

## Cosmic rays, CCN and clouds – a reassessment using MODIS data

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### Abstract

The response of clouds to sudden decreases in the flux of galactic cosmic rays (Forbush decrease events) has been investigated using cloud products from the spaceborne MODIS instrument, which has been in operation since 2000. By focusing on pristine Southern Hemisphere ocean regions we examine areas which are particularly susceptible to changes in cloud condensation nuclei (CCN) concentrations, and where a cosmic ray signal should be easier to detect than elsewhere. While previous studies on the subject 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 13 Forbush decrease events that were considered, no systematic correlation was found between any of the four cloud parameters and galactic cosmic radiation, with a seemingly random distribution of positive and negative correlations. When only the three Forbush decrease events with the largest amplitude are studied, the correlations fit the hypothesis better, with 8 out of 12 correlations having the expected sign. Splitting the area of study into several sub-regions, one sub-region in the Atlantic Ocean showed statistically significant correlations compatible with a cosmic ray-induced enhancement of CCN and cloud droplet number concentrations. However, the lack of correlation in any of the other 5 sub-regions suggests that this may be a statistical co-occurrence. Introducing a time lag of a few days for clouds to respond to the cosmic ray signal did not change the overall results. Singling out low clouds of intermediate optical depth with large susceptibility did not lead to higher correlations. In conclusion, no response to variations in cosmic rays associated with Forbush decrease events was found in marine low clouds in remote regions using MODIS data.

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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 ionising 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 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).

There have also been numerical and laboratory studies attempting to answer the

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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. Consistently with this notion, Eichkorn et al. (2002) carried out aircraft measurements of aerosols in the upper troposphere and found large cluster ions, which were presumably caused by GCR ionization. Also, Svensmark et al. (2006) 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.

Further, Yu (2002) investigated the variation with height of the influence of GCR ionization on particle formation. Even though GCR induced ionization peaks at around 13 km altitude in the atmosphere (Neher, 1971), Yu (2002) presented APM simulations in which the largest difference in ionization-aided particle formation between times of high and low solar activity was at 3 km altitude. This would suggest that low clouds might indeed be more sensitive to changes in GCR flux than higher clouds. 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

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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. These latter effects are highly uncertain, and are beyond the scope of this study.

5 If the correlation between cloud cover and GCR is caused by variations in the concentration and efficiency of CCN through ionisation, 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  
10 clouds, found a positive correlation between clouds and FD for U.K. 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  
15 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.

20 We feel that too many of the previous studies investigating possible GCR-cloud relations have focused on cloud cover alone, 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 cosmic rays influence clouds, a different approach is needed. In the present study we investigate the response of various cloud parameters to Forbush  
25 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. High, middle and low clouds are investigated separately, and cloud amount as well as microphysical parameters

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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

5 Cloud data in this study are from retrievals by the Moderate-resolution Imaging Spectroradiometer (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  
10 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  
15 for determination of cloud properties over ocean:  $0.645\ \mu\text{m}$  for cloud optical depth;  $1.640\ \mu\text{m}$  for snow/cloud distinction;  $2.130\ \mu\text{m}$  and  $3.750\ \mu\text{m}$  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  $0.55\ \mu\text{m}$ ,  $0.659\ \mu\text{m}$ ,  $0.865\ \mu\text{m}$ ,  $1.24\ \mu\text{m}$ ,  $1.64\ \mu\text{m}$  and  $2.13\ \mu\text{m}$  wavelength  
20 (Remer et al., 2005). The MODIS spatial resolution spans from 250 m to 1 km and the level 3 product used in this study has been interpolated to 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  
25 of geostationary satellites at 36 000 km height and polar-orbiting satellites at 850 km

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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 ( $0.6 \mu\text{m}$ ) and infrared ( $11 \mu\text{m}$ ) 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  $10 \mu\text{m}$ ; Cloud Liquid Water Path (LWP), which is the vertically integrated cloud water content, having typical values on the order of  $10\text{--}100 \text{ g m}^{-2}$  for clouds in the lower troposphere; Cloud Optical Depth (COD), which is related to the former two quantities through the relation:  $\text{COD} = 3/2 * \text{LWP} / (\text{CER} * \rho_l)$ , where  $\rho_l$  is the density of liquid water.

