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Short-term variability in satellite-derived cloud cover and galactic cosmic rays: An update

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Abstract

Previous work by Todd and Kniveton (2001) (TK2001) has indicated a statistically significant association (at the daily timescale) between short-term reductions in galactic cosmic rays, specifically Forbush decrease (FD) events, and reduced cloud cover, mainly over Antarctica (as recorded in International Satellite Cloud Climatology Project (ISCCP) D1 data). This study presents an extension of the previous work using an extended dataset of FD events and ISCCP cloud data over the period 1983-2000, to establish how stable the observed cloud anomalies are. Composite analysis of ISCCP data based on a sample of 32 FD events (excluding those coincident with solar proton events) indicates cloud anomalies with a very similar space/time structure to that previously reported, although of smaller magnitude. Substantial reductions in high level cloud (up to 12% for zonal mean, compared to 18% reported by TK2001) are observed over the high geomagnetic latitudes, especially of the southern hemisphere immediately following FD event onset. Largest anomalies are centred on the Antarctic plateau region during austral winter. However, the largest cloud anomalies occur where the accuracy of the ISCCP cloud retrievals is likely to be lowest, such that the results must be treated with extreme caution. Moreover, significant positive composite mean surface and tropospheric temperature anomalies centred over the same region are also observed for the FD sample from the National Center for Environmental Prediction (NCEP) reanalysis data. Such increased temperatures are inconsistent with the radiative effect of a reduction in high-level cloud during local winter. Overall, the results do not provide strong evidence of a direct galactic cosmic ray/cloud association at short timescales. The results highlight (a) the potential problems of data quality in the high latitude regions (b) the problems inherent in inferring cause and effect relationships from observational data alone (c) the need for further research to test competing hypotheses.

Introduction

The question of how and to what extent the climate system may be influenced by solar-related variability remains central to our understanding of any anthropogenic effects on climate. Most studies indicate that the direct radiative effect of solar variability over decadal to centennial time scales is unlikely to be the primary source of observed increases in global mean temperatures in recent decades (e.g. Crowley, 2000). However, the studies of Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000) and Marsh and Svensmark (2003) have proved notable in that a positive correlation between satellite-derived low level cloud and Galactic Cosmic Ray Flux (GCR) was demonstrated, at low to middle latitudes, albeit over a period of approximately one 11-year solar cycle. It is suggested that variations in GCR may influence clouds through the effect of GCR on ionisation in the atmosphere which may influence formation of cloud condensation nuclei (for a review see Carslaw et al., 2002). GCR is known to vary out of phase with the 11-year solar sunspot cycle, and thus with total solar irradiance, and may have exhibited a long-term decline since the 19th century (Lockwood et al., 1999), although this finding has recently been questioned (Richardson et al., 2002). The work of Marsh and Svensmark (2000) is potentially significant given the importance of clouds to the earths's radiation budget (Ramanathan et al., 1989). On the basis of the proposed GCR-low cloud association and the indirect evidence of a decline in GCR over the 20th century it has been conjectured that the globally averaged mean radiative forcing resulting from a consequent decline in low cloud could be comparable to that of greenhouse gases over the same period. Not surprisingly, these findings have proved to be one of the most controversial issues in climate science in recent years, and have stimulated a lively debate in the literature.

