Atmos. Chem. Phys., 8, 7373–7387, 2008
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Atmospheric Chemistry and Physics

Cosmic rays, cloud condensation nuclei and clouds – a reassessment using MODIS data

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Received: 7 May 2008 – Published in Atmos. Chem. Phys. Discuss.: 14 July 2008
Revised: 6 November 2008 – Accepted: 6 November 2008 – Published: 11 December 2008

Abstract. The response of clouds to sudden decreases in the flux of galactic cosmic rays (GCR) – Forbush decrease events – has been investigated using cloud products from the space-borne MODIS instrument, which has been in operation since 2000. By focusing on pristine Southern Hemisphere ocean regions we examine areas where we believe that a cosmic ray signal should be easier to detect than elsewhere. While previous studies have mainly considered cloud cover, the high spatial and spectral resolution of MODIS allows for a more thorough study of microphysical parameters such as cloud droplet size, cloud water content and cloud optical depth, in addition to cloud cover. Averaging the results from the 22 Forbush decrease events that were considered, no statistically significant correlations were found between any of the four cloud parameters and GCR, when autocorrelations were taken into account. Splitting the area of study into six domains, all of them have a negative correlation between GCR and cloud droplet size, in agreement with a cosmic ray – cloud coupling, but in only one of the domains (eastern Atlantic Ocean) was the correlation statistically significant. Conversely, cloud optical depth is mostly negatively correlated with GCR, and in the eastern Atlantic Ocean domain that correlation is statistically significant. For cloud cover and liquid water path, the correlations with GCR are weaker, with large variations between the different domains. When only the six Forbush decrease events with the largest amplitude (more than 10% decrease) were studied, the correlations fit the hypothesis slightly better, with 16 out of 24 correlations having the expected sign, although many of the correlations are quite weak. Introducing a time lag of a few days for clouds to respond to the cosmic ray signal the correlations tend to become weaker and even to change sign.

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1 Introduction

The magnitude of the Sun's contribution to 20th century climate variations has been the subject of some controversy, and many possible mechanisms have been suggested. Ten years ago, a link between the flux of ionizing galactic cosmic rays (GCR), modulated by solar activity, and global cloud cover was proposed by Svensmark and Friis-Christensen (1997). They proposed that the GCR flux stimulates the formation of cloud condensation nuclei (CCN) in the atmosphere, and that the higher CCN concentrations at times of high GCR fluxes would lead to increased cloud cover and a cooling of the Earth's climate. Three years later the hypothesis was modified to involve a GCR correlation to low clouds only (Marsh and Svensmark, 2000). High and statistically significant correlations between GCR and low cloud cover were presented, based on data for the period 1983–1994 from the International Satellite Cloud Climatology Project (ISCCP), using infrared sensors only.

Numerous reassessments were subsequently published (e.g., Kristjánsson and Kristiansen, 2000; Udelhofen and Cess, 2001; Kristjánsson et al., 2002; Laut, 2003; Damon and Laut, 2004), questioning both the physical and statistical basis for the earlier conclusions on cause and effect. Kristjánsson et al. (2002, 2004), adding new data up to the year 2001 to the ISCCP time series, showed that the ISCCP

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low cloud cover correlates somewhat better with total solar irradiance (TSI) than with GCR, and proposed a possible mechanism between variations in TSI and low cloud cover. They also pointed out that a version of the ISCCP low cloud cover, which combines infrared and visible channels, is more accurate and reliable than the IR-only version used by Marsh and Svensmark (2000), and that using the more accurate version yields much poorer correlations with GCR and TSI than the IR-only version does. The poorer correlations are not significant at the 90% level. Nevertheless, new analyses using the IR-only data have continued to appear in the literature (e.g., Marsh and Svensmark, 2003; Usoskin et al., 2004). Some studies have investigated possible contributions from overlapping cloud layers to the correlations (Pallé, 2005; Usoskin et al., 2006).

There have also been numerical and laboratory studies attempting to answer the question of a possible GCR-CCN link. Yu and Turco (2001) presented simulations with an Advanced Particle Microphysics (APM) model of the formation and subsequent evolution of aerosols in the atmosphere. When studying thermodynamically stable clusters, which are ultrafine particles that are precursors to aerosol formation, they found that charged clusters have a larger probability of resisting evaporation than uncharged ones. This indicates that GCR flux may have a beneficial influence on particle formation. The GCR induced ionization peaks at around 13 km altitude in the atmosphere (Neher, 1971), so one might expect the largest effect in the upper troposphere. Consistently with this notion, Eichkorn et al. (2002), who carried out aircraft measurements of aerosols in the upper troposphere, found large cluster ions, which were presumably caused by GCR ionization. On the other hand, Yu (2002) and Arnold (2008) have suggested that the bottleneck in the formation of upper tropospheric aerosol particles with sizes large enough to be climate relevant is mostly not nucleation but availability of condensable gases. Therefore, Yu (2002) suggested that the lower troposphere, despite a lower ionization rate, might be a more favorable region for a GCR influence on clouds, due to higher precursor gas concentrations. Yu (2002) presented APM simulations in which the largest difference in ionization-aided particle formation between times of high and low solar activity was in the lower troposphere. This would suggest that low clouds might indeed be more sensitive to changes in GCR flux than higher clouds, consistently with the Marsh and Svensmark (2000) results. More recently, Kazil et al. (2006) and Yu et al. (2008) have presented model simulations of aerosol nucleation under various atmospheric conditions. Both studies find support for the role of electrical charge for aerosol nucleation. In both studies the upper tropical troposphere is found to be a favored region for aerosol nucleation. The latter study also finds strong signals in the entire mid-latitude troposphere and over Antarctica.

Many observational and model studies have shown that high aerosol abundances (e.g., due to pollution) are associated with high cloud droplet number concentration and smaller cloud droplets (e.g., Nakajima et al., 2001; Penner et al., 2004). While it has been long been suggested that increased aerosols abundance may enhance the cloud cover by inhibiting the precipitation (Albrecht, 1989), supported by recent observations (e.g., Kaufman et al., 2005), newer information also indicates that absorbing aerosols may reduce the cloud cover by evaporating clouds and inhibiting cloud formation (semi-direct aerosol effect; see, e.g., Ackerman et al., 2000). Koren et al. (2008) provide further insight into this by using an analytical description and MODIS satellite data to show that in regions with absorbing aerosols the cloud lifetime effect overwhelms the semi-direct aerosol effect at low aerosol abundance whereas at higher aerosol abundance the semi-direct effect dominates due to saturation of the cloud lifetime effect.

Svensmark et al. (2007) found through laboratory experiments that ions help generate small thermodynamically stable clusters, which play a role in CCN production. The nature and extent of this role, however, is more uncertain, and the transition between the ultrafine particles and actual CCN is still a missing link in the GCR-CCN hypothesis. Most CCN in the atmosphere are about 100 nm in radius, and Yu and Turco (2001) did not find an enhancement of CCN concentrations when comparing GCR fluxes corresponding to solar minimum and solar maximum, respectively. More research is needed before we can ultimately conclude whether GCR-induced variations in the concentration of ultrafine particles lead to changes in CCN concentrations. However, among several hypotheses concerning links between GCR and clouds, this is the one that has received the most attention, and will be the topic of this study. In the review by Carslaw et al. (2002) of the cosmic ray – cloud hypothesis, another type of mechanisms was also described; in which electrical charge induced by GCR influences cloud microphysical processes. For instance, Tinsley et al. (2000) suggested that electrical charge may enhance the ability of particles in the atmosphere to serve as ice nuclei (electroscavenging), thereby enhancing glaciation of supercooled cloud droplets. Also, cloud microphysical effects such as collisions and coalescence, as well as scavenging, may conceivably be influenced by cloud edge charging, caused by ion removal by cloud droplets (see, e.g., Harrison and Carslaw, 2003). These latter effects are highly uncertain, and are beyond the scope of this study.