## 2.2 Forbush decreases

The first observations of temporary changes in cosmic radiation on Earth were made by Dr. Scott E. Forbush of the Carnegie Institution of Washington, D. C., U. S. A. (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 ( $39.37^\circ \text{ N}$ ,  $106.18^\circ \text{ W}$ ) 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 ( $65.05^\circ \text{ N}$ ,  $25.47^\circ \text{ E}$ ) and Moscow, Russia ( $55.47^\circ \text{ N}$ ,  $37.32^\circ \text{ E}$ ), 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, 13 episodes of 18 days with both neutron count and cloud data were retrieved from the

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period that MODIS has been 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 Potchefstroom, South Africa with those of Climax, Colorado for the 13 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 a 20% 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 ionisation rate.

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

$$\Delta F \propto -\frac{\tau}{(\tau + 6.7)^2} \quad (1)$$

the cloud reflectivity is most sensitive to a change in cloud droplet number at optical

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depths ( $\tau$ ) 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 concentrations.

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.

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## 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 ionisation 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 (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.

## 3 Results

In this section, we present results from the data analysis. The ocean regions 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 that we have investigated (Sect. 3.1). Then, in Sects. 3.2 and 3.3,

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we look more carefully at particular features in two of the sub-domains.

### 3.1 Main features

The correlation coefficients between GCR and various cloud parameters for the ocean areas investigated in the present study are shown in Table 3. The largest correlations are found in the Atlantic Ocean area far from the coast (AT1), see Fig. 1. Here, correlations are significant between GCR and total cloud amount, GCR and cloud optical depth, and GCR and liquid water path. Furthermore, in all three cases, the correlation has the same sign as indicated in Table 2. In the case of cloud effective radius, the correlation is not statistically significant, but we note that also for this quantity the sign is consistent with Table 2. Among the near-coastal areas, the Atlantic Ocean (AT2) is the only one to display any significant correlations – here in terms of cloud cover and liquid water path. Note, however, that these correlations are negative, so that less GCR is in fact associated with increased cloudiness, in contrast to the signs in Table 2. None of the remaining near-coastal regions 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. Values that correspond to large cloud susceptibility, according to Sect. 2.3, are marked in italics. We note that in the region as a whole (TOT), cloud amount, cloud effective radius and the cloud optical depth all satisfy the cloud susceptibility condition, while in the sub-domains the results are more mixed.

Table 5 shows correlations between GCR and the cloud parameters for the whole area investigated (TOT), and for each of the 13 FD events. Although 10 of the 13 individual GCR-CA correlations are significant, 6 of the correlations are negative, as opposed to the GCR-CA hypothesis. Those statistically significant correlations that are consistent with Table 2 are marked with an asterisk. We note that this applies to about half of the significant correlations, thus displaying a behaviour more consistent with a random process than a systematic relationship.

Figure 2 shows how the investigated cloud parameters, averaged over the 13 periods

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and over the entire latitude band 0 to 40° S, evolved over the 18 days prior to, during and after the Forbush event. The total variation in cloud cover is less than 2% over a Forbush period, and there is not a clear decline in the cloud cover at the day of the FD (day 0). Moreover, the time lag studies described in Sect. 2.4 (not shown) showed no significant deviation of the FD day values from the values before and after the event. This is demonstrated in Fig. 3, which shows the correlation between cosmic ray flux and each of the four cloud parameters for time lags of 0–5 days in steps of 1 day. For three of the quantities, i.e., cloud amount, cloud optical depth and liquid water path, the negative correlation already shown in Table 3 is slightly enhanced as the lag is introduced, having the largest negative correlations at 3–4 day lags. For cloud droplet effective radius, the correlation which at zero lag was small, negative becomes negligible at lags of 3–4 days. If anything these results seem to weaken the case for a cosmic ray-cloud coupling.

Figure 4 shows the time variation of the 4 cloud parameters (cloud cover, cloud droplet effective radius, cloud optical depth, cloud liquid water path) over the average of the 13 Forbush events. We note that in all 4 cases the standard deviation of the cloud parameters completely overwhelms any potential cosmic ray signal, so that the result is not statistically distinguishable from white noise.

### 3.2 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 three strongest events (16 July 2000, 31 October 2003, 19 January 2005), having amplitudes of 15%, 20% and 17%, respectively. It turns out that the results for these three events are more conducive to cosmic ray signals of the expected sign than the other events are. For instance, for the 16 July 2000 event all four quantities have the

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expected sign (Table 5), and for three of them, the correlations are higher than 0.5 in absolute value. The signature of the strongest event, 31 October 2003, is 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, is probably quite weak. 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 has the expected sign, and for two of them the correlation coefficient exceeds 0.4 in absolute value.

