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The effects of Forbush decreases on Antarctic climate variability: a re-assessment

B. A. Laken and D. R. Kniveton

Department of Geography, University of Sussex, Falmer, Brighton, BN1 9QJ, UK

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Correspondence to: B. A. Laken (bal22@sussex.ac.uk)

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Abstract

In an attempt to test the validity of a relationship between Galactic cosmic rays (GCRs) and cloud cover, a range of past studies have performed composite analysis based around Forbush decrease (FD) events. These studies have produced a range of conflicting results, consequently reducing confidence in the existence of a GCR-cloud link. A potential reason why past FD based studies have failed to identify a consistent relationship may be that the FD events themselves are too poorly defined, and require calibration prior to analysis. Drawing from an initial sample of 48 FD events taken from multiple studies this work attempts to isolate a GCR decrease of greater magnitude and coherence than has been demonstrated by past studies. After this calibration composite analysis revealed increases in high level (10–180 mb) cloud cover (of ∼20%) occurred over the Antarctic plateau in conjunction with decreases in the rate of GCR flux during austral winter (these results are broadly opposite to those of past studies). The cloud changes occurred in conjunction with locally significant surface level air temperature increases over the Antarctic plateau (∼4 K) and temperature decreases over the Ross Ice Sheet (∼8 K). These temperature variations appear to be indirectly linked to cloud via anomalous surface level winds rather than a direct radiative forcing. These results provide good evidence of a relationship between daily timescale GCR variations and Antarctic climate variability.

1 Introduction

It has been hypothesised that variations in the GCR flux may be causally linked to changes in cloud cover, thereby providing an indirect pathway connecting small variations in solar activity to the Earth's climate (Svensmark and Friis-Christensen, 1997). This relationship may potentially operate through a variety mechanisms involving: A direct influence of GCR on aerosol nucleation; an effect on the entrainment and growth of liquid droplets and ice crystals within clouds; and an indirect influence on cloud microphysics via modifications to the global electric circuit (GEC) (Tinsley, 2008). Such a link may provide an explanation for the wide range of relationships which have been observed between solar activity and climate in several palaeoclimatic reconstructions (Bond et al., 2001; Neff et al., 2001).

In an attempt to test the validity of a GCR-cloud link a range of studies have focused on the onset of unique large declines in the GCR flux known as FD events. These events result from magnetohydrodynamic disturbances in the solar wind created by solar coronal mass ejections (Kirkby, 2007), and for the purposes of this work are specifically defined by a decline in neutron counts of greater than 3% at the earth's surface recorded by the neutron monitor at Mount Washington, USA (39.23° N, 76.41° W) (Todd and Kniveton, 2004). Composite ("epoch superpositional") analysis of these transient events enables independent samples to be compiled, providing an opportunity to assess the influences of GCR variations on Earth's climate separate from internal periodicities such as El Niño (Farrar, 2000), and disambiguate the influences of long term solar irradiance and UV changes from short term variations in the GCR flux and the interplanetary magnetic field (IMF).

However despite the advantages of composite analysis, the findings of past FD based studies have not provided unambiguous evidence of a relationship between the GCR flux and cloud cover changes, instead such studies have demonstrated widely conflicting results. Some have found statistically significant cloud decreases occurring over high latitude regions following FD events (Pudovkin and Veretenenko, 1995; Veretenenko and Pudovkin, 1997; Todd and Kniveton, 2001), while other studies have also found no statistically significant relationship at high latitudes (Lam and Rodger, 2002), or even demonstrated the occurrence of cloud changes of a different sign altogether (Wang et al., 2006; Troshichev et al., 2008). Furthermore significant cloud changes have failed to be demonstrated over other environments hypothesised to be sensitive to variations in the GCR flux (Kristjansson et al., 2008). Consequently, the wide ranging and conflicting results of such studies limits the level of confidence we can place in the validity of a GCR-cloud link.

There are a number of possibilities to explain this range of results: (1) the onset of FD events may have no relationship to cloud cover changes, and therefore any significant results obtained may just be random noise. (2) The onset of FD events may be indicators of variability in other causal parameters such as the IMF. (3) The onset of FD events may only be poor indicators of times when GCR may influence cloud cover, resulting in poor observations of a climate signal. (4) Variations in initial internal conditions may impact the extent to which cloud responds to potential external forcings (such as variations in GCRs/IMF) during composite studies.