However, numerous re-appraisals of the findings of Svensmark and Friis-Christensen (1997) and Marsh and Svensmark (2000) have been published. It has been suggested that there are alternative explanations of the observed GCR/low cloud correlation, including the effects of ENSO (Farrar, 2000) and dynamical processes associated with the effect of variability in the UV wavelengths associated with solar irradiance variability (Kristjansson et al., 2003). Others (e.g. Jorgensen and Hansen, 2000; Kernthaler et al., 1999; Kristjansson and Kristianseen, 2000; Kristjansson et al., 2002) have cast doubt on the validity of the observed correlation. From this it is clear that any influence of GCR on clouds operating on interannual to decadal timescales cannot be determined unambiguously from that of total solar irradiance and internal modes of climate variability using observational data alone, especially from the ISCCP dataset which is inappropriate for detecting long term trends of small magnitude. As such, repeated analysis of ISCCP data over these timescales is unlikely to resolve the question fully. However, using a different sampling basis for an analysis of ISCCP data, Todd and Kniveton (2001, hereafter TK2001) provided results which shed further light on this issue. On the basis of a sample of short term decreases in GCR (known as Forbush decrease (FD) events whose duration is of the order of a few days) composite analysis of a number of ISCCP cloud types was conducted. FD events represent a relatively 'pure' sampling basis for studying the association of cloud and GCR as there are no internal modes of climate variability operating simultaneously with FD events. In addition, by distinguishing only those FD events where other potential solar influences are minimal it may be possible to highlight the role of GCR relative to other effects of solar variability such as those identified by Arnold and Robinson (1998), Bezprozvannaya et al. (1997), Brasseur and Solomon (1995); Gabis and Troshichev (2000); Haigh (1996, 1999), Labitzke and van Loon (1989, 1992); van Loon and Labitzke (1998) and Tinsley (2000). The results of TK2001 indicated a highly specific response in the cloud data. Substantial decreases in the highest level cloud (10-180mb) immediately following the onset of FD events was observed over the polar latitudes especially in the Southern Hemisphere (SH) (see TK2001 their Figure 5). A randomised Monte Carlo simulation revealed this upper level cloud anomaly structure to be field significant, in contrast to that of all other ISCCP cloud variables. However, the authors noted that the accuracy of ISCCP cloud retrieval in SH polar regions is likely to be poor and that the results should be interpreted with caution.

This present paper provides an extension to the results of TK2001 to determine to what extent those results are robust and stable. Using further releases of ISCCP data we can now utilise data over an extended period 1983-2000 (an additional 6 years of data) and can repeat the composite analysis. In addition, we present equivalent composite mean anomalies of surface temperature from National Center for Environmental Prediction (NCEP) reanalysis data in an attempt to corroborate the results from independent data. We focus specifically on the SH polar region where the largest cloud anomalies are observed.

Data and methods

The data and methodology adopted here is essentially the same as that described in TK2001. However, we now have available ISCCP D1 for the period 1983 to 2000 representing the full extent of currently available data (TK2001 used the period 1984-94). The D1 format provides global estimates of a range of cloud parameters every 3 hours on a 2.5 latitude-longitude grid (Rossow et al., 1996). These ISCCP D1 data were accumulated over 24-hour periods to remove the effects of diurnal variability in cloud cover. We focus on a restricted set of ISCCP cloud variables in this case; the proportion of total cloud (C_T) and the proportion of cloud at levels 1-7 in the atmosphere (C_{L1}-C_{L7}), where C_{L1} represent upper level clouds between 10-180mb and C_{L7} represent lowest level clouds between 850-1000mb. The NCEP produces the most extensive set of atmospheric reanalysis data currently available (Kalnay et al., 1996).

Daily mean fields of surface and upper atmosphere temperature, on a 2.5° grid were used in this study.

A composite analysis (or ‘epoch superposition’) methodology is adopted, in which we have selected a sample of isolated FD events (separated by more than 11 days from another event). These dates (listed in Table 1) represent the onset of FD events (defined by a decline greater than 3%) at the earth’s surface as recorded by the neutron monitor at Mount Washington, USA (39.23˚N, 76.41˚W). All GCR observations at the Mount Washington station are corrected for the influence of barometric pressure variations. Over the study period for which we have ISCCP data there are total of 67 FD events (compared to 50 in TK2001). Some of these coincide (within 3-days either side) with SP events. It has been hypothesised (Pudovkin and Veretenenko, 1995) that during FD events associated with SP events an increase in ionisation (and any effect on cloud) from solar protons is likely to oppose any decrease associated with a decline in GCR. To isolate the GCR signal from that of SP we have distinguished the FD events into separate samples of 32 FD events when no SP event occurs (hereafter referred to simply as FD events) and 35 coincident FD events coincident with SP events (FD-SP). This has the additional benefit of facilitating a distinction of any GCR signal from other effects associated with solar flares and other phenomena which may also influence cloud. The FD-SP events represent a ‘control sample’ of solar proton events in which the effect of GCR changes may be minimised but not that of other solar related parameters.