### 3.3 Results from the domain AT1

In view of the overall negative results above, with the notable exception of domain AT1, 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 regions to exhibit correlations favourable 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  $-5$  (relative to the Forbush minimum) all four variables – cloud amount, liquid water path, cloud droplet effective radius and cloud optical depth – 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

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regions, as in Figs. 2–4, such meteorological variability would tend to be evened out by the spatial averaging.

Table 6 shows a more detailed study of the AT1 area. Here we have partitioned the region 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. (1) and the suggestion of Yu (2002), presented in the introduction. Figure 7 shows the horizontal distribution of cloud optical depth in 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 region, are optically thinner, and according to Eq. (1), 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 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. However, in many cases these correlations have the opposite sign of what would be expected from the microphysical arguments that lie behind Table 2. All in all, the results of Table 6 do not strengthen the

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case for a causal relationship between cosmic rays and clouds.

### 3.4 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 note that the cloud optical depth variations seem to be dominated by variations in liquid water path, which have a three-peaked structure with minima at  $-6$ ,  $-2$  and  $+6$  days relative to the Forbush minimum. The highest values are found at  $+3$  days. Cloud amount variations have a similar pattern, while the effective radius curve is quite flat. As in Fig. 6, the contributions of meteorological variability are likely to be a major contributor to the variations found here, even though the much larger size of the region 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 regions being considered, region AT1 with high correlations being the smallest region, and region PA1 with poor correlations being the largest one. In order to investigate the sensitivity to how the regions were defined, we have divided the PA1 region into 5 sub-regions, with the results being given in Table 7. Clearly, none of these sub-regions display statistical behaviour 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 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 inconclusive. In the present study we have circumvented this problem by using observational data from the MODIS instrument, which has

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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 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 correlate well with variations in GCR flux associated with Forbush decrease events. This is also the case for 1–5 day lagged correlations.
- The three Forbush decrease events with the largest amplitude show on average stronger indications of a cosmic ray signal in the cloud parameters than the average of the other cases, with 8 out of 12 explored correlations having the expected sign, and 5 of these having correlations above 0.45 in absolute value. Due to the limited number of cases studied, the significance of this result is difficult to evaluate.
- One of the regions studied (mid-Atlantic) showed quite high correlations, which for all four cloud parameters have signs that are consistent with a cosmic ray induced CCN formation. In this rather small region cloud susceptibility is large, implying a potentially large impact on cloud albedo.

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- The high correlations in the mid-Atlantic region disappear when it is subdivided into smaller regions. Subdividing the largest region of study (in the Pacific) into areas of the same size as the mid-Atlantic region does not yield statistically significant or physically meaningful correlations.
- 5 – Subdividing the clouds in the vertical column into cloud types also fails to bring out any indications of a relationship between cosmic rays and clouds.

The overall conclusion, built on a series of independent statistical tests, is that a cosmic ray signal associated with Forbush decrease events is not found in highly susceptible marine stratocumulus clouds over the Southern Hemisphere oceans. To what extent 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 higher correlations than the average events. Even though those strong events are rare, with only 3 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 cosmic rays for clouds and climate. For the ongoing global warming, however, the role of cosmic rays would be expected to be small, 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).

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**Table 1.** Timing of the 13 Forbush decrease events that were investigated.

Date of FD event	18-day period surrounding FD event
16 July 2000	9 July 2000–26 July 2000
18 September 2000	11 September 2000 – 28 September 2000
29 November 2000	22 November 2000 – 9 December 2000
12 April 2001	5 April 2001 – 22 April 2001
28 August 2001	21 August 2001 – 7 September 2001
26 September 2001	19 September 2001 – 6 October 2001
30 July 2002	23 July 2002 – 9 August 2002
19 November 2002	12 November 2002 – 29 November 2002
31 May 2003	24 May 2003 – 10 June 2003
23 June 2003	16 June 2003 – 3 July 2003
31 October 2003	24 October 2003 – 10 November 2003
10 January 2004	3 January 2004 – 20 January 2004
19 January 2005	12 January 2005 – 29 January 2005

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

Parameters	Expected sign of correlation	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

13286

**Table 3.** Correlations between GCR and the four cloud parameters, averaged over all 13 Forbush decrease events. The correlations are given for the whole region of study (TOT, leftmost column), as well as for the individual sub-regions shown in Fig. 1. Statistical p-values are given in parentheses. The first p-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. Bold numbers indicate that the sign of the statistically significant correlation is consistent with Table 2. One asterisk indicates 90% significance while two asterisks indicate 95% significance, ignoring auto-correlations in the data.