If the correlation between cloud cover and GCR is caused by variations in the concentration and efficiency of CCN through ionization, the signal should not only be visible over the solar cycle but also during sudden dramatic decreases in GCR called Forbush decreases (FD). To date, studies of the response of clouds to FD show varying results. Harrison and Stephenson (2006), who used radiation measurements to infer clouds, found a positive correlation between clouds and FD for UK sites, while Pallé and Butler (2001), using ISCCP and Irish sunshine data combined, found no FD correlation. Todd and Kniveton performed several studies on FD and clouds from ISCCP, and found significant correlations mainly for high clouds at high latitudes (Todd and Kniveton, 2001; Todd and Kniveton, 2004; Kniveton, 2004). It should be kept in mind that these clouds are known to be extremely difficult to detect accurately by satellite retrievals (Rossow and Schiffer, 1999). Recently, significant inhomogeneities in the ISCCP datasets have been pointed out by e.g., Evan et al. (2007). The presence of these spatial inhomogeneities means that time series analyses using the ISCCP data have to be carried out with great caution.

Most of the previous studies investigating possible GCR-cloud relations have focused on cloud cover, which may not be a reliable indicator of cloud microphysical characteristics. In order to come closer to an answer to the question of whether or not galactic cosmic rays influence clouds, a different approach is needed. The high spectral resolution cloud data from the Moderate-resolution Imaging Spectroradiometer (MODIS) enable us to investigate possible couplings to cloud microphysical parameters, in a manner that was not possible to do with earlier cloud data. We investigate the response of various cloud parameters to Forbush decreases in galactic cosmic radiation. We concentrate specifically on pristine ocean areas frequently covered by stratocumulus clouds, which are particularly sensitive to changes in cloud droplet concentration (Hobbs, 1993), and where there consequently would be a potential for a large impact of GCR on clouds. Cloud amount, as well as microphysical parameters such as cloud droplet radius, liquid water path and cloud optical depth are tested for correlation. The next section describes the data used, as well as the methodology. Results are presented in Sect. 3, while Sect. 4 presents the conclusions of this study.

2 Data and methods

Cloud data in this study are from retrievals by MODIS, while measurements of galactic cosmic radiation are taken from the neutron monitor at Climax, Colorado, which has a reliable measurement series dating back to 1953. Below follow some specifications of the MODIS instrument, a sub-section on Forbush decreases, a description of the geographical areas we focus on, and a presentation of the statistical methods.

2.1 The MODIS instrument

The MODIS instrument onboard the Terra and Aqua polar-orbiting platforms of the Earth Observation System, was launched in December 1999 and May 2002, respectively, and is a 36-band scanning radiometer. MODIS uses the following main channels for determination of cloud properties over ocean: 0.645 μm for cloud optical depth; 1.640 μm for snow/cloud distinction; 2.130 μm and 3.750 μm for cloud droplet size (Platnick et al., 2003). Liquid water path is obtained from a combination of cloud optical depth and cloud droplet size. Remote sensing of aerosols over ocean uses the channels at 0.55 μm, 0.659 μm, 0.865 μm, 1.24 μm, 1.64 μm and 2.13 μm wavelength (Remer et al., 2005). The MODIS spatial resolution spans from 250 m to 1 km, and the level 3 product used in this study is provided on a $1^\circ \times 1^\circ$ grid, while the temporal resolution is 24 h, corresponding to one daily overpass. Collection 4 of the MODIS data set is used.

By comparison, the ISCCP uses several instrument platforms and a combination of geostationary satellites at 36 000 km height and polar-orbiting satellites at 850 km height. The ISCCP data have a spatial grid spacing of about 5 km and a temporal resolution of 3 h, and are mainly based on visible (0.6 μm) and infrared (11 μm) channels.

The MODIS data set consists of a large number of parameters characterizing aerosol and cloud properties. We have used the following variables for investigation of correlations with GCR: Cloud Amount (CA), which is the fractional or percentwise area covered by the clouds; Cloud Droplet Effective Radius (CER), which is an estimate of the mean size of cloud droplets, having typical values around 10 μm; Cloud Liquid Water Path (LWP), which is the vertically integrated cloud water content, having typical values on the order of 10–100 g m^{-2} for clouds in the lower troposphere; Cloud Optical Depth (COD), which is related to the former two quantities through the relation:

$$\mathrm{COD} = 3/2 * \mathrm{LWP}/(\mathrm{CER} * \rho_l) \quad (1)$$

where ρ_l is the density of liquid water.

2.2 Forbush decreases

The first observations of temporary changes in cosmic radiation on Earth were made by Scott E. Forbush of the Carnegie Institution of Washington, D.C., USA (Forbush, 1938). Now called Forbush decreases, these events are found to be caused by coronal mass ejections on the Sun, deflecting the interstellar magnetic field between the Sun and the Earth and thus creating a barrier that prevents some of the galactic cosmic radiation from reaching Earth's atmosphere (Cane, 2000). These events are typically marked by a sudden decrease in cosmic radiation, followed by a more slow recovery on the order of a few days.

In the present study, we identified Forbush decrease (FD) days using the CLIMAX, Colorado (39.37° N, 106.18° W) neutron monitor record as a basis. The resulting FD days were then compared to FD days found using the neutron monitor records of Oulu, Finland (65.05° N, 25.47° E) and Moscow, Russia (55.47° N, 37.32° E), to ensure consistency. We define a Forbush event as a situation with neutron counts equal to or lower than 5% below the 90-day running mean. In our analysis we have included data from 7 days before and 10 days after the onset of the Forbush event. In all, 22 episodes of 18 days with both neutron count and cloud data were retrieved from the period that MODIS has been

Table 1. Timing and intensity of the 22 Forbush decrease events that were investigated.

