Atmos. Chem. Phys. Discuss., 10, 18235–18253, 2010
www.atmos-chem-phys-discuss.net/10/18235/2010/
doi:10.5194/acpd-10-18235-2010

Atmospheric
Chemistry
and Physics
Discussions

Cosmic rays linked to rapid mid-latitude cloud changes

B. A. Laken, D. R. Kniveton, and M. R. Frogley

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

Received: 7 June 2010 – Accepted: 21 July 2010 – Published: 2 August 2010

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

Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

The effect of the Galactic Cosmic Ray (GCR) flux on Earth's climate is highly uncertain. Using a novel sampling approach based around observing periods of significant cloud changes, a statistically robust relationship is identified between the rate of GCR flux and the most rapid mid-latitude (60°–30° N/S) cloud decreases operating over daily timescales; this signal is verified in surface level air temperature (SLAT) reanalysis data. A General Circulation Model experiment is used to test the causal relationship of the observed cloud changes to the detected SLAT anomalies. Results indicate that the cloud anomalies were responsible for producing the observed SLAT changes, implying a link between significant decreases in the rate of GCR flux (∼0.79%/day (relative to the peak-to-peak amplitude of 11-yr solar cycle)), decreases in cloud cover (∼1.9%/day) and increases in SLAT (∼0.05 K/day). The influence of GCRs is clearly distinguishable from changes in solar irradiance and the interplanetary magnetic field. These results provide the most compelling evidence presented thus far of a GCR-climate relationship. From this analysis we conclude: (i) a GCR-climate relationship is governed by both the rate of GCR flux and internal precursor conditions; and (ii) it is likely that this natural forcing has not contributed significantly to recent anthropogenic temperature rises.

1 Introduction

Evidence of links between small changes in solar activity and Earth's climate has been identified by numerous palaeoclimatic studies (Bond et al., 2001; Neff et al., 2001; Mauas et al., 2008). However, as yet, there is no accepted process which can fully account for such a connection. Several theories have been suggested, and, of these, perhaps the most contentious proposes a relationship between the GCR flux and cloud cover (Svensmark and Friis-Christensen, 1997).

Previous studies attempting to test the validity of a GCR – cloud connection have tried to use the GCR flux to infer cloud changes; the majority of these studies have either revolved around the daily timescale, high magnitude, low frequency GCR decreases known as Forbush Decrease (FD) events (Laken et al., 2009; Laken and Kniveton, 2010), or long term (annual-to-decadal) correlations between the GCR flux and cloud cover (Marsh and Svensmark, 2000). Both approaches are inherently flawed as they assume a first-order relationship (i.e. presuming that cloud changes consistently accompany GCR changes), when instead, a second-order relationship is more likely (i.e. that cloud changes only occur with GCR changes if environmental conditions are suitable) (Harrison and Ambaum, 2009). To address this issue we adopt a fresh approach by performing a composite (epoch-superpositional) analysis based on periods of significant cloud change and then examining corresponding solar-related variations. If, under certain conditions, GCR-related effects influence cloud changes, then constructing the composite in this manner will automatically account for any dependence of a GCR – cloud connection on initial precursor conditions (as such conditions will have been met for GCR-related cloud changes to occur).

The composite sample is based around the most rapid (>0.95 percentile) daily timescale decreases in the rate of cloud change occurring over mid-latitude regions. We chose to focus on this region for several reasons: (i) a prevalence of stratified clouds (which may be an important precursor condition) (Nicoll and Harrison, 2010); (ii) reliable satellite cloud retrievals compared to high- latitude regions; and (iii) past studies suggest sensitivity of cloud modulation by GCRs over such regions (Harrison and Ambaum, 2009; Tinsley and Dean, 1991; Veretenenko et al., 2007; Harrison and Stephenson, 2006). Critically, rates of change are used over absolute values, as we propose that neutral and electrically-enhanced cloud variability may be distinguished by the rapidity of their changes; this hypothesis is based on the results of model and observational studies which suggest that GCRs may (either directly or indirectly) increase the efficiency of cloud forming processes. Rates of cloud change are calculated from the infrared (IR) retrieved International Satellite Cloud Climatology Project (ISCCP) D1 dataset, while rates of GCR flux are based on an amalgamated dataset of neutron monitors from locations across the globe.