	TOT	AT1	PA1	IN1	AT2	PA2	IN2
Cloud amount (CA)	-0.217 (0.390 / 0.496)	<b>0.438*</b> (0.069 / 0.201)	-0.095 (0.707 / 0.793)	-0.146 (0.565 / 0.828)	-0.358 (0.144 / 0.372)	0.210 (0.404 / 0.555)	0.039 (0.877 / 0.937)
Cloud effective radius (CER)	-0.3367 (0.172 / 0.289)	-0.356 (0.147 / 0.606)	-0.093 (0.714 / 0.777)	<b>-0.533**</b> (0.023 / 0.165)	-0.081 (0.750 / 0.871)	0.177 (0.483 / 0.545)	-0.395 (0.105 / 0.567)
Cloud optical depth (COD)	-0.1530 (0.545 / 0.633)	<b>0.680**</b> (0.002 / 0.218)	-0.454* (0.059 / 0.249)	-0.162 (0.521 / 0.729)	-0.362 (0.140 / 0.461)	0.382 (0.117 / 0.340)	0.034 (0.892 / 0.938)
Liquid water path (LWP)	-0.2619 (0.294 / 0.574)	<b>0.643**</b> (0.004 / 0.152)	-0.511** (0.030 / 0.238)	(-0.338/ (0.170 / 0.581)	-0.331 (0.027 / 0.617)	0.276 (0.2670 / 0.436)	-0.117 (0.645 / 0.857)

13287

**Table 4.** Average values of the four cloud parameters for respectively, the whole domain (TOT) and for the sub-regions indicated in Fig. 1. Those values on each line of the table which have the largest cloud susceptibility are shown in italics (see text for details).

	TOT	AT1	PA1	IN1	AT2	PA2	IN2
Cloud amount (CA) [%]	<i>66.9</i>	70.8	<i>69.1</i>	74.0	77.1	81.4	75.4
Cloud effective radius (CER) [ $\mu\text{m}$ ]	17.93	<i>19.34</i>	<i>19.72</i>	18.85	16.72	17.87	18.53
Cloud optical depth (COD)	<i>6.35</i>	<i>6.25</i>	5.71	<i>6.45</i>	<i>7.03</i>	8.01	<i>6.36</i>
Liquid water path (LWP) [ $\text{g m}^{-2}$ ]	<i>81.8</i>	87.6	<i>82.9</i>	89.1	86.6	104.1	86.8

13288

**Table 5.** Correlation coefficients between GCR and the cloud parameters for the TOT area, for each of the 13 periods investigated. Statistical p-values are given in parentheses. The first p-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. Bold numbers indicate that the sign of the statistically significant correlation is consistent with Table 2. One asterisk indicates 90% significance while two asterisks indicate 95% significance, ignoring auto-correlations in the data.

	CA	CER	COD	LWP
16 July 2000	<b>0.566**</b> (0.014 / 0.140)	-0.299 (0.229 / 0.650)	<b>0.542**</b> (0.020 / 0.241)0.245)	<b>0.526**</b> (0.025 / 0.258)
18 September 2000	<b>-0.437*</b> (0.070 / 0.347)	-0.0845 (0.739 / 0.899)	-0.222 (0.376 / 0.585)	-0.370 (0.131 / 0.442)
29 November 2000	<b>0.443*</b> (0.066 / 0.477)	<b>-0.453*</b> (0.059 / 0.234)	0.234 (0.351 / 0.631)	0.0011 (0.997 / 0.999)
12 April 2001	<b>0.659**</b> (0.003 / 0.239)	0.141 (0.576 / 0.661)	0.151 (0.549 / 0.711)	0.069 (0.786 / 0.869)
28 August 2001	-0.237 (0.343 / 0.409)	0.214 (0.393 / 0.544)	0.210 (0.403 / 0.471)	0.258 (0.302 / 0.370)
26 September 2001	<b>-0.437*</b> (0.070 / 0.352)	0.209 (0.405 / 0.770)	<b>-0.670**</b> (0.002 / 0.239)	<b>-0.750**</b> (0.001 / 0.173)
30 July 2002	<b>-0.812**</b> (0.000 / 0.140)	0.332 (0.178 / 0.284)	<b>-0.721**</b> (0.001 / 0.194)	<b>-0.659**</b> (0.003 / 0.248)
19 November 2002	<b>0.479**</b> (0.045 / 0.136)	-0.2901 (0.243 / 0.556)	<b>0.427*</b> (0.077 / 0.270)	0.360 (0.142 / 0.376)
31 May 2003	<b>-0.499**</b> (0.035 / 0.274)	0.376 (0.124 / 0.570)	<b>-0.327</b> (0.186 / 0.514)	<b>-0.353</b> (0.151 / 0.482)
23 June 2003	<b>-0.825**</b> (0.000 / 0.104)	-0.252 (0.314 / 0.428)	<b>-0.204</b> (0.417 / 0.757)	<b>-0.281</b> (0.258 / 0.663)
31 October 2003	<b>-0.602**</b> (0.008 / 0.101)	<b>-0.546**</b> (0.019 / 0.146)	-0.125 (0.622 / 0.799)	-0.185 (0.464 / 0.708)
10 January 2004	-0.083 (0.743 / 0.727)	<b>-0.422*</b> (0.081 / 0.385)	<b>-0.648**</b> (0.004 / 0.256)	<b>-0.754**</b> (0.001 / 0.178)
19 January 2005	0.368 (0.052 / 0.456)	0.294 (0.133 / 0.441)	0.343 (0.237 / 0.561)	<b>0.465*</b> (0.164 / 0.605)