With regards to the third possibility there has been some recent effort to determine the usefulness of FD onset dates as a basis for composite analysis studies. Using satellite measurements of cloud, Todd and Kniveton (2004) (hereafter TK04) demonstrate statistically significant zonal mean cloud decreases (of ∼12%) occurring over high tropospheric levels (10–180 mb) during austral winter over parts of the Antarctic plateau following the onset of FD events. These FD events excluded FD events associated with solar proton (SP) events (TK04 found that FD events associated with SP events did not demonstrate any statistically significant cloud changes). Troshichev et al. (2008) reassess several of the dates selected by TK04, suggesting the FD onset dates are poorly defined indicators of GCR change, and argue that between various studies the onset dates can differ by as wide a range as 5 days. After realigning dates to reflect maximal GCR decrease rather than FD onset date they find cloud changes of opposite sign to the initial TK04 results. Although these results cover only a limited period and are based on indirect station based assessments of cloud, they indicate it may be more appropriate to consider the date of maximal decrease in the GCR flux over the FD period rather than the FD onset date itself. By adopting such an approach this study intends to accurately isolate the maximal GCR decrease occurring over an extensive list of FD events, and determine (based on satellite retrieved cloud changes and NCEP reanalysis data) if a statistically significant GCR-climate signal is present.

2 Data and methodology

This work initially drew from a sample of 48 individual FD events occurring between 1988–2006 sourced from two past studies (TK04 and Kristjansson et al., 2008). From these events we compiled a list of key dates, these dates were then adjusted so as to align the date of maximal GCR decrease occurring over the FD event with the key date of the composite (the composite period of this study ranges from day −15 to +3). The dates were then subdivided into two samples in order to separate coherent changes in the GCR flux from incoherent changes. Specifically incoherent GCR changes refer to events where the GCR flux undergoes a large (≥1.5%) decrease prior to the key date within a time period where the decrease is included in the averaging period against which the key date (or immediately surrounding dates) are differenced against. This process is designed to isolate the cloud cover changes not influenced by any ionisation changes preceding the key event (or the immediately surrounding dates).

TK04 isolate FD events which do not coincide with SP events, as it has been hypothesised that during an SP event increases in ionisation may oppose any decrease associated with a decline in the GCR flux (Pudovkin and Veretenenko, 1995). In keeping with this approach the adjusted 48 dates were cross checked against the occurrence of SP events, any date occurring within 3 days either-side of an SP event were not included in the analysis (SP flagged dates are displayed in Table 1), this treatment lead to the removal of 14 dates (data regarding SP events was obtained from the NOAA Space Environment Services Centre web page on Solar Proton Events Affecting the Earth Environment). All original and adjusted dates used in this study are displayed in Table 1. Ultimately the aim of this calibration is to isolate the most high fidelity coherent GCR decrease possible from the FD onset dates in order to best observe any potential impacts to Antarctic cloud cover and climate.

Cloud cover changes are determined using infrared derived measurements of cloud taken from the International Satellite Cloud Climatology Project (ISCCP) D1 dataset, which provides global estimates of cloud parameters every 3 h over a 2.5° latitudelongitude grid, averaged over a 24 h period to remove diurnal effects (Rossow and Schiffer, 1999). In addition daily average surface level air temperature changes were also considered, these were taken from the National Centre for Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996). GCR data for this study is taken from the high latitude McMurdo neutron monitor, situated in Antarctica (77.9° S, 166.6° E). All neutron data is corrected for barometric pressure variations. Variations in the azimuthal (B_y), and vertical (B_z) IMF measured by spacecraft in Earth's environment (taken from NASA's OMNIWeb database) are also analysed.

Additionally, this study considers the rate of cloud change with respect to each parameter rather than actual values of each parameter. This is primarily because considering rate will allow a ready comparison between sample dates reducing the impact of the wide variations in initial conditions of each parameter. Furthermore, if GCR variations do influence cloud cover it is likely that such GCR influenced cloud changes will be distinguishable from "natural" variations by the rapidity of the changes, therefore a large alteration in the rate of cloud cover change over the key date may be highly suggestive of a GCR-cloud link.

Throughout this work the average rate of change of each date over the composite was calculated as the difference between the tested date and an averaging period of three days beginning five days prior to each date. Zonal cloud cover changes are calculated as a relative cloud cover change (in percent), only taking into account areas of cloud cover rather than the total area of the grid cells (thereby excluding locations devoid of cloud cover). The Antarctic region (70° S–90° S) is considered in this study, as past work has indicated climate in region may be sensitive to variations in the GCR flux. Temporal autocorrelation was found to persist in the datasets for a two day period, to adequately account for this 1000 random Monte Carlo simulated T-values were used to calculate statistical significance at the 0.95 critical level for each dataset, statistically significant changes are indicated on graphs by markers.