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2 Data and methods

The epoch-superposition (composite) methodology used in this study is similar to the approach of previous FD based studies (see Laken and Kniveton, 2010; Todd and Kniveton, 2001). The composite is constructed to represent the largest (top 5%) decrease in the daily rate of cloud change over the mid-latitude (60°–30° N/S) regions (i.e. the most rapid decreases in cloud cover over the mid-latitudes) detected by the IR retrieved ISCCP D1 (Rossow et al., 1996) dataset between 1986 to 2006. The mid-latitudes are selected for study since previous work has indicated that such regions may be sensitive to changes in the GCR flux (Harrison and Ambaum, 2009; Nicoll and Harrison, 2010; Tinsley and Dean, 1991; Veretenenko et al., 2007; Harrison and Stephenson, 2006). Furthermore, satellite retrieved cloud cover over these regions is of relatively high quality.

In this study, the rate of change is used instead of absolute values; this is a first order derivative, determined by taking the difference of an average daily value against a moving three day averaging period beginning five days prior to each date. The two-day interval between the averaging period and the differenced date accounts for temporal autocorrelation present in the data. GCR data for this study are drawn from nine different barometric pressure-adjusted neutron monitor datasets, selected for both their long term monitoring records and their global distribution (namely: Apatity, Climax, Kiel, Magadan, Mcmurdo, Moscow, Newark, South Pole and Thule). Daily rates of change are calculated for each individual neutron monitor; the values are then all calibrated to be relative to the peak-to-peak GCR flux changes experienced at each individual neutron monitor over the 11-yr Schwabe cycle and finally integrated into one dataset. Statistical significance of the datasets are evaluated using paired two-tailed Students T-tests, with critical T-values (at the 0.95 level) established by Monte Carlo simulations.

An estimate of the long- term impact of the effects of GCRs on global SLAT over the last 50 years is given in Sect. 4, the value is calculated as follows: The global SLAT change resulting from a 1% decrease in the rate of GCR flux is calculated from the composite sample presented in this work. This value is used as a scale factor applied to the daily rate of GCR flux over the last >50 yr (using pressure adjusted Climax Colorado neutron data). The square root of the resulting value is taken, since changes in ion density in the atmosphere have been shown to be proportional to the square root of the ionisation rate (Usoskin et al., 2004; Sloan and Wolfendale, 2008). An 11-yr running mean is applied to the data and the difference between 1953 and 2006 is taken as an estimate of the long-term impact of GCR on global SLAT. Although this procedure provides an interesting estimate, it has several non-trivial caveats: it assumes a linear trend; it ignores long-term cloud changes resulting from natural climate variations such as El Niño and anthropogenic warming; the estimated value is based on the composite sample presented in this work, wherein, it is likely that the GCR flux may have been acting to enhance natural variability; it ignores the existence of feedbacks; and the estimate assumes that no other GCR – climate links exist other than those outlined in this work.

3 Results

The composite sample shows a positive correlation between statistically significant cloud changes and variations in the rate of GCR flux (Fig. 1): increases in the rate of GCR flux occur around day –5 of the composite, and correspond to significant localised mid-latitude increases in the rate of cloud change. After this time, the rate of GCR flux undergoes a statistically significant decrease (~1.2%/day) centred on the key date of the composite; these changes correspond to widespread statistically significant decreases in the rate of cloud change (~3.5%/day (~1.9%/day globally averaged)) over mid-latitude regions. A latitude/height profile of the key date cloud changes reveals that the anomalous cloud decreases are predominantly located at mid- to low tropospheric levels (Fig. 2). It is important to note that these cloud anomalies bear a remarkable latitudinal symmetry and appear linked to the high-pressure return-flow regions associated with the Hadley cells. Comparable cloud anomalies are identified over both IR and VIS ISCCP channels (Fig. 3).