13289

**Table 6.** Correlations between GCR flux and the various cloud types for latitudinal sub-divisions of the domain AT1 defined in Fig. 1. Statistical p-values are given in parentheses. The first p-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. Bold numbers indicate that the sign of the statistically significant correlation is consistent with Table 2. One asterisk indicates 90% significance while two asterisks indicate 95% significance, ignoring auto-correlations in the data.

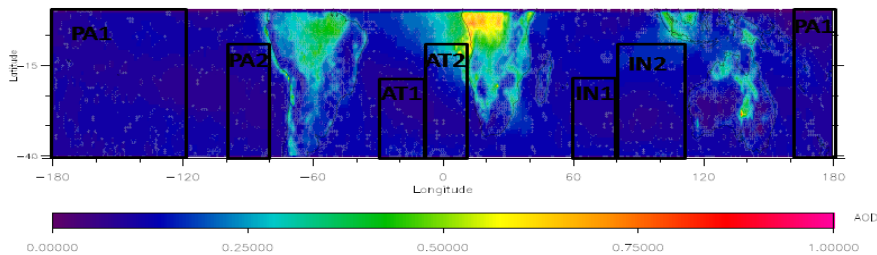
	AT1 15–20° S	AT1 20–30° S	AT1 30–40° S
CA, all cloud types	<b>0.418*</b> (0.085 / 0.290)	<b>0.501**</b> (0.034 / 0.190)	-0.058 (0.819 / 0.853)
CA, high clouds	0.312 (0.208 / 0.312)	0.356 (0.147 / 0.457)	-0.307 (0.215 / 0.142)
CA, stratocumulus	<b>0.479**</b> (0.045 / 0.306)	0.293 (0.239 / 0.543)	<b>0.437*</b> (0.069 / 0.114)
CER, all cloud types	-0.066 (0.794 / 0.925)	<b>-0.435*</b> (0.071 / 0.684)	0.106 (0.676 / 0.678)
CER, high clouds	0.186 (0.461 / 0.488)	0.274 (0.272 / 0.501)	-0.386 (0.113 / 0.166)
CER, stratocumulus	0.170 (0.500 / 0.797)	0.119 (0.638 / 0.857)	0.443* (0.066 / 0.083)
COD, all cloud types	<b>0.469**</b> (0.050 / 0.310)	<b>0.652**</b> (0.003 / 0.257)	<b>0.429*</b> (0.076 / 0.160)
COD, high clouds	0.324 (0.189 / 0.402)	<b>0.520**</b> (0.027 / 0.186)	-0.017 (0.948 / 0.937)
COD, stratocumulus	0.349 (0.156 / 0.259)	0.375 (0.126 / 0.496)	<b>0.448*</b> (0.062 / 0.102)
LWP, all cloud types	0.337 (0.172 / 0.486)	<b>0.636**</b> (0.005 / 0.261)	<b>0.424*</b> (0.079 / 0.145)
LWP, stratocumulus	0.244 (0.329 / 0.619)	0.285 (0.252 / 0.653)	<b>0.458*</b> (0.056 / 0.094)

13290

**Table 7.** Correlations between GCR flux and the various cloud types for sub-divisions of the domain PA1 defined in Fig. 1. statistical p-values are given in parentheses. The first p-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. Bold numbers indicate that the sign of the statistically significant correlation is consistent with Table 2. One asterisk indicates 90% significance while two asterisks indicate 95% significance, ignoring auto-correlations in the data.