3 Results

Comparing the rate of GCR change occurring over the events used in the original studies to those of the calibrated "coherent" sample demonstrates a confined and consistent decrease was not isolated in the original studies to the same degree that has been achieved in this work (Fig. 1). Although the mean rate of GCR flux appears similar in both the original and coherent samples (with a comparable magnitude and statistical significance) it is clear a wide range of inconsistent GCR variations are occurring around the key period of the original sample (Fig. 1a). This demonstrates a consistent GCR decrease is not effectively isolated by compositing events based on the FD onset date alone, indicating FD onset dates without adjustment may be unsuitable for composite analyses if the aim is to focus on a direct influence of GCR ionisation on climate.

After adjustment to the date of maximal GCR decrease, dates coincident with SP events are removed and the dates are filtered by the coherence of their GCR variations to create two subsamples ("coherent" (n=18) and "incoherent" (n=13)). Large differences between these subsamples are evident in both the mean rate of GCR flux and observed cloud changes (Fig. 2). The coherent sample demonstrates a larger decrease in the mean rate of GCR flux, undergoing statistically significant decreases two days before the incoherent sample with statistically significant changes occurring on four consecutive days (beginning two days before the key date). While conversely the incoherent sample demonstrates a far less pronounced decrease in the mean rate of GCR flux, and only shows statistically significant changes after the key date. The coherent sample demonstrates statistically significant increased zonal mean cloud cover; these increases develop coevally with decreases in the rate of GCR flux and reach a peak one day after the key date. No similar patterns of cloud change are evident in the incoherent sample (Fig. 2b). Ranking the daily average rate of cloud cover change over Antarctica reveals the mean zonal average rate change to be greater than ~89% of all high level (10–180 mb) cloud cover changes occurring between 1988–2006, suggesting that the observed increases in the rate of cloud change are considerably greater than that of average daily cloud variations. No statistically significant variations in the IMF B_z (north-south) or B_y (east-west) components occur during the coherent sample prior to the key event (Fig. 3).

Further analysis of the coherent sample indicates the anomalous cloud response is primarily occurring during austral winter. During this time zonal mean cloud cover changes demonstrate a far more consistent increase around the key period of the composite, the increased cloud cover also corresponds to a statistically significant decline in zonal mean surface level air temperatures by ∼2 K (Fig. 4). Spatial analysis demonstrates locally significant cloud increases (of ∼20%) are occurring over the Antarctic plateau on the key date of the composite, following these changes locally significant positive temperature anomalies develop over widespread areas of the continent (Fig. 5b). However the spatial structure of the cloud and temperature anomalies differs, indicating the positive temperature anomalies may predominantly result from observed anomalous surface level vector wind changes rather than a direct radiative forcing (Fig. 6). These wind changes may also likely be resulting in the observed temperature decrease over the Ross ice shelf (Fig. 5b), as wind drainage appears to have been enhanced in this region.

4 Discussion

The finding that significant cloud changes were restricted to austral winter is in agreement with the conclusions reached by TK04, who speculated this was suggestive of polar stratospheric clouds (which primarily occur during this time). The observation of statistically significant cloud cover increases broadly compliments the findings of Troshichev et al. (2008), confirming their observations with a larger and less restricted sample that does not rely on indirect station based measurements of cloud. Furthermore, the identification of locally significant temperature increases over the Antarctic plateau also compliment similar findings by Egorova et al. (2000), whose work similarly demonstrates anomalous air temperature increases of comparable magnitude occur immediately following FD events in response to widespread alterations to the regional wind system.

Cloud changes may potentially alter climate in two ways, either by altering the radiation balance (direct forcing), or by modifying circulatory patterns (indirect forcing). While the anomalous temperature increases identified over the Antarctic continent are consistent with the influence of increased cloud over high albedo surfaces (resulting in a reduction in the loss of long-wave radiation) (Ambach, 1974; Stone and Khal, 1991), the spatial structure of the cloud and temperature anomalies differs, and furthermore a statistically significant temperature anomaly of opposite sign is also present; this indicates the temperature changes are likely related to alterations in wind drainage observed over the continent rather than the result of a direct radiative cloud forcing (Fig. 6).

Troshichev et al. (2008) attribute the observed cloud increases identified in their study to variations in the IMF B_z component. However, this study finds no statistically significant variations in the IMF (B_z and B_y) component until after the significant cloud and temperature changes have occurred, making it unlikely that IMF variations are causally related to the observed cloud increases. This leads us to conclude that it is more likely that the GCR decreases are responsible for the observed cloud cover changes.