An analysis of solar interplanetary magnetic field (IMF) (Fig. 4a–b), 10.7 cm radio flux as a proxy for total solar irradiance (TSI) (Fig. 4c) and ultraviolet (UV) activity (Fig. 4d) suggests that the IMF and irradiance parameters demonstrate some variability over the composite; when considered together, these changes probably indicate the occurrence of short-term minima/maxima in solar activity that are most likely related to solar Carrington rotations. However, only the rate of GCR flux undergoes correlated and statistically significant co-temporal variations to cloud changes over the composite period. These results suggest that the effects we observe are independent of other solar phenomena and that we can therefore discount the possibility that an alternative solar–terrestrial mechanism is operating (Tinsley, 2008; Douglas and Clader, 2002; Haigh, 1996; Kniveton et al., 2003).

During the key day mid-latitude cloud cover decreases, NCEP/NCAR reanalysis data (Kalany et al., 1996) show that SLAT underwent a statistically significant increase of ∼0.1 K/day over mid-latitude regions (∼0.05 K/day as a global average) (Fig. 5a); this temperature forcing is consistent with the radiative impacts of decreasing mid- to low-level cloud over mid-latitudes. Although a correlation between cloud changes and the GCR flux is evident, it cannot be determined if the cloud/SLAT changes are causally related to the GCR, or if the cloud anomalies are merely a product of internal climate variations. To address this issue, a General Circulation Model (GCM) experiment is conducted which attempts to reproduce the observed mid-latitude cloud anomalies; this is done by directly manipulating the SW/LW radiation schemes within a HadAM3 GCM to simulate cloud changes in repeating cycles over several 5-yr periods. These cycles are then composited to create a composite period and sample size consistent with observations. This experiment is designed to test if SLAT anomalies evident over the composite can be reproduced merely by altering cloud, thereby indicating if there is a causal link between cloud and temperature changes over the composite.

The GCM results successfully produced a pattern of SLAT increase comparable to observations (Fig. 5b). Between days −5 to 3 (after the first appearance of significant

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cloud changes) the observed correlation coefficient between SLAT and cloud cover was found to be $r^2=-0.91$. Over the same period, the GCM demonstrated a correlation of $r^2=-0.93$, indicating that the observed cloud-climate relationship was reproduced by the GCM. However, the magnitude of the SLAT changes was far smaller than that observed (by ~75%) and the anomalies did not demonstrate any statistical significance. These differences may be attributed to the shortcomings of modelled cloud cover which, while reasonable for a GCM of its type, still deviates conspicuously from observations (Fig. 6).

4 Discussion

The strong and statistically robust connection identified here between the most rapid cloud decreases over mid-latitude regions and the rate of GCR flux is clearly distinguishable from the effects of solar irradiance and IMF variations. The observed cloud anomalies show a strong latitudinal symmetry around the equator; alone, this pattern gives a good indication of an external forcing agent, as there is no known mode of internal climate variability at the timescale of analysis, which could account for this distinctive response. It is also important to note that these cloud anomalies are detected over regions where the quality of satellite-based cloud retrievals is relatively robust; results of past studies concerned with high-latitude cloud anomalies have been subject to scrutiny due to a low confidence in polar cloud retrievals (Laken and Kniveton, 2010; Todd and Kniveton, 2001) but the same limitations do not apply here.

Although mid-latitude cloud detections are more robust than those over high latitudes, Sun and Bradley (2002) identified a distinctive pattern of high significance between GCRs and the ISCCP dataset over the Atlantic Ocean that corresponded to the METEOSAT footprint. This bias does not appear to influence the results presented in this work: Fig. 7 shows the rates of anomalous IR-detected cloud change occurring over Atlantic, Pacific and land regions of the mid-latitudes during the composite period, and a comparable pattern of cloud change is observed over all regions.

Additional considerations should be given to the results of Kristjánsson et al. (2002), who demonstrated the presence of large differences between IR and VIS ISCCP cloud retrievals; a low confidence should be placed in detected cloud changes where IR and VIS cloud detections disagree. However, the results presented in this work identify comparable, locally significant cloud anomalies over both IR and VIS channels (Fig. 3), confirming that the IR-detected cloud anomalies are reliable.