For each of these FD and FD-SP events ISCCP D1 data are extracted for the period from 5 days before to 5 days following each event. The cloud parameters are then averaged over the sample (32 FD and 35 FD-SP events) for each time slot (day -5 to 5, hereafter t=-5 to t=5) separately. In this way the mean value of any cloud parameter for day n is taken to be representative of the conditions on such days. The difference between conditions prior to, during and after FD events can then be established by subtracting the mean values at different time slots. Here, we define a 'base period' sample representative of conditions prior to an event as the mean of t=–5 to t=–3. The mean cloud values at all days from t=–1 to t=5 are then derived and from this the anomaly is obtained by subtracting the mean of the base period. The same compositing procedure is also applied to the NCEP surface and tropospheric temperature data. This analysis is conducted on 5-degree geomagnetic latitude (φ) bands (from ISCCP D1 data) and for each 2.5-degree grid cell over the globe (for NCEP and ISCCP D1 data). Because the actual area of grid cells varies with latitude, it is necessary to ensure that the quantities derived at all scales larger than that of individual cells represent an accurate estimate of the true areal average. Thus, cloud proportions for latitude bands are derived from the actual numbers of satellite pixels (total and cloudy) within the entire band rather than by averaging the grid cell cloud proportions. The resulting cloud anomalies at the pixel and the latitude band scale were tested for local statistical significance using a t-test. Throughout, the anomalies are given as absolute values rather than as a percentage of the base period value.

Results

We present the results of composite mean cloud anomalies in two forms (i) the time evolving (geomagnetic) zonal anomalies in time-longitude plots and (ii) the 2-D spatial structure of gridded cloud anomalies at a particular time slot. The structure of statistically significant anomalies in C_T following the onset of FD events (Figure 1a) is similar to those reported by TK2001. There is a pronounced decline in cloud coincident with FD onset concentrated over high geomagnetic latitudes (poleward of φ=70˚S) of the SH. The peak reduction occurs at t=1 and declines to t=5. C_T anomalies in this region are significant (at the 0.05 level) on all days from t=0 to t=5. The magnitude of this cloud anomaly (up to 12% for zonal mean), although statistically significant, is less than that (up to 18%) observed by TK2001 (their Figure 5). Unlike those reported by TK2001 there are no significant total cloud reductions observed over the high geomagnetic latitudes of the Northern Hemisphere, nor substantial variations in total cloud amount at mid-low latitudes. Cloud anomalies in the SH polar region are strongly concentrated in the highest level cloud, notably C_{L1} (10-180mb) (not shown). The 2-D map at t=1 shows the largest anomalies to be located in C_{L1} over the Antarctic Plateau with local anomalies in excess of 35% (Figure 2a). If the ISCCP cloud pressure level estimates are accurate then level 1 cloud represents polar stratospheric clouds. The SH polar cloud anomalies are also restricted to the local winter months (Figure 1b) when polar stratospheric clouds are most prevalent. However during the polar night the absence of daylight precludes multi-spectral cloud type identification in ISCCP data such that cloud identification relies on satellite IR data only. During the austral summer months there is no pronounced reduction in clouds over the SH polar region (not shown). Finally, the results of the analysis conducted on the FD-SP events show no coherent total cloud anomaly response (not shown). This occurs despite the far larger magnitude of reduction in GCR during FD-SP compared to FD events (Table 1) and is in line with the findings of TK2001.

Composite mean anomalies of surface temperature derived from NCEP reanalysis data show that the period immediately following FD event onset is characterised by statistically significant positive temperature anomalies over Antarctica (Figure 2b). The spatial structure of these positive anomalies closely matches those of C_{L1} anomalies, centred over the Antarctic plateau. The magnitude of the anomalies is greatest at the surface (up to 12K) and extends throughout the troposphere (not shown).

Discussion

The question of how, and to what extent, the climate system may be influenced by solar-related variability remains central to our understanding of any anthropogenic effects on climate. The possible influence of variability in cosmic ray flux on cloud cover, and thus the planet's radiation budget, has stimulated a lively debate within climate science in recent years. The focus of previous empirical work has been on variations in satellite-derived cloud and GCR over multi-annual timescales. Such a project is severely compromised by (i) long-term calibrations problems within the multi-satellite ISCCP datasets (ii) the difficulty in separating the effects of GCR from those of (a) solar UV effects and (b) modes of natural climate variability. We argue that short term variability in GCR (using FD events) may provide a more suitable sampling basis for empirical study. FD events represent a relatively 'pure' indicator of GCR variability because (i) there are no known natural internal modes of climate variability that operate with similar temporal characteristics and (ii) by distinguishing FD and FD-SP events we may be able to highlight the role of GCR relative to other effects of solar variability. As such, the methodology adopted here may provide a useful way of separating the GCR signal from other possible external and internal influences on cloud cover.