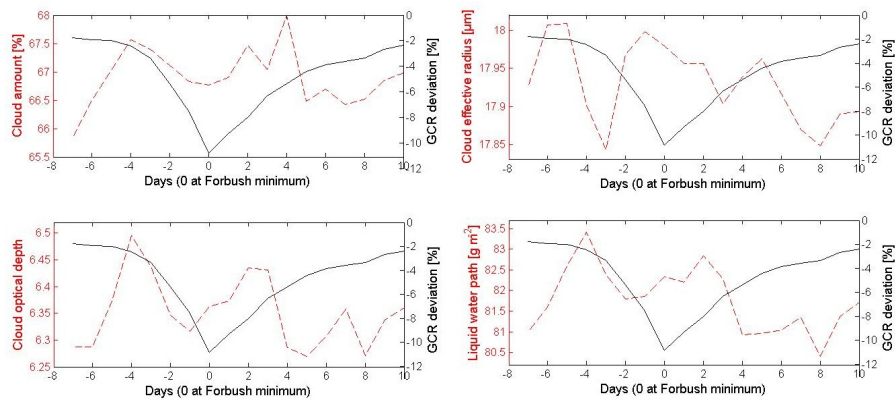
	PA1, 165–184° E	PA1, 184–203° E	PA1, 203–222° E	PA1, 222–241° E	PA1, 241–260° E
CA, all cloud types	-0.136 (0.591 / 0.617)	-0.207 (0.411 / 0.472)	-0.114 (0.651 / 0.753)	-0.114 (0.653 / 0.698)	-0.475** (0.047 / 0.157)
CA, high clouds	0.339 (0.169 / 0.482)	0.666** (0.003 / 0.184)	-0.058 (0.818 / 0.871)	<b>-0.603**</b> (0.008 / 0.095)	-0.408 (0.093 / 0.351)
CA, stratocumulus	-0.356 (0.148 / 0.581)	-0.680** (0.002 / 0.256)	0.125 (0.621 / 0.788)	<b>0.473**</b> (0.048 / 0.305)	-0.436* (0.070 / 0.256)
CER, all cloud types	-0.1178 (0.642 / 0.564)	-0.271 (0.277 / 0.343)	-0.227 (0.365 / 0.397)	-0.229 (0.361 / 0.358)	-0.188 (0.454 / 0.643)
CER, high clouds	0.156 (0.537 / 0.754)	<b>0.557**</b> (0.016 / 0.352)	-0.155 (0.540 / 0.665)	-0.671** (0.002 / 0.055)	-0.367 (0.135 / 0.408)
CER, stratocumulus	-0.243 (0.331 / 0.620)	<b>-0.719**</b> (0.001 / 0.215)	-0.059 (0.817 / 0.887)	0.427* (0.077 / 0.360)	-0.301 (0.225 / 0.317)
COD, all cloud types	-0.212 (0.398 / 0.367)	-0.313 (0.206 / 0.234)	-0.436* (0.070 / 0.233)	-0.278 (0.264 / 0.491)	-0.432* (0.074 / 0.262)
COD, high clouds	0.207 (0.410 / 0.555)	0.466* (0.051 / 0.441)	-0.424 (0.080 / 0.275)	<b>-0.682**</b> (0.002 / 0.036)	-0.323 (0.192 / 0.517)
COD, stratocumulus	-0.339 (0.168 / 0.492)	-0.703** (0.001 / 0.227)	0.060 (0.813 / 0.885)	<b>0.435*</b> (0.071 / 0.358)	-0.365 (0.136 / 0.352)
LWP, all cloud types	-0.170 (0.500 / 0.496)	-0.419* (0.083 / 0.171)	-0.448* (0.062 / 0.252)	-0.227 (0.365 / 0.571)	-0.433* (0.073 / 0.352)
LWP, stratocumulus	-0.253 (0.311 / 0.613)	-0.719** (0.001 / 0.218)	-0.012 (0.962 / 0.977)	<b>0.444*</b> (0.065 / 0.350)	-0.431* (0.074 / 0.265)