GCR decreases may theoretically produce the observed cloud cover changes in a number of ways: (1) by increasing the concentration of cloud condensation nuclei by enhancing aerosol nucleation processes at high altitudes; such an effect is predicted to principally concern environments with abundant ions concentrations but limited concentrations of sulphate aerosols such as Antarctica (Yu, 2002). (2) By reducing electroprotection, which may inhibit the growth of small ($<4\,\mu$m) particles by reducing their collision efficiency (this is calculated to inhibit coagulation by up to several orders of magnitude) (Tinsley and Zhou, 2006). (3) A decrease in the vertical current density as a result of a decrease in the GCRs may also reduce the electroscavenging of ice forming nuclei (IFN) at cloud boundaries. The presence of IFN may rapidly lead to the development of precipitation, thereby reducing the longevity of clouds (Tinsley, 2008). This may be of significant importance in supercooled stratus clouds with small droplet sizes, which are common feature over the Antarctic plateau (Morley et al., 1989; Mahesh et al., 2001). However the response of the atmospheric circuit to changes in GCR ionisation is not well established, the local atmospheric response may relate to a combination of how thunderstorm formation in the equatorial regions respond to ionisation changes and how the latitudinal distribution of ionisation balances the current flow (Tinsley, 2008). Burns et al. (2008) postulate an increase in Antarctic plateau cloud following a local current increase. However, it is currently impossible to determine which (if any) of the theoretical mechanisms may be responsible for the observed cloud changes, it is possible multiple processes may potentially be operating simultaneously.

There are several major problems associated with the ISCCP cloud detection over Polar regions, principally these stem from a lack of visible data during polar night, and problematic detection over regions where temperature inversions occur. As a result extreme caution must be applied when interpreting results concerning high latitude cloud retrievals, similarly NCEP reanalysis data concerning Antarctica is also of questionable quality (Todd and Kniveton, 2004). However, while individually each dataset is flawed when considered together these data provides a fair indication that Antarctic climate may potentially be influenced over daily timescales by GCR variations.

Additionally, it is important to note the sensitivity of cloud cover changes to the GCR flux is likely to be dependent on a variety of internal parameters such as precursor aerosol concentrations, cloud type, cloud height, cloud droplet sizes, and ice crystal content. Initial conditions may have a large impact on the GCRs ability to affect cloud cover, as a result this may greatly reduce the detectability of a GCR-cloud signal. This may offer a tentative explanation as to why significant cloud changes are apparent over Antarctica; as with regard to variations in cloud type and aerosol concentrations conditions in this region are relatively homogenous, therefore we speculate this may facilitate a relatively coherent cloud cover change in response to GCR variations.

In order to attempt to understand why the past TK04 study demonstrated statistically significant cloud changes of opposite sign, it is necessary to note several important differences between TK04 and this study: (1) examining individual GCR variations occurring over the dates used in TK01 reveals the composite largely fails to isolate a uniform GCR decrease (Fig. 7). (2) TK04 considered absolute cloud values rather than a percentage.(3) This study utilises a moving averaging period to calculate cloud changes, the three day averaging period maintains a relative position beginning five days prior to the key date, whereas TK04 assigns a base period (day-5, -4, and -3) against which the mean value of all dates is subtracted to calculate anomalous changes. Utilising the methodological approach of this study zonal mean cloud changes occurring during the TK04 composite period are re-evaluated; significant changes are found across the composite, however no discernable patterns are readily apparent (Fig. 7b), furthermore while significant decreases in the rate of GCR flux do occur following the key date a coherent decrease is not isolated, suggesting that the cloud changes are not obviously related to GCR decreases occurring during the FD events. The cloud changes identified in TK04 may therefore possibly be the result of a combination of date misalignment and methodological artefacts.

5 Summary and conclusions

This work combined FD events from multiple studies to create a sample of events ranging from 1988–2006. The key dates of this sample were realigned to reflect the maximal date of GCR decrease rather than the onset of the FD date itself, the key dates were then separated into two subsamples, which excluded dates coincident with SP events (coherent (n=18) and incoherent (n=13)) in order to isolate cloud cover changes most likely to be influenced by GCR related variations. After this calibration composite analysis of the coherent sample revealed statistically significant increases in zonal mean high level Antarctic cloud cover occurred during the GCR decrease. However no spatially significant cloud changes were identified until after the sample was restricted to events occurring during austral winter, after which locally significant cloud cover increases of up to 20% were found to occur over the Antarctic plateau, followed by locally significant anomalous surface level air temperature increases over the continent (of ∼4 K) and simultaneous decreases over the Ross ice shelf (of ∼8 K). These air temperature changes however appear to result from alterations to wind drainage over Antarctica, rather than a direct radiative cloud forcing. Anomalous decreases in vector wind occur concurrently with areas of significantly increased air temperatures, while simultaneously increased wind drainage occurs over the Ross ice shelf.