Date of FD event	GCR deviation	18-day period surrounding FD event
16 July 2000	−13%	9 July 2000 to 26 July 2000
18 September 2000	−6.7%	11 September 2000 to 28 September 2000
29 November 2000	−8.2%	22 November 2000 to 9 December 2000
12 April 2001	−12%	5 April 2001 to 22 April 2001
29 April 2001	−6.5%	22 April 2001 to 9 May 2001
28 August 2001	−5.5%	21 August 2001 to 7 September 2001
26 September 2001	−6.4%	19 September 2001 to 6 October 2001
25 November 2001	−5.3%	18 November 2001 to 5 December 2001
30 July 2002	−6.2%	23 July 2002 to 9 August 2002
19 November 2002	−5.8%	12 November 2002 to 29 November 2002
31 May 2003	−7.6%	24 May 2003 to 10 June 2003
23 June 2003	−5.9%	16 June 2003 to 3 July 2003
31 October 2003	−22%	24 October 2003 to 10 November 2003
24 November 2003	−9.0%	17 November 2003 to 4 December 2003
10 January 2004	−7.0%	3 January 2004 to 20 January 2004
25 January 2004	−7.0%	18 January 2004 to 4 February 2004
27 July 2004	−10%	20 July 2004 to 6 August 2004
10 November 2004	−7.3%	3 November 2004 to 20 November 2004
19 January 2005	−17%	12 January 2005 to 29 January 2005
16 May 2005	−6.6%	9 May 2005 to 26 May 2005
17 July 2005	−5.9%	10 July 2005 to 27 July 2005
13 September 2005	−14%	6 September 2005 to 23 September 2005

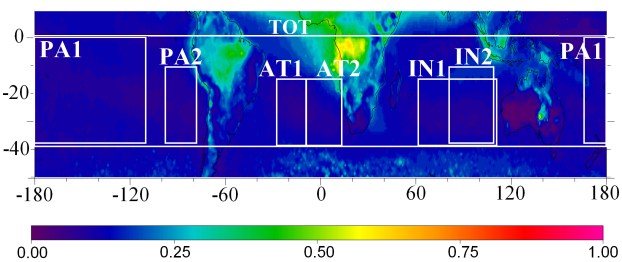

Fig. 1. The geographical regions of study along with their acronyms are indicated by white boxes. The color shading shows the aerosol optical depth averaged over the 22 Forbush decrease events.

in operation, see Table 1. Due to the variation of the cosmic ray ionization with latitude, the choice of a monitoring station geographically closer to the cloud fields being investigated might be considered. Comparing cosmic ray data from Potchefstoom, South Africa with those of Climax, Colorado for the 22 events (not shown) reveals that the amplitude at the South African station is lower by about a factor of 2 in most cases, but otherwise the signal is the same at these two locations.

The amplitude of the cosmic ray change varies significantly from one Forbush decrease event to another, from about 5% for the weakest events to about 25% amplitude for the strongest events. Below we have looked for possible sensitivity to this variation in our results.

2.3 Areas susceptible to GCR influence

When searching for a cosmic ray signal in the clouds, we focus on the areas where such a connection is most likely to manifest itself. To meet this demand, we have concentrated on regions that fulfil the criteria described below.

In his investigation of the aerosol indirect effect, Twomey (1991) invented the term "cloud susceptibility" to indicate that clouds in areas of low aerosol burden are more susceptible to changes in cloud properties due to anthropogenic aerosols than clouds in areas of high aerosol burden. By analogy we apply this concept to our study of the sensitivity to GCR influence on clouds. Hence, regions characterized by clean air with low cloud droplet number concentrations and large droplet radii are the ones most susceptible to changes in the ionization rate.

In any discussion of cloud susceptibility, optical depth is an important factor. As shown in the following relation based on Storelvmo et al. (2006), which expresses the change in cloud reflectivity due to a change in cloud droplet number

Table 2. Relationships between GCR flux and the cloud properties that would be expected if GCR were to influence clouds through a mechanism involving ionization and CCN production.

Parameters	Correlation sign	Physical explanation
GCR vs. CER	–	More aerosol particles → More numerous CCN → More numerous cloud droplets → Smaller cloud droplets
GCR vs. CA (all clouds or low clouds)	+	More numerous and smaller cloud droplets → Less precipitation → Larger spatial extent of clouds (e.g., Kaufman et al., 2005)
GCR vs. CA (high clouds)	–	More aerosol particles → More numerous ice nuclei → More numerous ice crystals → More precipitation
GCR vs. COD	+	Smaller cloud droplets → Larger COD
GCR vs. LWP	+	Less precipitation → Larger LWP

(ΔF),

$$\Delta F \propto -\frac{\tau}{(\tau+6.7)^2} \quad (2)$$

the cloud reflectivity is most sensitive to a change in cloud droplet number at optical depths (τ) of approximately 6.7, corresponding to moderately thick clouds. Hence, the clouds of intermediate optical thickness are the ones that may experience the largest influence of a small change in cloud droplet concentration. Earlier, Hobbs (1993) showed that the cloud susceptibility also depends on cloud amount, being largest for cloud amounts near 50%.

In order to avoid areas of high aerosol loads due to anthropogenic pollution, biomass burning or windblown dust, we have chosen to focus our study on remote Southern Hemisphere ocean regions, i.e., parts of the Atlantic Ocean (AT), the Indian Ocean (IN) and the Pacific (PA), shown in Fig. 1. We focus on subtropical regions, as both the tropics and higher latitudes more often have multi-layered clouds, which makes it more difficult for satellites to assess the cloud parameters. On the one hand, we have studied the areas far from land, which should be particularly pristine and susceptible to CCN changes. These areas are marked with postfix 1, so that AT1 is the mid-ocean part of the Southern Hemisphere Atlantic Ocean. We have also looked at areas where upwelling ocean currents meet the descending branch of the Hadley cell, forming stratocumulus layers underneath the subtropical subsidence inversion. These areas are marked with postfix 2, and so AT2 is the part of the Atlantic Ocean close to the African coast. A clear demonstration of the susceptibility of clouds in such areas is given by the numerous reports of persistent ship tracks (e.g., Ferek et al., 1998; Rosenfeld et al., 2006). Both Stevens et al. (2005) and Rosenfeld et al. (2006) suggested a mechanism by which the atmosphere in the marine stratocumulus regions can undergo a transition from an open cell regime with small cloud cover to a closed cell regime with high cloud cover, through a relatively modest increase in cloud droplet number concentration.

Along the same line of reasoning, Kirkby (2007) recently suggested that a cosmic ray – cloud coupling might have been particularly relevant in pre-historic times, due to the much lower aerosol burden in the atmosphere at that time, compared to present.

2.4 Statistical methods

In order to study the variations in the cloud parameters over a Forbush event, we performed studies of correlation coefficients between clouds and GCR. The correlation coefficients and their significance (p-value$<$0.05 for 95% significance) were found by comparing each 18-day period of cloud parameters to the corresponding 18-day period of GCR values. We moreover examined the ratios of the FD day values to values of the preceding and following days, in order to see if the day of minimum GCR corresponded to significant changes in the cloud variables. This was also performed with delays of 1 to 5 days, to examine the possibility that cloud changes might need some time to respond to the GCR changes.

Table 2 shows how the signs of the GCR-cloud variable correlations are expected to be if clouds and GCR are connected through ionization and CCN production. We will refer to this table in the discussion of the results below. A word of caution is needed concerning liquid water path, because even though from a cloud microphysical point of view the general expectation is that a higher cloud droplet number would suppress collisions and coalescence among the cloud droplets, resulting in enhanced LWP (Albrecht, 1989), as shown in the Table 2, observations and model simulations indicate that the opposite is also possible (e.g., Xue and Feingold, 2006). This is partly because the smaller and more numerous cloud droplets evaporate more readily than larger droplets, and this may reduce the LWP. Conversely, the expectation of reduced cloud droplet radius with increasing cloud droplet number is robust.