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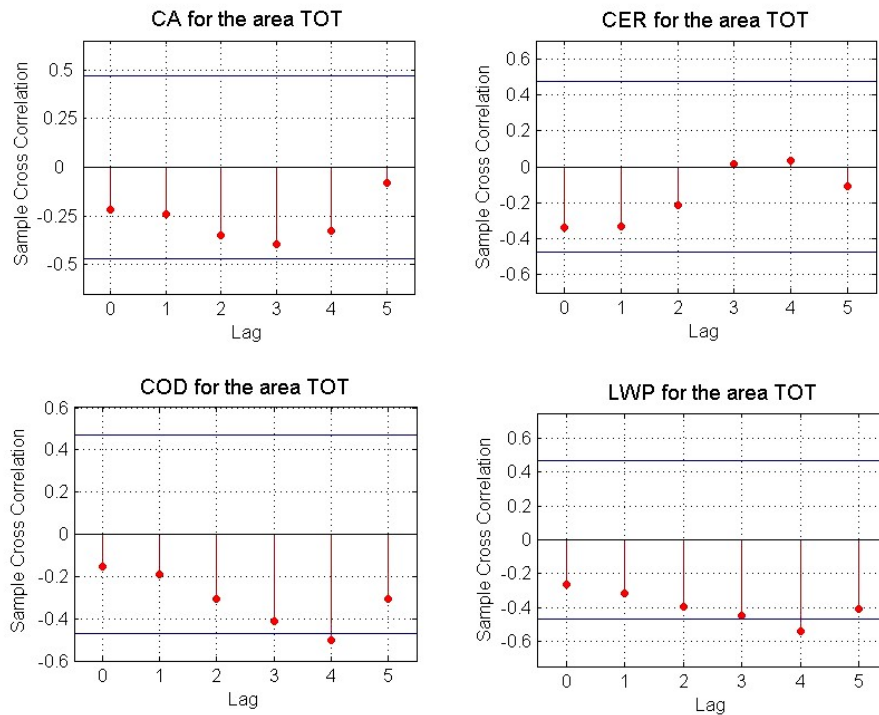
**Fig. 1.** The geographical regions of study along with their acronyms are indicated by black boxes. The color shading shows the aerosol optical depth averaged over the 13 Forbush decrease events.

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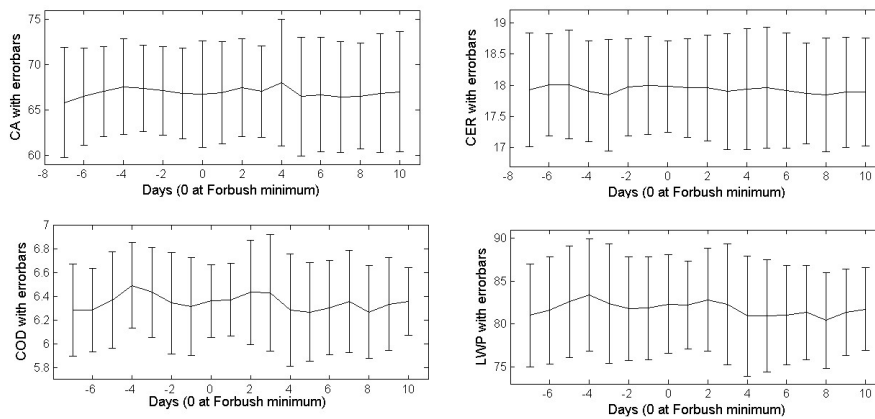
**Fig. 2.** GCR flux (solid curves) and cloud amount, cloud effective radius, cloud optical depth and liquid water path, averaged over all 13 events and the whole domain (dashed curves).

13293



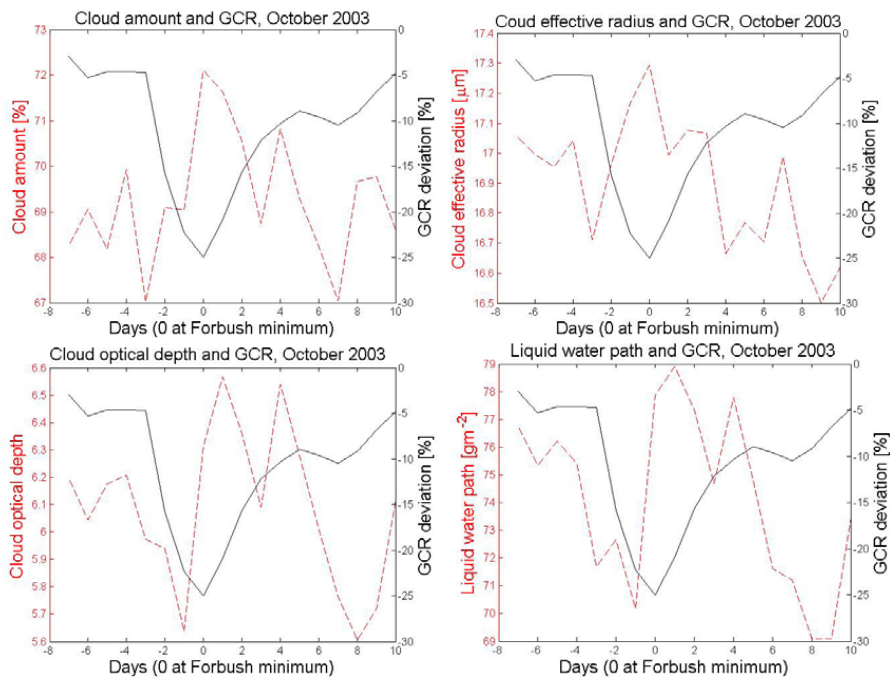
**Fig. 3.** Correlations between GCR and four cloud parameters (cloud amount, CA; cloud droplet effective radius, CER; cloud optical depth, COD; and liquid water path, LWP) for the whole area (TOT) of investigation at lags of 0 to 5 days.