A decrease in the GCR flux may be causally related to the observed cloud increases via either direct or indirect mechanisms involving a reduction of electroprotection/electroscavenging and/or a sign dependent effect on aerosol nucleation. Currently however there is not enough evidence to distinguish which processes may be responsible for the observed changes, and it is possible multiple processes may be acting synergistically. In conclusion, these results demonstrate good evidence of a statistically significant relationship occurring at the daily timescale between the GCR flux and Antarctic climate variability, and also provide a good indication as to why past studies concerned with FD onset dates may have arrived at inconsistent and sometimes conflicting results.

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Table 1. Dates used in this study. TK04 and Ketal.08 display dates sourced from the original Todd and Kniveton (2004) and Kristjansson et al. (2008) studies respectively (“**” indicates a date coincident with a SP event, coincident dates are excluded from the samples).

			Adjusted dates	
Event	TK04	Ketal.08	Coherent	Incoherent
1	20/02/1988	16/07/2000	18/07/1988	21/02/1988
2	20/07/1988	18/09/2000	13/02/1989	28/08/1989
3	11/02/1989	29/11/2000	20/08/1989	10/03/1991
4	19/08/1989	12/04/2001	19/09/1989	27/02/1992
5	28/08/1989	29/04/2001	20/05/1990	10/09/1992
6	18/09/1989	28/08/2001	26/04/1991	09/04/1998
7	17/05/1990	26/09/2001	19/08/1991	14/01/1999
8	12/03/1991	25/11/2001	29/10/1991**	15/10/1999
9	24/04/1991	30/07/2002	24/02/1993	07/02/2000
10	18/08/1991	19/11/2002	26/10/1993	04/07/2000
11	07/11/1991	31/05/2003**	17/04/1994	30/07/2002
12	25/02/1992	23/06/2003	20/06/1994	19/11/2002
13	08/09/1992	31/10/2003	03/12/1999	23/06/2003
14	19/02/1993	24/11/2003	03/05/2000	27/07/2004**
15	22/10/1993	10/01/2004	24/05/2000	17/07/2005**
16	16/04/1994	25/01/2004	16/07/2000**	
17	17/06/1994	27/07/2004	18/09/2000	
18	03/04/1998	10/11/2004	29/11/2000**	
19	12/01/1999	19/01/2005	12/04/2001**	
20	16/08/1999	16/05/2005	29/04/2001**	
21	07/10/1999	17/07/2005	28/08/2001	
22	06/12/1999	13/09/2005	26/09/2001**	
23	04/02/2000		25/11/2001**	
24	01/05/2000		31/05/2003**	
25	20/05/2000		31/10/2003**	
26	09/07/2000		18/11/2003**	
27			11/01/2004	
28			22/01/2004	
29			10/11/2004**	
30			19/01/2005**	
31			09/05/2005	
32			11/09/2005**	

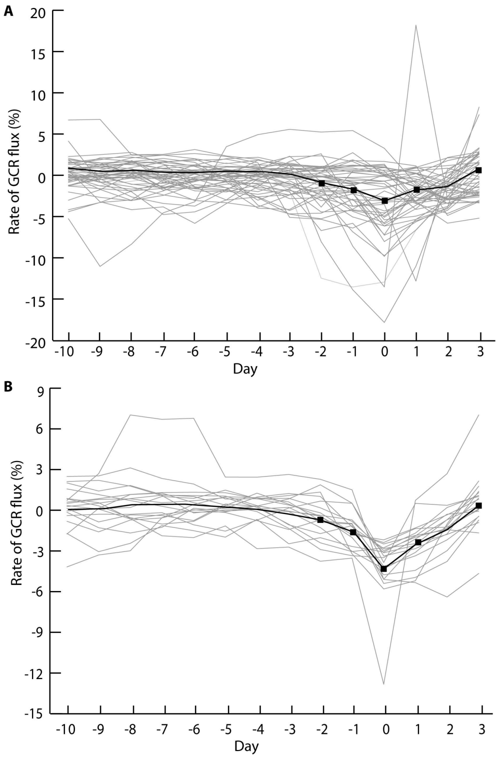

Fig. 1. *Comparing the rate of GCR flux occurring over past work and this study.* Changes in the rate of GCR flux occurring over individual FD events (grey lines), and the mean rate of GCR flux (black line) during: (**A**) Todd and Kniveton (2004), and Kristjansson et al. (2008) dates (n=47) specific dates listed in Table 1. (**B**) A subsample of the events after calibration to align the key date of the composite to the maximal GCR decrease occurring over each FD event with incoherent decreases removed (n=18). Statistically significant changes above the 0.95 critical level are indicated on the mean rate of GCR flux (black line) by markers where applicable.

