCR data for the five strongest FDs in the period covered by AERONET from 1998 onward (order numbers 1, 3, 4, 6, and 7 in Table 1). A rapid decrease in the Angstrom exponent for 340 nm and 440 nm closely follows the GCR decline, leading to a minimum about 5 days after the Forbush minimum, and is consistent with an increase in the effective radius of the fine mode due to a progressive decline in the abundance of the smallest particles among the fine mode aerosols, or, equivalently, their enhanced removal to larger particles.

[6] Figure 1b superposes the SSM/I data for CWC for the same five FD events. Notice that the CWC minimum occurs 4 days later than the fine aerosol minimum in the AERONET plot, as might be expected if an aerosol change precedes cloud changes, and if there is no appreciable transport time between the region in which changes occur and the sampling region. Figures 1c and 1d plot observations of the LWCF from MODIS, and low oceanic clouds from ISCCP, superposed for the same events.

4. Clouds and Aerosols in Many FD Events

[7] The robustness of FD effects on the Earth's lower atmosphere was tested by using the events in Table 1 to see

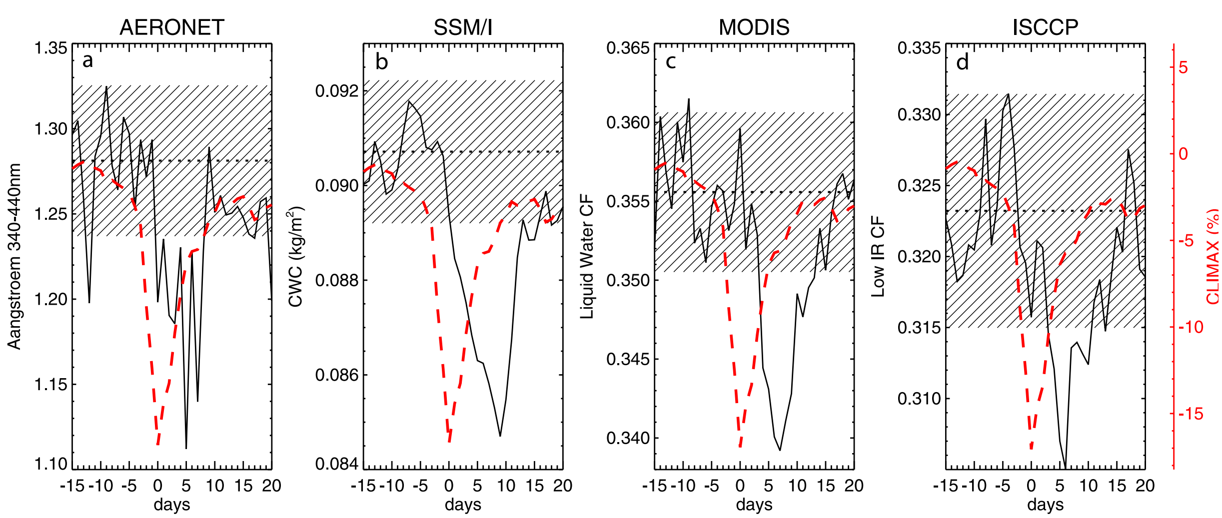

Figure 1. The evolution of (b) cloud water content (SSM/I), (c) liquid water cloud fraction (MODIS), and (d) low IR-detected clouds (ISCCP) is here averaged for the 5 strongest Forbush decreases that their data sets have in common (order numbers 1, 3, 4, 6, and 7 in Table 1) and is compared with (a) the corresponding evolution of fine aerosol particles in the lower atmosphere (AERONET). In (a) each data point is the daily mean from about 40 AERONET stations world-wide, using stations with more than 20 measurements a day. Red curves show % changes in GCR neutron counts at Climax. The broken horizontal lines denote the mean for the first 15 days before the Forbush minimum, and the hatched zones show $\pm 1\sigma$ for the data, estimated from the average variance of a large number of randomly chosen periods of 36 days of each of the four data sets. The effects on clouds and aerosols are not dominated by any single event among the 5 averaged. Examples of SSM/I data for several individual events are shown in the auxiliary material.