The location of the cloud anomalies, over mid- to -low tropospheric levels of the mid-latitude regions, may highlight a potential forcing mechanism. It has been suggested that Bernard cell cloud systems (located in the high-pressure return-flow regions of the Hadley cells) may be highly sensitive to changes in cloud condensation nuclei (CCN) (Rosenfeld et al., 2006). Differences in CCN concentrations may drive a change from closed state to open state Bernard cells, thereby varying the amount of cloud over mid-latitude regions. Furthermore, it has also been established that ion-induced nucleation processes are most likely to be significant over aerosol impoverished clean-air oceanic regions (such as those where Bernard cells are located) (Yu et al., 2008). Therefore, potential changes in CCN populations by ion-induced nucleation processes over mid-latitude oceanic regions may play a role in regional cloud modulation.

It is important to note that the use of rates of GCR flux throughout this work is crucial: there are key differences between rates of change and absolute changes (Fig. 8). Although these parameters are related, they do not always change together; the rate of GCR flux only correlates to the mean GCR flux during periods of intense change. The identification of a relationship between the climate and the rate of GCR flux is significant as, over the last few decades, solar–climate studies have notoriously identified transient relationships (such as the link between decadal cloud cover and the GCR flux, Laut, 2003). The existence of such relationships may be tentatively explained as a mistaken link to the mean GCR flux, when in actuality the rate of GCR flux change may be key.

Further investigation is needed to fully quantify the impacts of GCR variations on climate. However, based on this work, we tentatively estimate that the SLAT change resulting from a GCR-climate relationship over the last 50 years to be approximately +0.03 K. This result strongly implies that GCR-related natural forcings are not able to account for recent anthropogenic climate trends, as some groups have controversially proposed (Svensmark, 2007).

Acknowledgements. The authors would like to thank Loïs Steenman-Clark (University of Reading) for her invaluable assistance with the GCM. We also thank Sir Arnold Wolfendale (Durham University), Tom Goren (University of Jerusalem) and Daniel Rosenfeld (University of Jerusalem) for enlightening discussions. The NCEP Reanalysis Project data is provided by the NOAA/OAR/ERSL PSD, Boulder, Colorado, USA from http://www.cdc.noaa.gov/. Mg II index data were obtained from NOAA's Space Weather Prediction Center; the ISCCP D1 data are available from the ISCCP web site at http://isccp.giss.nasa.gov/, maintained by the ISCCP research group at the NASA Goddard Institute for Space Studies. IMF and TSI datasets were obtained from National Geophysical Data Center (NGDC) Space Physics Interactive Data Resource (SPIDR).

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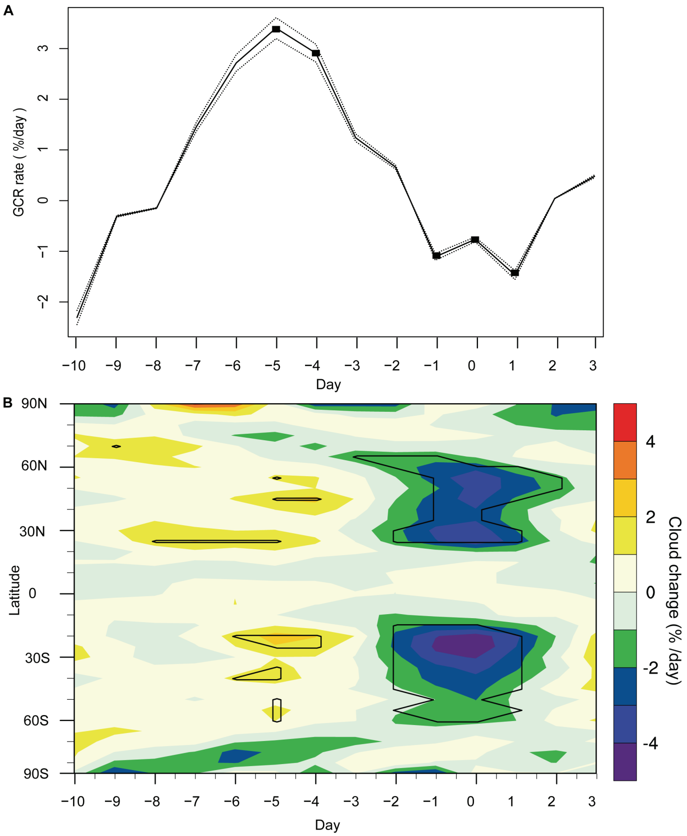