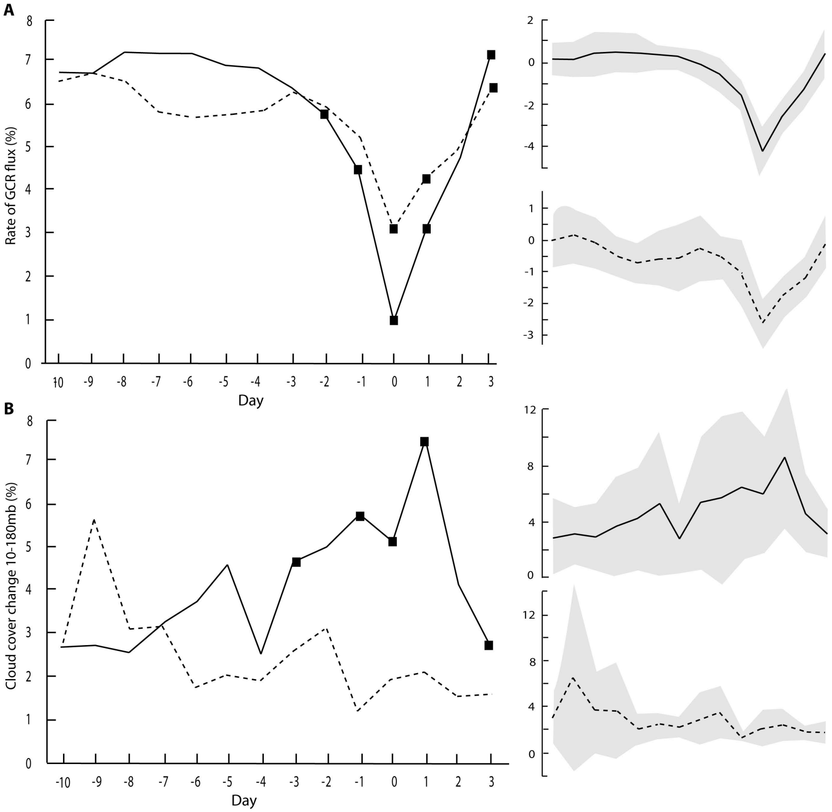

Fig. 2. *GCR and Antarctic high level cloud changes*. (**A**) Rate of GCR flux and (**B**) high level (10–180 mb) cloud cover changes occurring over Antarctica (70° S–90° S) across the coherent sample (solid line) and incoherent sample (dashed line). Statistically significant changes above the 0.95 critical level are indicated on the primary figure by markers. The graphs to the right of the primary figures display the error range of the data to one standard deviation (indicated by the full range of the grey shading).