Table 3. Correlations between GCR and the four cloud parameters, averaged over all 22 Forbush decrease events. The correlations are given for the whole region between 0° S and 40° S (TOT, leftmost column), as well as for the individual domains shown in Fig. 1. Statistical p-values are given in parentheses; the first value is based on an assumption of statistical independence between the data points, while the second value is obtained by a reduction in the number of degrees of freedom due to auto-correlations. An asterisk indicates 95% significance when disregarding auto-correlation, while bold numbers indicate 90% statistical significance or more when auto-correlation is considered.

	TOT	AT1	PA1	IN1	AT2	PA2	IN2
Cloud amount	0.313	0.486*	**0.461***	−0.137	0.048	0.297	0.134
(CA)	(0.205/0.425)	(0.041/0.286)	(0.054/0.045)	(0.589/0.719)	(0.851/0.883)	(0.231/0.428)	(0.595/0.727)
Cloud effective	−0.624*	−0.061	−0.027	−0.204	**−0.726***	−0.068	−0.374
radius (CER)	(0.006/0.142)	(0.810/0.789)	(0.917/0.922)	(0.416/0.327)	(0.001/0.095)	(0.790/0.861)	(0.126/0.498)
Cloud optical	−0.508*	0.482*	−0.139	0.004	**−0.544***	0.115	0.293
depth (COD)	(0.032/0.245)	(0.043/0.255)	(0.581/0.639)	(0.988/0.992)	(0.020/0.025)	(0.650/0.608)	(0.238/0.322)
Liquid water	−0.380	0.615*	−0.463*	−0.418	−0.449	0.340	−0.264
path (LWP)	(0.119/0.329)	(0.007/0.172)	(0.053/0.292)	(0.084/0.476)	(0.061/0.424)	(0.168/0.277)	(0.289/0.555)

3 Results

In this section, we present results from the data analysis. The domains shown in Fig. 1 and the cloud parameters described in Sect. 2.1 were tested for a response to the FD. First we consider the overall results, including average results for the whole geographical area between 0° S and 40° S (TOT), as well as main results for the six individual domains (Sect. 3.1). The importance of violent solar events to our results will be discussed in Sect. 3.2, and finally, in Sects. 3.3 and 3.4, we look more carefully at particular features in two of the domains.

3.1 Main features

The correlation coefficients between GCR and various cloud parameters for the areas investigated in the present study are shown in Table 3. In the whole domain between 0° S and 40° S (TOT), we note that the cloud droplet size (CER) has a rather large negative correlation with GCR, and the sign of that correlation is consistent with Table 2. The correlation for cloud optical depth (COD) is also relatively high, though again not statistically significant. Interestingly, the correlation between GCR and COD is negative, meaning that a reduction in cosmic ray flux leads to an increase of cloud albedo, which is opposite to what Table 2 suggests. The reason for this is apparently the negative correlation between GCR and liquid water path (LWP, Table 3), as understood from Eq. (1). As mentioned at the end of Sect. 2, it is not clear what sign should be expected for a correlation between GCR and LWP, if the GCR-CCN mechanism holds. Therefore, the negative correlation between GCR and COD does not necessarily violate a GCR-CCN mechanism, but it does argue against the climate coupling suggested by Marsh and Svensmark (2000), which assumes a positive correlation between GCR and the Earth's albedo. For cloud amount (CA), the correlation with GCR is positive, but weak.

Considering now the 6 ocean domains that were studied, the Atlantic Ocean area far from the coast (AT1) has all four correlations of the sign indicated in Table 2. The correlations for CA, COD and LWP are rather high, though not statistically significant. Another mid-ocean domain of interest, PA1, has a statistically significant positive correlation between GCR and CA, in agreement with Table 2. There is a rather large, though not significant, negative correlation between GCR and LWP. For the other two quantities, however, the correlations are weak. For the Indian Ocean domain, IN1, all the correlations are weak.

Among the near-coastal areas, the Atlantic Ocean (AT2) is the only one to display significant correlations – here in terms of CER and COD. The significant negative correlation between GCR and CER, in agreement with Table 2 is particularly noticeable. The significant negative correlation between GCR and COD violates Table 2, and we refer to the discussion of the results in TOT at the beginning of Sect. 3.1 for an interpretation of this result. Neither of the remaining two near-coastal domains show statistically significant correlations, and the signs of the correlations do not display any systematic pattern. Table 4 displays the average values of the various parameters of study. Interestingly, all the domains have large cloud droplet sizes, intermediate cloud covers and optical depths close to the maximum susceptibility value indicated in the discussion of Eq. (2). The cloud susceptibility appears to be particularly large for the domain PA1 over the Pacific Ocean. Table 5 shows correlations between GCR and the cloud parameters for the whole area investigated (TOT), and for each of the 22 FD events. Overall, 44 out of the 88 values in the Table have signs consistent with Table 2, suggesting a purely random distribution. Only three of the entries in Table 5 are statistically significant, and one of those – cloud amount on 31 October 2003 – has a sign that is inconsistent with Table 2. On the other hand, as expected from Table 3, many of the events have a rather high negative

Table 4. Average values of the 22 Forbush decrease events of the four cloud parameters for respectively, the whole domain between 0° S and 40° S (TOT), and for the domains indicated in Fig. 1. Bold type indicates those values on each line of the table that have the largest cloud susceptibility (see text for details).

	TOT	AT1	PA1	IN1	AT2	PA2	IN2
Cloud amount [%]	**65.5**	69.6	**66.0**	72.0	74.3	80.0	73.7
Cloud effective radius [μm]	17.96	**19.28**	**19.77**	18.80	16.02	18.18	18.61
Cloud optical depth	7.32	7.30	**6.68**	7.28	7.65	8.48	7.18
Liquid water path [g m^{-2}]	87.8	95.3	90.6	93.8	84.5	105.7	91.9

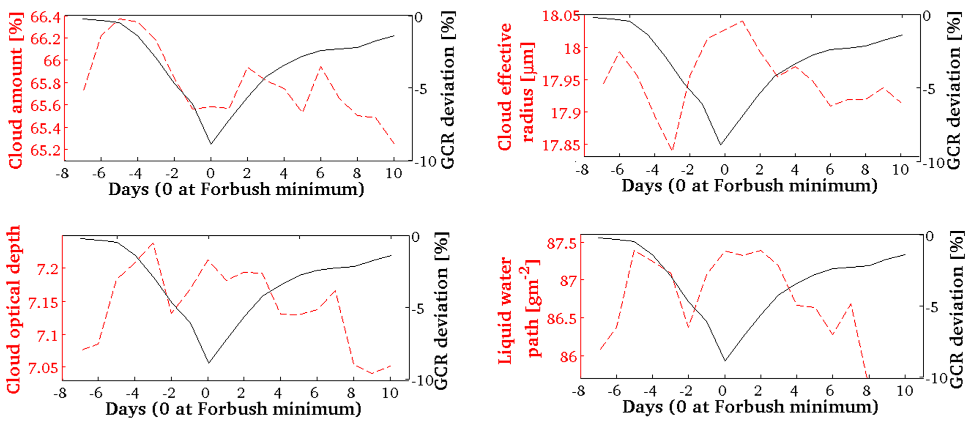

Fig. 2. GCR flux (solid curves) and cloud amount, cloud effective radius, cloud optical depth and liquid water path, averaged over all 22 events and the TOT domain (dashed curves).

correlation between GCR and CER, consistently with Table 2. The first event, 16 July 2000 has rather high correlations of all 4 quantites, in all cases of the same sign as in Table 2. However, this seems to be a statistical co-incidence, as e.g., the 31 May 2003 case shows the exactly opposite behaviour.