Fig. 1. GCR variations and cloud changes. **(A)** The rate of GCR flux (significance indicated by markers) and **(B)** anomalous mid-latitude cloud cover changes (significance indicated by solid contours) occurring over the composite period. GCR data sourced from multiple neutron monitors, variations normalised against changes experienced over a Schwabe cycle. Cloud changes are a tropospheric (10–1000 mb) average from the ISCCP D1 IR cloud values.

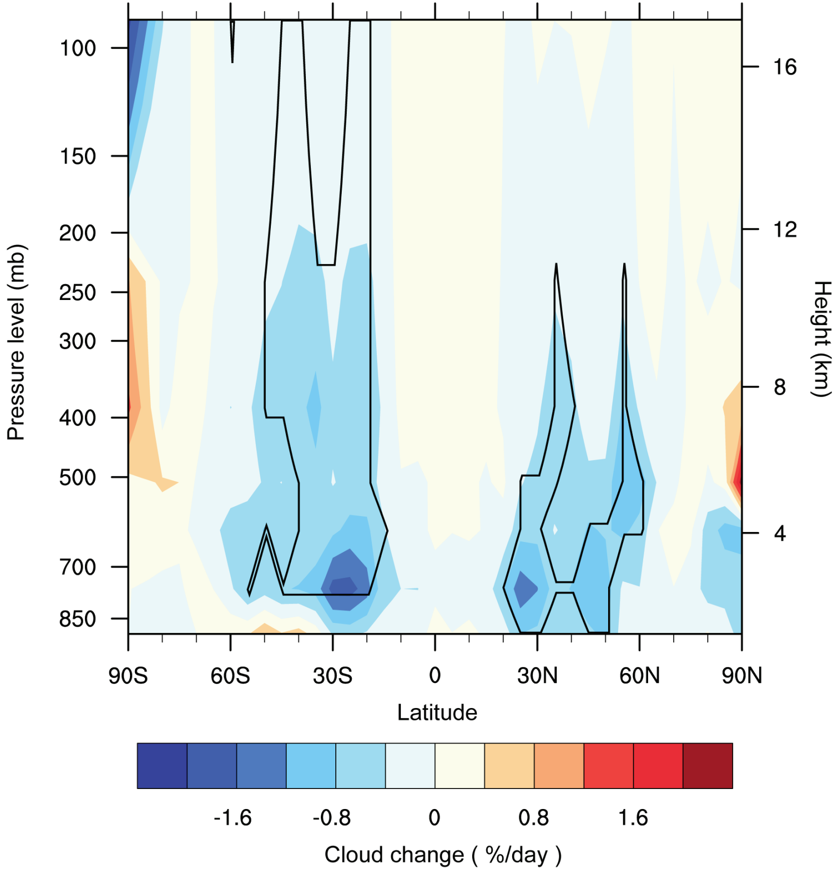

Fig. 2. Key date cloud changes. A latitude/height profile of anomalous cloud cover changes occurring on the key date of the composite. Statistically significant changes (above the 0.95 level) are indicated by solid contours.