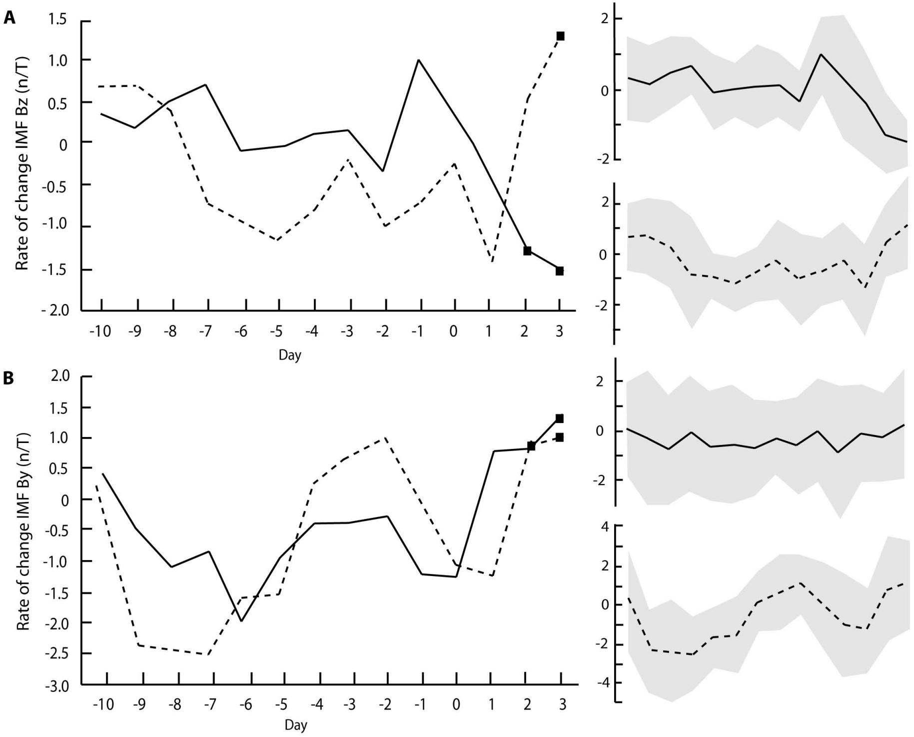

Fig. 3. *IMF variations over coherent and incoherent samples.* (**A**) Rate of IMF B_z and (**B**) Rate of IMF B_y variations occurring over the coherent (solid line (n=18)) and incoherent (dashed line (n=13)) samples. Statistically significant changes above the 0.95 critical level are indicated on the primary figure by markers. The graphs to the right of the primary figures display the error range of the data to one standard deviation (indicated by the full range of the grey shading).

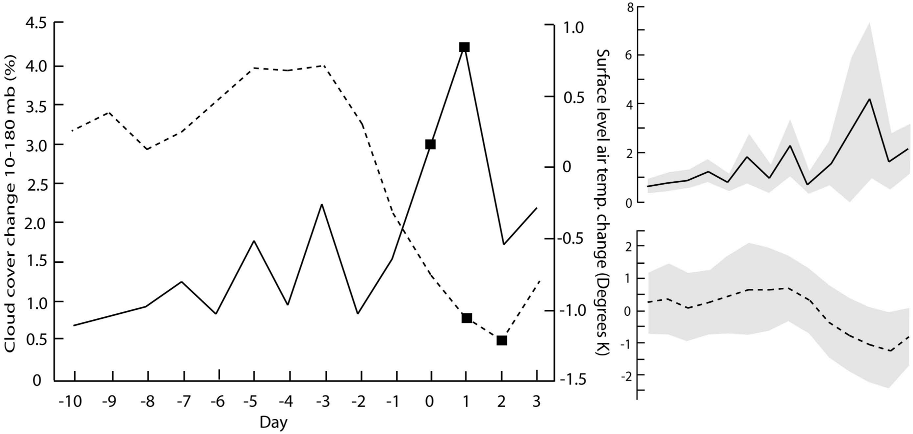

Fig. 4. *Austral winter cloud cover and surface level air temperature changes.* High level (10–180 mb) zonal mean cloud cover changes (solid line) and zonal mean surface level air temperature changes (dashed line) over Antarctica (70° S–90° S) during the coherent sample austral winter dates (April–September) (n=13). Statistically significant changes above the 0.95 critical level are indicated on the primary figure by markers. The graphs to the right of the primary figures display the error range of the data to one standard deviation (indicated by the full range of the grey shading).

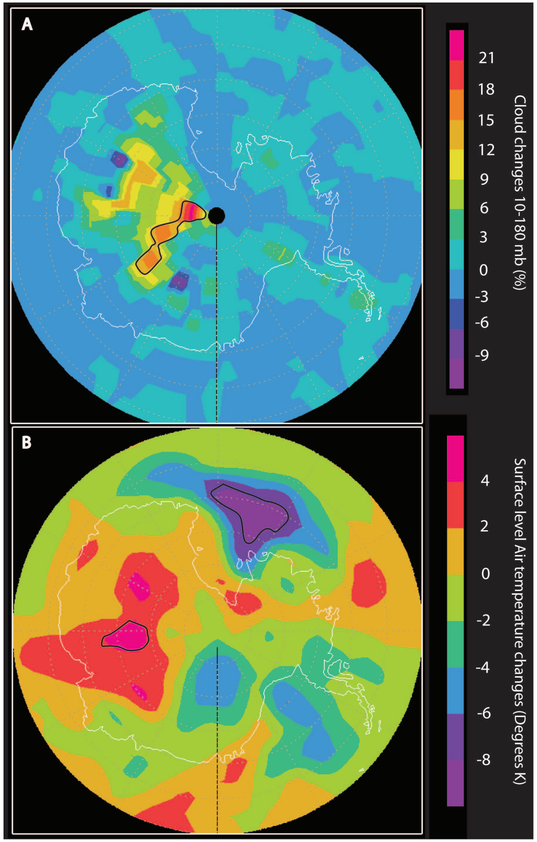

Fig. 5. *Austral winter spatial cloud cover and air temperature changes*. Spatial analysis of (**A**) key date high altitude (10–180 mb) cloud cover changes and (**B**) day 1 surface level air temperature changes occurring in the coherent sample during austral winter (April–September) (n=13). Regions of local statistical significance (above the 0.95 critical level) are indicated by a solid black contour.