Figure 2 shows how the investigated cloud parameters, averaged over the 22 periods and over the entire latitude band 0 to 40° S, evolved over the 18 days prior to, during and after the Forbush event. The amplitude of variation in all parameters is rather small, i.e., about 1.2% in CA, about 0.2 μm in CER, about 0.2 in COD and about 1.7 g m^{-2} in LWP. Consistently with Table 3, we see a tendency for cloud amount to be slightly smaller, cloud droplet size to be larger, cloud optical depth to be larger and liquid water path to be slightly larger at the day of the FD than at the surrounding days. In order to allow for the possibility that a change in GCR may take a few days to manifest itself in terms of changes in cloud properties, we show in Fig. 3 the correlation between cosmic ray flux and each of the four cloud parameters for time lags in the latter quantity of 0–5 days in steps of 1 day. Somewhat conflicting results are found. For cloud amount, which had a positive correlation at day 0, consistently with Table 2, the correlation drops and then becomes increasingly negative at a lag of 5 days. Conversely, for cloud droplet size, which had a rather large negative correlation at day 0, consistently with Table 2, the correlation weakens with increasing lag, and changes sign after 2 days. The negative correlation for cloud optical depth weakens as a 1–5 day lag is introduced, while for liquid water path the correlation stays on the negative side, and changes little with increasing lag. It is difficult to draw a common conclusion from these four different types of behaviour, but clearly the case for a GCR-CCN-cloud coupling is not strengthened when a 1–5 day lag is introduced.

3.2 Ground level enhancements

As explained in Sect. 2.2, Forbush decrease events occur when galactic cosmic rays are deflected from Earth by coronal mass ejections on the Sun. On rare occasions, some of these coronal mass ejections are violent enough to accelerate solar protons to energies comparable to or even higher than those of the galactic cosmic rays. These episodes are called solar proton events. While solar protons normally have insufficient energies to penetrate Earth's magnetic field, solar proton events are strong enough to be recorded by ground-based neutron monitors as "ground level enhancements" (GLE) in the neutron count rate. As the event on the Sun at the same

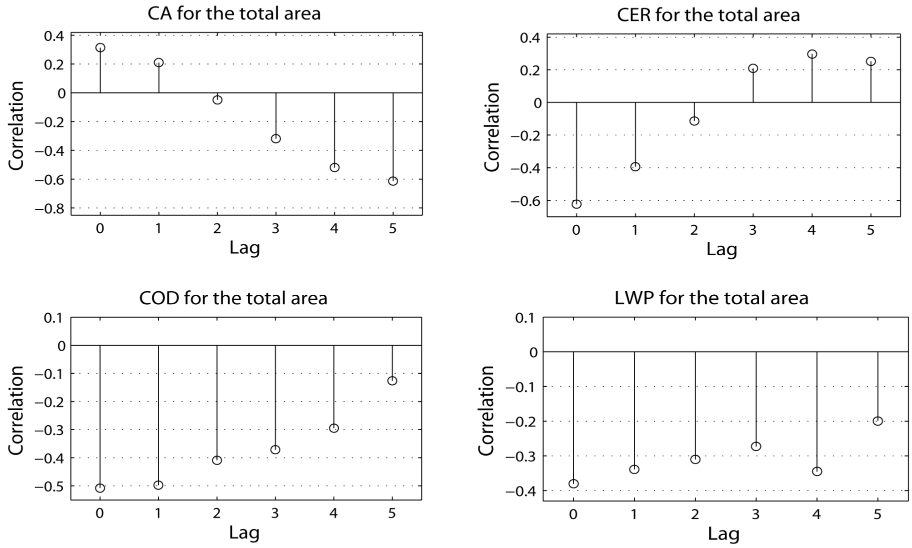

Fig. 3. Correlations between GCR and four cloud parameters (cloud amount, CA; cloud droplet effective radius, CER; cloud optical depth, COD; and liquid water path, LWP) for the whole area (TOT) of investigation at lags of 0 to 5 days.

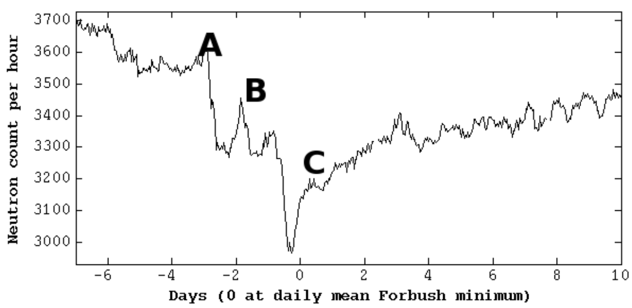

Fig. 4. The July 2000 Forbush period (see Table 1) shows a ground level event (at B) within a Forbush decrease event (starting at A and ending around day 10).

time will be shielding the Earth from galactic cosmic radiation, GLEs typically occur during Forbush decrease events, being more energetic but not as long lasting (on the order of hours) as the Forbush events.

In equatorial regions, the protons need energies larger than 15 GeV (Bazilevskaya et al., 2000) to penetrate Earth's geomagnetic field, which at these latitudes is close to perpendicular to the direction of entry. In our study, 4 of the 22 Forbush events coincided with solar proton events of energies exceeding 10 GeV (dates and energies retrieved from the NOAA Space Environment Services Center web page on Solar Proton Events Affecting the Earth Environment). In Fig. 4 we show hourly means of neutron counts for the 18-day period surrounding one of these events, that took place in July 2000. At A in the figure, coronal mass ejections on the Sun mark the onset of a Forbush decrease event, manifested as a distinct decrease in the neutron count. At B, one (or more) of the coronal mass ejections is strong enough to be characterized as a solar proton event, and we see the GLE as a sharp rise in the neutron count. By C, the neutron count is slowly recovering, as is the course of a standard Forbush decrease event.

To explore if these intense but short-lived peaks within the Forbush events may have affected our results, inducing poorer correlations between GCR and cloud parameters, we take a closer look at the four episodes coinciding with large solar proton events, namely July 2000 (solar proton event of 24 GeV), September 2001 (13 GeV), November 2001 (19 GeV) and October 2003 (30 GeV). As Table 5 shows, these four events do not show systematically poorer correlations between GCR and cloud parameters than the other 18 events. In fact, among all 22 events included in this study, the July 2000 event shows the most consistent correlations between GCR and the cloud variables, in spite of the GLE.

3.3 Strong vs. weak Forbush decrease events

Conceivably, some of the Forbush decrease events studied here are too weak to yield a cloud response. In that case stronger correlations than those found in Table 3 might be expected if only the largest amplitude events were considered. Clearly, the number of events under investigation is too small to allow for a detailed stratification of the data. Therefore, a simple approach was taken, by looking more carefully into the results from the six strongest events (16 July 2000, 12 April 2001, 31 October 2003, 27 July 2004, 19 January 2005 and 13 September 2005), having amplitudes of 13%, 12%, 22%, 10%, 17% and 14%, respectively. It turns out that the results for these six events are slightly more favourable to a GCR-CCN-cloud coupling than the results for all 22 cases, in

Table 5. Correlation coefficients between GCR and cloud amount (CA), cloud effective radius (CER), cloud optical depth (COD) and liquid water path (LWP), respectively. Numbers are for the whole domain between 0° S and 40° S (TOT) and for each of the 22 periods investigated. An asterisk indicates 95% significance when disregarding auto-correlation, while bold numbers indicate 90% statistical significance or more when auto-correlation is considered (corresponding p-values are given in parentheses).