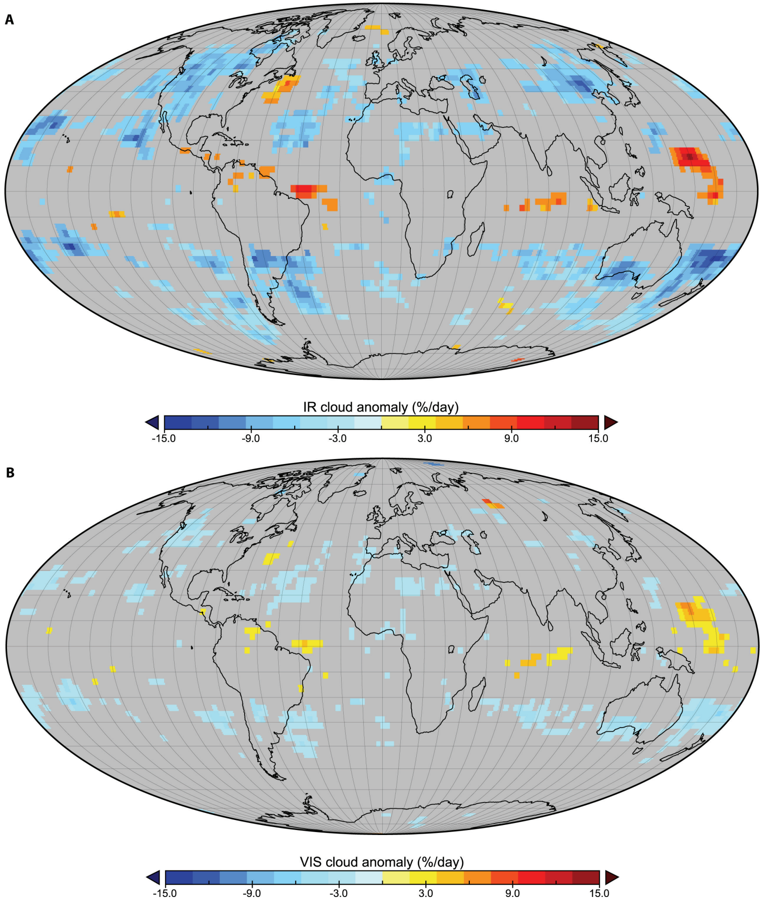

Fig. 3. Locally significant cloud anomalies. Anomalous rates of cloud changes (10–1000 mb) displayed over the globe for both **(A)** IR and **(B)** VIS ISCCP D1 channels; only locally significant (0.95 level) anomalies are displayed.

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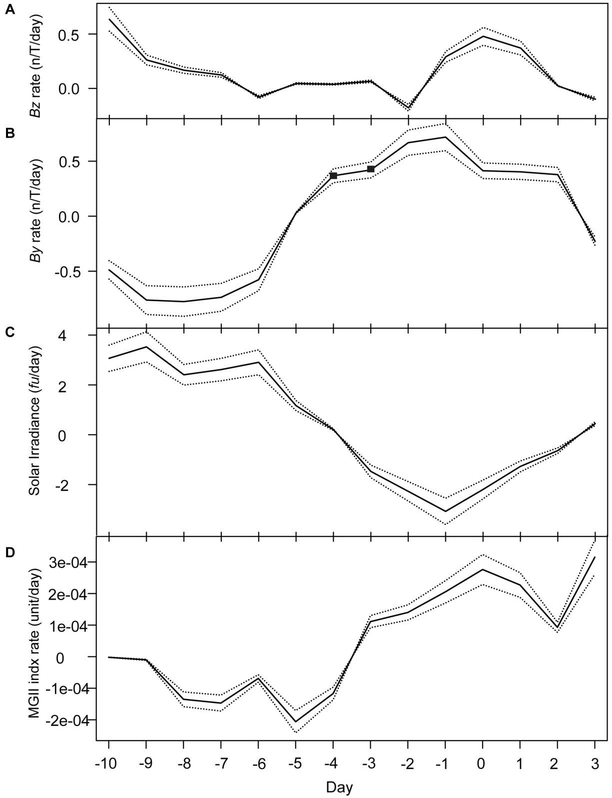

Fig. 4. Solar activity changes over the composite. Anomalous changes in the **(A)** IMF *Bz* (north-south) component, **(B)** IMF *By* (east-west) component, **(C)** 10.7 cm radio flux and **(D)** MGII UV index. Statistically significant anomalies indicated by markers, dotted line indicates 0.95 confidence level. Sourced from: NASA's SPIDR archive (Ottawa 10.7 cm (2800 MHz) solar radio flux data); NOAA (UV Mg II core to wing ratio data); and NASA's OMNI project (IMF data). For the 10.7 cm radio flux, 1 flux unit (fu)=10^{-22} W/m^2/Hz.