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**Fig. 4.** Cloud amount (CA), cloud effective radius (CER), cloud optical depth (COD) and liquid water path (LWP) versus day number relative to a Forbush decrease event (day 0) averaged over all the 13 cases considered. The solid line gives the average value, while the bars indicate 1 standard deviation on each side of the average.

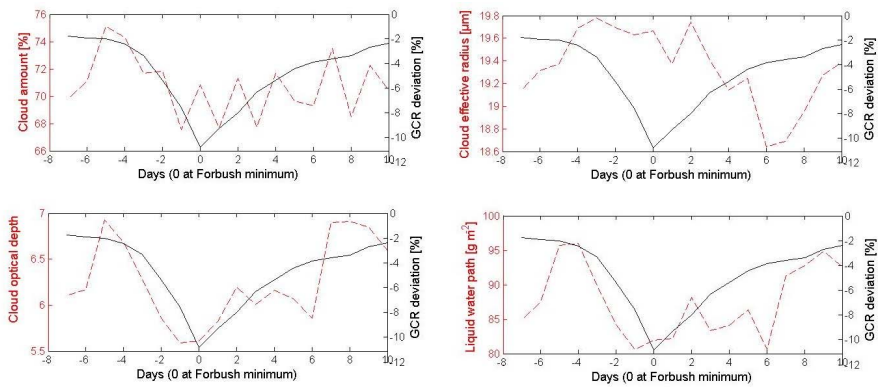
13295



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

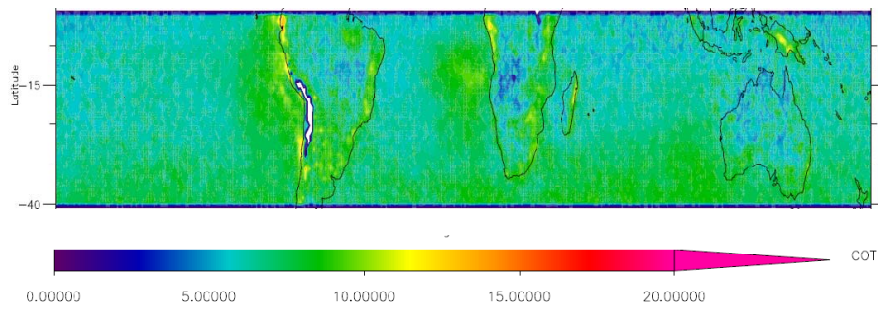
13296





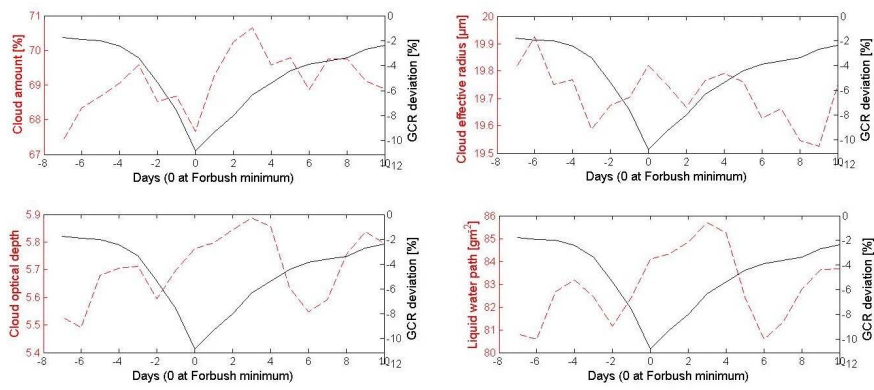
**Fig. 6.** As Fig. 2, but for the sub-area AT1 depicted in Fig. 1.

13297



**Fig. 7.** Cloud optical depth for low clouds in the area of interest, averaged over all 13 events.

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