	CA	CER	COD	LWP
16 July 2000	**0.652***	−0.378	0.641*	0.622*
	(0.095)	(0.493)	(0.163)	(0.129)
18 September 2000	−0.425	−0.001	−0.203	−0.340
	(0.312)	(0.899)	(0.609)	(0.456)
29 November 2000	0.414	−0.552*	0.313	0.046
	(0.423)	(0.114)	(0.452)	(0.907)
12 April 2001	0.715*	0.056	0.232	0.158
	(0.120)	(0.860)	(0.551)	(0.699)
29 April 2001	−0.186	−0.085	−0.246	−0.173
	(0.616)	(0.847)	(0.565)	(0.592)
28 August 2001	−0.083	−0.487*	−0.254	−0.446
	(0.847)	(0.448)	(0.574)	(0.399)
26 September 2001	0.011	−0.372	−0.277	−0.412
	(0.977)	(0.482)	(0.530)	(0.398)
25 November 2001	−0.026	0.098	0.107	0.222
	(0.938)	(0.732)	(0.769)	(0.537)
30 July 2002	−0.342	−0.164	−0.339	−0.423
	(0.605)	(0.663)	(0.522)	(0.384)
19 November 2002	0.450	−0.290	0.392	0.326
	(0.159)	(0.536)	(0.265)	(0.409)
31 May 2003	−0.497*	0.374	−0.345	−0.354
	(0.214)	(0.527)	(0.487)	(0.476)
23 June 2003	−0.691*	−0.256	−0.247	−0.292
	(0.211)	(0.417)	(0.642)	(0.577)
31 October 2003	**−0.606***	−0.488*	−0.108	−0.150
	(0.093)	(0.193)	(0.801)	(0.744)
24 November 2003	0.170	0.583*	−0.570*	−0.427
	(0.784)	(0.349)	(0.288)	(0.261)
10 January 2004	−0.032	−0.478*	−0.579*	−0.706*
	(0.898)	(0.329)	(0.232)	(0.221)
25 January 2004	0.237	**−0.879***	0.273	−0.147
	(0.404)	(0.011)	(0.543)	(0.721)
27 July 2004	0.475*	−0.264	0.022	0.175
	(0.220)	(0.496)	(0.953)	(0.614)
10 November 2004	0.222	0.396	−0.104	0.028
	(0.765)	(0.262)	(0.849)	(0.954)
19 January 2005	0.188	0.504*	0.158	0.367
	(0.658)	(0.286)	(0.798)	(0.504)
16 May 2005	0.472*	−0.025	−0.157	−0.140
	(0.399)	(0.954)	(0.613)	(0.705)
17 July 2005	0.464*	0.378	−0.365	−0.085
	(0.655)	(0.408)	(0.423)	(0.863)
13 September 2005	−0.314	−0.255	−0.429	−0.479*
	(0.625)	(0.285)	(0.500)	(0.453)

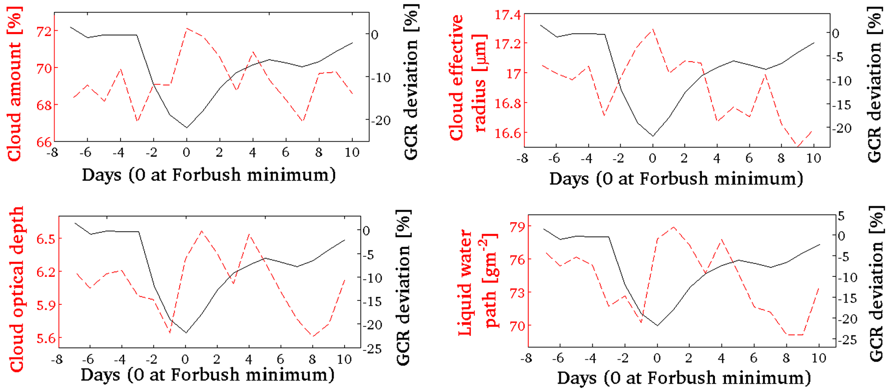

Fig. 5. As Fig. 2, but for the 31 October 2003 event (cf. Table 3).

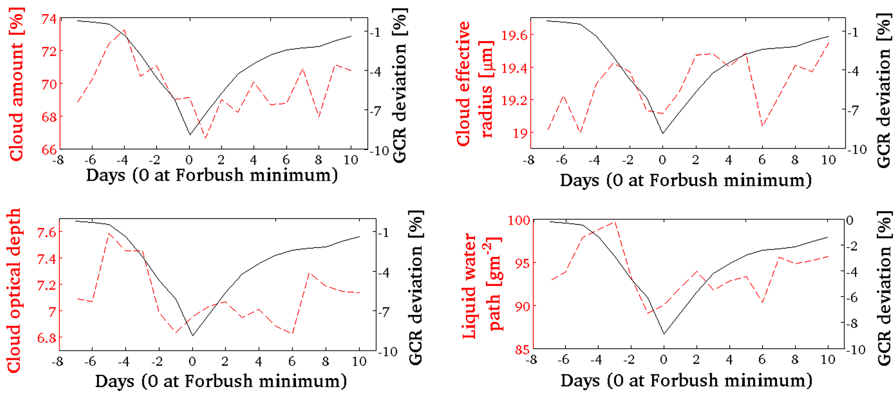

Fig. 6. As Fig. 2, but for the sub-area AT1 depicted in Fig. 1.

the sense that 16 out of the 24 correlations are of the sign indicated in Table 2. For instance, for the 16 July 2000 event, all four quantites have the expected sign (Table 5), and for three of them, the correlations are higher than 0.6 in absolute value. However, a different impression is given by the strongest event, 31 October 2003, shown in Fig. 5. A cloud signal that coincides quite well in time with the Forbush decrease is found, but it is only for cloud droplet size that the signal has the expected sign. The fact that cloud amount, cloud droplet effective radius, cloud optical depth and liquid water path all increase at the same time, near day 0, may indicate the occurrence of a meteorological event, rather than an aerosol event. This highlights the difficulty of separating a possible cosmic ray signal from the natural variability, which at the same time suggests that the cosmic ray signal, if it exists in the cloud data, is probably quite weak. The other 4 strong events, none of which coincided with GLEs, do not show any systematic behaviour as far as correlations with GCR are concerned (Table 5). It is also noticeable that one of the weakest Forbush decrease events, on 19 November 2002 with an amplitude of only 6%, has correlations that for all the cloud parameters have the expected sign, and for two of them the correlation coefficient is around 0.4 in absolute value.