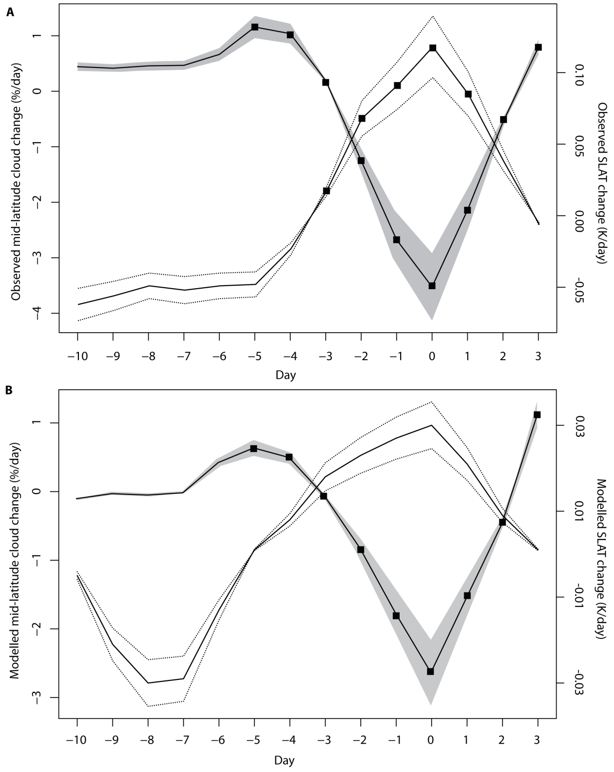

Fig. 5. Observed and modelled air temperature changes. Anomalous mid-latitude (60°–30° N 30°–60° S) average tropospheric (10–1000 mb) cloud cover changes (solid line) and surface level air temperature changes (dashed line) from **(A)** observations and **(B)** the HadAM3 GCM. Markers indicate statistically significant anomalies at the 0.95 critical level. Solid grey shade and dotted lines indicate the 0.95 level confidence intervals (for mean cloud and air temperature changes, respectively).

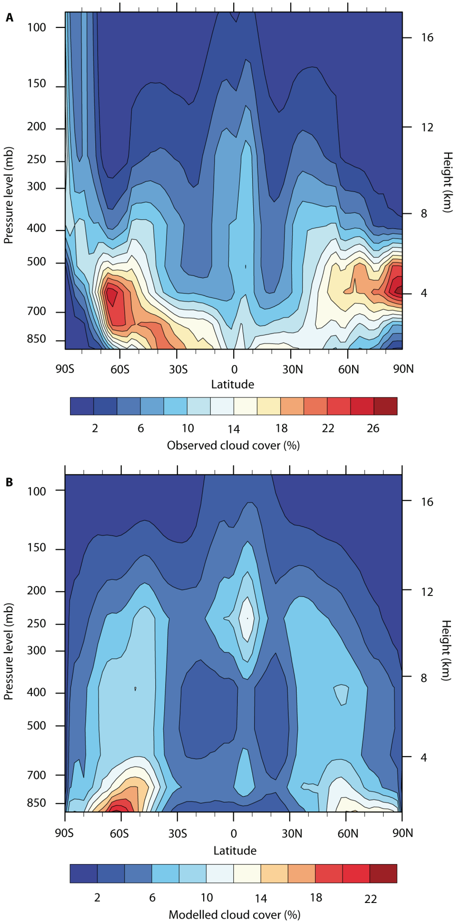

Fig. 6. Modelled and observed tropospheric cloud climatology profile. **(A)** Vertical climatology of averaged cloud cover over the 7 ISCCP D1 IR retrieved pressure levels (corresponding to ISCCP variables 23–29), and **(B)** co-spatial UM HadAM3 cloud cover climatology.