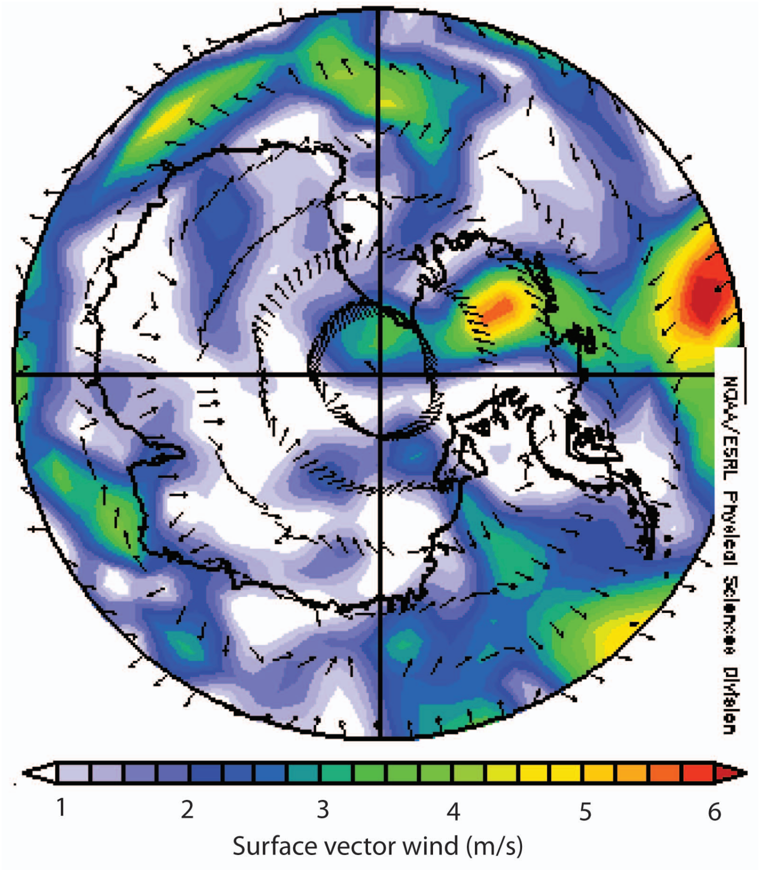

Fig. 6. *Surface level anomalous vector wind.* Anomalous surface level vector wind occurring on the key date of the coherent sample during austral winter (April–September) (n=13).

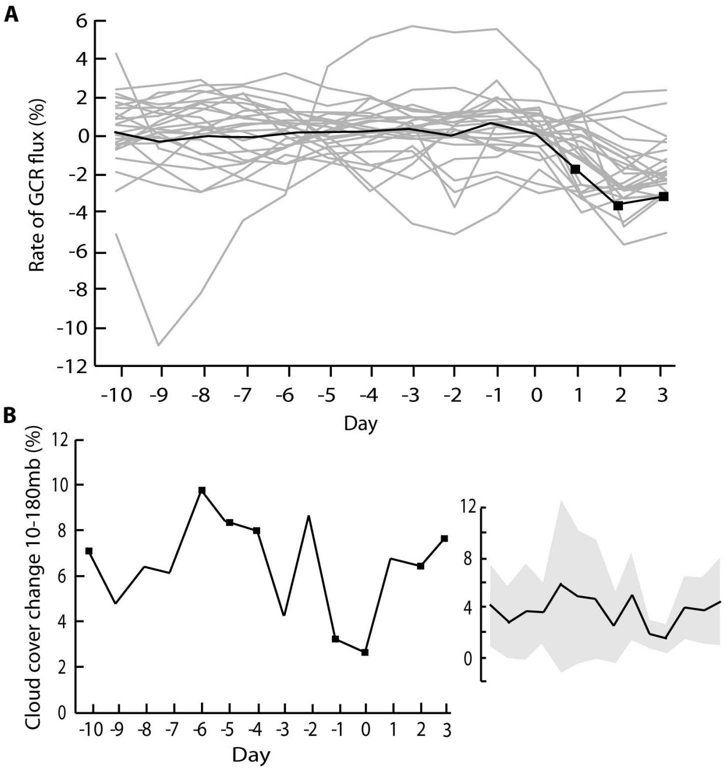

Fig. 7. *Cloud cover and GCR rate changes during Todd and Kniveton (2004) events.* (**A**) Variations in the rate of GCR flux during 26 original Todd and Kniveton (2004) FD onset events used in this study, the mean rate of GCR flux (black line) is also displayed. (**B**) Antarctic (70° S–90° S) zonal mean cloud cover changes occurring between 10–180 mb during the original TK04 dates. Statistically significant changes above the 0.95 critical level are indicated on the primary figures by markers, the graphs to the right of the primary cloud change figure displays the error range of the data to one standard deviation (indicated by the full range of the grey shading).