3.4 Results from the domain AT1

One of the domains that showed correlations that were rather high, having signs that were in agreement with Table 2, was domain AT1. Therefore we now consider the results from this domain in some detail. Clearly, it could be argued on statistical grounds that one should expect, by chance, one of the domains to exhibit correlations favorable to the hypothesis being tested. The purpose of this subsection is precisely to seek validation or falsification of such a conclusion. First, Fig. 6 shows the time evolution of the four cloud parameters for this area, overlaid on the cosmic ray flux. We note that between days −8 and −4 (relative to the Forbush minimum) all four variables – cloud amount, liquid water path, cloud optical depth and, to a lesser degree, cloud droplet effective radius – show a substantial increase. It is possible that this increase is caused by changes in the meteorological conditions. To what extent the subsequent fall in cloud amount, cloud optical depth and liquid water path from day −4 to day −1 is caused by meteorological variability or a physical connection is not possible to determine, but in any case, that fall appears to be a large contributor to the high correlations found for the AT1 area in Table 3. When averaging over large domains, as in Figs. 2–3 for TOT, such meteorological variability would tend to be evened out by the spatial averaging.

Table 6. Correlations between GCR flux and the various cloud parameters for latitudinal sub-divisions of the domain AT1 defined in Fig. 1. An asterisk indicates 95% significance when disregarding auto-correlation, while bold numbers indicate 90% statistical significance or more when auto-correlation is considered (corresponding p-values are given in parentheses). CA denotes cloud amount, CER denotes cloud effective radius, COD denotes cloud optical depth and LWP denotes liquid water path.

	AT1 15–20° S	AT1 20–30° S	AT1 30–40° S
CA, all cloud types	0.057	0.659*	−0.027
	(0.876)	(0.160)	(0.946)
CA, high clouds	0.565*	0.701*	0.132
	(0.160)	(0.159)	(0.660)
CA, stratocumulus	−0.043	−0.124	0.161
	(0.835)	(0.795)	(0.557)
CER, all cloud types	−0.467*	−0.426	0.466*
	(0.343)	(0.308)	(0.343)
CER, high clouds	0.446	0.644*	0.235
	(0.272)	(0.199)	(0.456)
CER, stratocumulus	−0.467*	−0.505*	0.294
	(0.198)	(0.290)	(0.342)
COD, all cloud types	−0.036	0.683*	0.159
	(0.922)	(0.120)	(0.641)
COD, high clouds	0.664*	0.707*	0.186
	(0.164)	(0.203)	(0.514)
COD, stratocumulus	−0.039	−0.212	0.171
	(0.891)	(0.662)	(0.512)
LWP, all cloud types	0.250	0.617*	0.419
	(0.580)	(0.202)	(0.148)
LWP, stratocumulus	0.166	0.334	0.430
	(0.686)	(0.522)	(0.143)

Table 6 shows a more detailed study of the AT1 area. Here we have partitioned the domain into three latitude bands, as the increase of GCR with geomagnetic latitude, caused by the orientation of Earth's geomagnetic field lines, is well-established (Forbush, 1938). We also checked for correlations in areas of high clouds (cloud top pressure $<$440 hPa) and areas of low clouds of intermediate optical thickness (cloud top pressure $>$680 hPa and $3.6<\tau<23$; dubbed "stratocumulus" as in Rossow and Schiffer, 1999). The motivation for focusing on stratocumulus clouds is that they would be expected to be more susceptible to GCR changes than other clouds, according to Eq. (2) and the suggestion of Yu (2002), presented in the introduction. Figure 7 shows the horizontal distribution of the optical depth of low clouds from the MODIS data. We note that the highest optical depths are found off the west coasts of Peru, Namibia and Australia, as expected (e.g., Klein and Hartmann, 1993), while the clouds over the open oceans, e.g., the AT1 domain, are optically thinner, and according to Eq. (2), more susceptible to changes in cloud droplet number.

The motivation for also singling out high clouds is that, as mentioned in the introduction, Eichkorn et al. (2002) have found evidence for cosmic ray induced aerosol formation precisely at those levels in the atmosphere where high clouds would form. Interestingly, high clouds may have a reverse

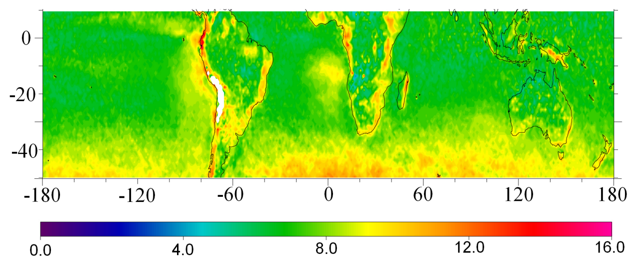

Fig. 7. Cloud optical depth for low clouds in the area of interest, averaged over all 22 events.

correlation to GCR, according to Yu (2002). Furthermore, their microphysical characteristics are very different from those of low clouds, since they consist largely of ice crystals, while low clouds consist mainly of liquid cloud droplets. While the release of precipitation from thin liquid clouds tends to be suppressed by adding more cloud condensation nuclei (Albrecht, 1989), the addition of ice nuclei to a cold cloud would rather be expected to enhance the precipitation release. As it turns out, the specific cloud types do indeed show correlations that are not present when only studying the total cloud cover. For instance, for high clouds, both CA

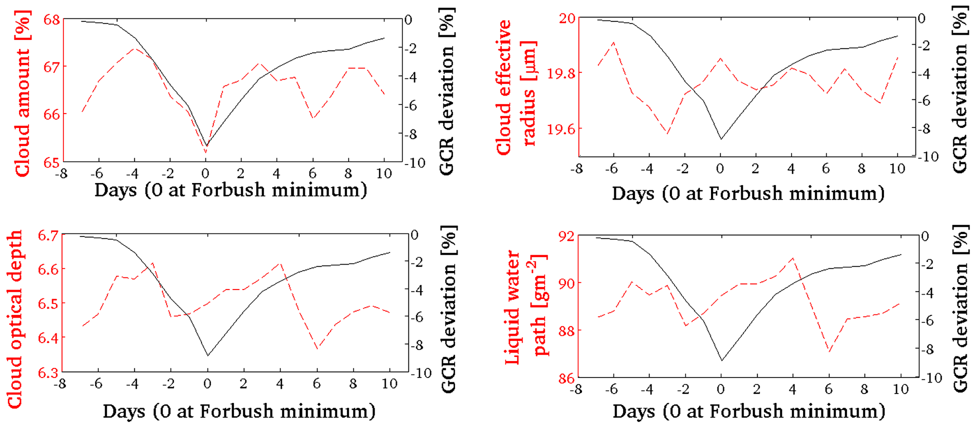

Fig. 8. As in Fig. 2, but for the sub-area PA1 depicted in Fig. 1.

and COD show a rather high correlation with GCR in the two northernmost sub-domains. For stratocumulus clouds, CER correlates favourably with GCR in those same sub-domains. Although none of the correlations are statistically significant at the 90% level, when auto-correlations are taken into account, 11 out of the 12 highest correlations, marked with asterisks, are of the sign indicated in Table 2.

3.5 Results from the domain PA1

To contrast with the results of Fig. 6, we show in Fig. 8 the time evolution of cosmic ray flux and the four cloud parameters for the much larger domain PA1, which in Table 3 displayed few signs of correlations consistent with the hypothesis outlined in Table 2. We keep in mind that the domain PA1 was found to have a particularly high cloud susceptibility (Table 4 and discussion thereof in Sect. 3.1). We note that the cloud optical depth variations seem to be dominated by variations in liquid water path, having a three-peaked structure with minima at −4, −2 and +6 days relative to the Forbush minimum. The highest values are found at −3 and +4 days. Cloud amount variations have a similar pattern, while the effective radius curve is more flat. As in Fig. 6, meteorological variability is likely to be a significant contributor to the variations found here, even though the much larger size of the domain means that such variations would be suppressed in the case of PA1.