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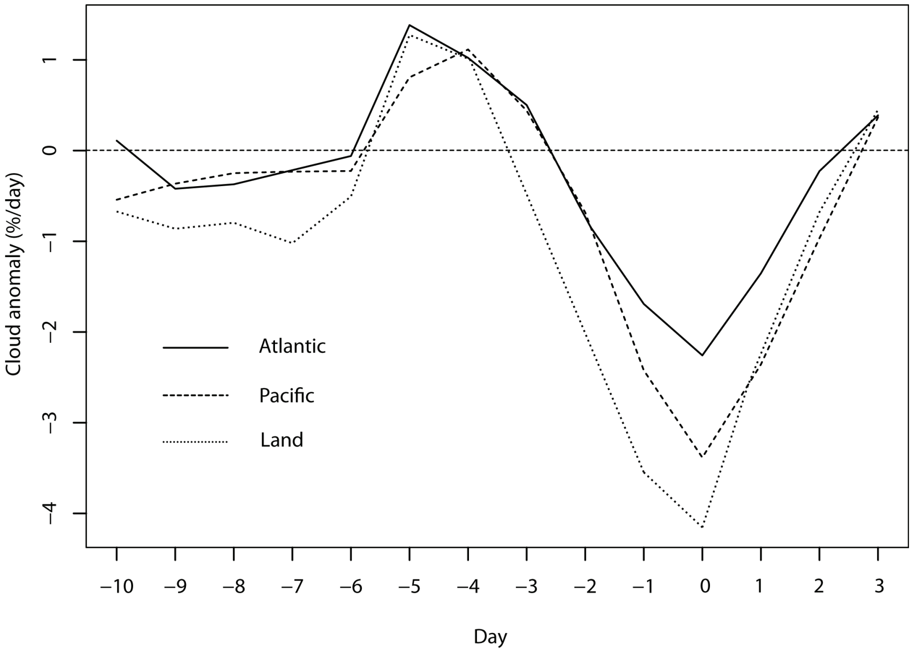

Fig. 7. IR cloud changes over different mid-latitude regions. The mean rate of IR-detected cloud change (10–1000 mb) over mid-latitude regions between days −10 and 3, over land regions (dotted line) and Pacific/Atlantic Ocean areas (solid and dashed lines, respectively).

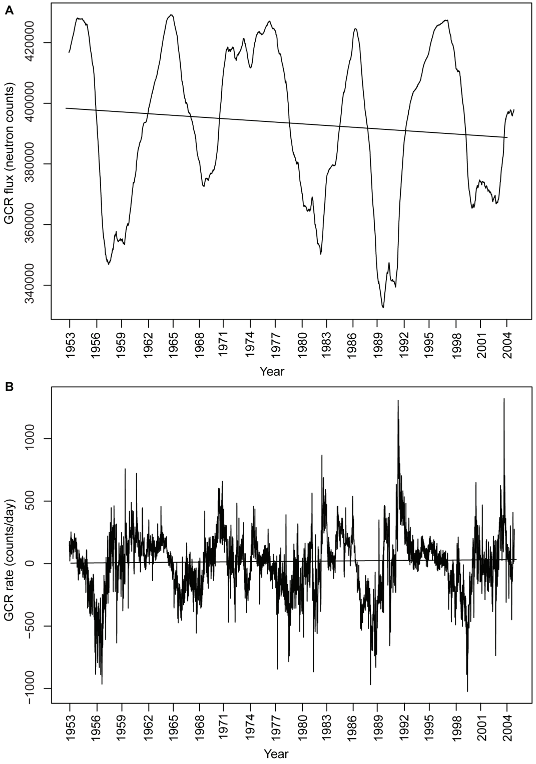

Fig. 8. Long term GCR changes: mean GCR flux and rate of GCR flux 360-day moving average **(A)** GCR flux and **(B)** GCR rate, taken from pressure-adjusted Climax Colorado neutron monitor data (39.7° N; −106.18° W, 3400 m a.s.l.). Linear regression is displayed (black line). Rates of change are a first order derivative calculated on an individual daily basis (prior to 360-day averaging): each daily rate change is calculated by differencing the daily average neutron counts from an average of 3 days of neutron counts beginning 5 days prior to each date.