Indeed, it might be suggested that the variable results obtained in Table 3 could be related to the different sizes of the domains being considered, the domain AT1 with high correlations being the smallest domain, and the domain PA1 with poor correlations being the largest one. In order to investigate the sensitivity to how the domains were defined, we have divided the PA1 region into 5 sub-domains, with the results being given in Table 7. Clearly, none of these sub-domains display statistical behavior that would strengthen the case for a cosmic ray – cloud relationship, as depicted in Table 2.

4 Summary and concluding remarks

Most previous studies investigating the possibility of a relationship between galactic cosmic rays, CCN and clouds have focused solely on cloud cover, and have often used an inferior version of the ISCCP cloud cover data set. For this reason their results have sometimes been conflicting and potentially misleading. In the present study we have taken advantage of recent developments in satellite retrieval technologies by using observational data from the MODIS instrument, which has a much higher spectral resolution than the instruments forming the ISCCP dataset. In addition to cloud cover, we carefully investigate the cloud microphysical variables expected to be most sensitive to changes in CCN formation, i.e., cloud droplet radius, cloud water path and cloud optical depth. Furthermore, with a few exceptions, we focus on moderately thick low clouds, which would be expected to be more susceptible to changes in CCN concentrations than any other clouds. Finally, we deliberately limit the investigation to the subtropical oceans of the Southern Hemisphere, which is an area characterized by very little pollution, again enhancing the cloud susceptibility. While the previous studies have often dealt with decadal-scale variations, we instead seek relations between galactic cosmic rays and cloud properties in connection to Forbush decrease events, which have a time scale of a few days. If such a relationship exists we feel that it should be most easily detectable on such short time scales.

Our main findings from the data analysis can be summarized as follows:

– In general, variations in cloud properties (cloud amount, cloud droplet effective radius, cloud optical depth, cloud liquid water path) from MODIS over the Southern Hemisphere subtropical oceans do not show statistically significant correlations with variations in GCR flux associated with Forbush decrease events. This is also the case for 1–5 day lagged correlations.

Table 7. Correlations between GCR flux and the various cloud parameters for sub-divisions of the domain PA1 defined in Fig. 1. An asterisk indicates 95% significance when disregarding auto-correlation, while bold numbers indicate 90% statistical significance or more when auto-correlation is considered (corresponding p-values are given in parentheses). CA denotes cloud amount, CER denotes cloud effective radius, COD denotes cloud optical depth and LWP denotes liquid water path.

	PA1, 165–184° E	PA1, 184–203° E	PA1, 203–222° E	PA1, 222–241° E	PA1, 241–260° E
CA, all cloud types	0.174	−0.099	−0.062	−0.017	−0.310
	(0.532)	(0.657)	(0.829)	(0.945)	(0.268)
CA, high clouds	0.380	0.172	−0.014	−0.435	−0.441*
	(0.338)	(0.745)	(0.969)	(0.209)	(0.308)
CA, stratocumulus	0.083	−0.184	0.195	0.432	−0.035
	(0.862)	(0.762)	(0.609)	(0.299)	(0.890)
CER, all cloud types	−0.104	−0.157	−0.163	−0.205	−0.322
	(0.629)	(0.556)	(0.518)	(0.357)	(0.392)
CER, high clouds	0.121	0.554*	−0.072	−0.417	−0.435
	(0.764)	(0.241)	(0.854)	(0.214)	(0.324)
CER, stratocumulus	−0.185	−0.512*	0.095	0.417	−0.178
	(0.593)	(0.346)	(0.785)	(0.384)	(0.748)
COD, all cloud types	−0.292	−0.220	−0.127	−0.081	−0.213
	(0.428)	(0.448)	(0.674)	(0.776)	(0.323)
COD, high clouds	−0.067	0.314	−0.215	−0.384	−0.309
	(0.829)	(0.478)	(0.442)	(0.262)	(0.428)
COD, stratocumulus	0.071	−0.302	0.251	0.408	−0.086
	(0.829)	(0.389)	(0.534)	(0.320)	(0.831)
LWP, all cloud types	−0.202	−0.438	−0.393	−0.128	−0.405
	(0.395)	(0.138)	(0.299)	(0.734)	(0.359)
LWP, stratocumulus	−0.134	0.607*	0.136	0.562*	−0.478*
	(0.719)	(0.257)	(0.743)	(0.193)	(0.192)

- Cloud droplet size has a rather large negative correlation with GCR, in agreement with a possible GCR-CCN-cloud coupling. In one of the domains studied (off the coast of SW Africa), that correlation was statistically significant.

- The six Forbush decrease events with the largest amplitude show on average slightly stronger indications of a cosmic ray signal in the cloud parameters than the average of the other cases, with 16 out of 24 explored correlations having the expected sign, but only 4 of these have correlations above 0.5 in absolute value. Due to the limited number of cases studied, the significance of this result is difficult to evaluate.

- One of the domains studied (mid-Atlantic) showed correlations which for all four cloud parameters have signs that are consistent with a cosmic ray induced CCN formation. In this rather small domain cloud susceptibility is large, implying a potentially large impact on cloud albedo. A more detailed analysis of this domain revealed high correlations between GCR and the properties of high clouds in general and low clouds of intermediate optical depth.

- Subdividing the largest domain of study (in the Pacific) into areas of the same size as the mid-Atlantic domain does not yield statistically significant or physically meaningful correlations for any of the four cloud parameters.

The overall conclusion, built on a series of independent statistical tests, is that no clear cosmic ray signal associated with Forbush decrease events is found in highly susceptible marine low clouds over the southern hemisphere oceans. Whether such a signal exists at all can not be ruled out on the basis of the present study, due to the small number of cases and because the strongest Forbush decrease events indicate slightly higher correlations than the average events. Even though those strong events are rare, with only 6 events over 5 years, the amplitude is similar to that occurring during the solar cycle, so from a climate perspective these strong events may deserve particular attention. Further investigations of a larger number of such events are needed before final conclusions can be drawn on the possible role of galactic cosmic rays for clouds and climate. Also, future investigations should explore the sensitivity to the selection of geographical regions for study. For instance, the recent studies of Kazil et al. (2006) and Yu et al. (2008) indicate that ion-induced aerosol nucleation may be most effective in the upper tropical troposphere, which was not considered here. For the ongoing global warming, however, the role of galactic cosmic rays would be expected to be negligible, considering the fact that the cosmic ray flux has not changed over the last few decades – apart from the 11-year cycle (Lockwood and Fröhlich, 2007).

Acknowledgements. The MODIS data were obtained from the NASA MODIS web site http://modis.gsfc.nasa.gov/, while the cosmic ray data associated with Forbush decrease events were obtained from the National Geophysical Data Center's web site http://www.ngdc.noaa.gov/stp/SOLAR/ftpcosmicrays.html. The authors are grateful to the two anonymous reviewers for their constructive and helpful comments.

Edited by: J. Quaas

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