TK2001 reported a substantial decline of up to 18% in zonally average high cloud in polar regions immediately following FD events. The findings here confirm that this pattern is apparent over the extended period. Although the magnitude of cloud anomalies is reduced, indicating greater dispersal within the larger sample of FD events, the statistical significance is maintained such that the result appears to be robust. TK2001 also reported that decreases in high latitude cloud are accompanied by a small increase in cloud at φ=30N. The present findings show that the large polar latitude cloud reductions occur during the local winter and that any increase in cloud at subtropical latitudes is not coincident with this. That significant cloud anomalies are restricted to polar latitudes of the SH is in contrast to the findings of Pudovkin and Veretenenko (1995), who document changes in surface observations of high cloud cover over the former USSR, as well as the observations at longer timescales of Marsh and Svensmark (2000). Finally, as with TK2001 there is no coherent pattern of statistically significant total cloud anomalies observed for FD events associated with solar proton events.

However, the only field significant cloud anomalies observed in this study (and TK2001) occur in locations where, and during periods when, the ISCCP cloud detection algorithm is likely to be most unreliable. The accuracy of ISCCP cloud detection and classification has been evaluated in many regions but not over the high latitudes of the SH, where surface validation data is sparse. Cloud detection from satellite data is particularly problematic (i) during polar night conditions when no visible data is available, and (ii) over polar regions where surface temperatures are often lower than those of the overlying atmosphere. This is particularly relevant over the Antarctic where the wintertime surface temperature inversion can be of the order of 20-30K (Bromwich and Parish, 1998). The ISCCP data must be treated with extreme caution over polar latitudes. Therefore, interpretation of the results here is extremely problematic, given the absence of any long-term record of surface observations of cloud cover over Antarctica during the polar night.

Broadly, there are three possible interpretations. First, and we believe most likely, we can infer that the ISCCP cloud detection is not reliable. The observation of significant positive surface and tropospheric temperature anomalies over the Antarctic plateau coincident with high level cloud decreases is physically inconsistent, if we assume that the temperature anomalies are primarily a response to the radiative effect of cloud changes. Pavolonis and Key (2003) suggest that clouds have a positive net radiative effect during the polar winter (largely through the long wave radiative component as net solar radiation is close to zero) such that any reduction in cloud might be expected to result in decreased surface and tropospheric temperatures, rather than the increases observed from NCEP data. Over Antarctica large, short-term variations in surface temperature can occur associated with the breakdown of the surface temperature inversion due to circulation variability (Bromwich and Parish, 1998). It is possible, therefore, that the ISCCP cloud response may in fact be an artefact of rapid changes in surface temperature over the Antarctic plateau, as suggested by the observed NCEP temperature anomalies. In this case, there is no evidence for a direct GCR-cloud mechanism. It should be borne in mind, however, that NCEP reanalysis data too are of questionable quality in this region where observations for the model assimilation process are limited.

However, in the absence of comprehensive validation of ISCCP products over Antarctica, we cannot rule out the possibility that the ISCCP cloud classification is accurate. As such, the results may be in line with hypotheses describing the direct effect of GCR induced ionisation on cloud microphysics (see Carslaw et al., (2002) for a review). Polar regions experience the greatest penetration of GCR and there is evidence that GCR induced ionisation peaks in the upper troposphere and lower stratosphere, precisely where ISCCP level 1 cloud occurs (see TK2001 for a full discussion). That no significant cloud anomalies emerge for the FD-SP sample, when the reduction in GCR is accompanied by an increase in SP flux, may suggest a specific role of GCR (and solar protons) in modulating ice cloud processes in the polar stratosphere.

Third, it is also possible that both the ISCCP cloud and NCEP temperature anomalies are consistent and that both result from variability in the atmospheric circulation coincident with FD events, through dynamical mechanisms. Other solar related mechanisms may influence the atmospheric circulation such as the effects of the solar wind (Brasseur and Solomon, 1995) and UV related perturbations to stratospheric ozone (e.g. van Loon and Labitzke, 1998; Haigh, 1999). It is expected that changes in UV, stratospheric chemistry and solar wind will occur during all FD events including those associated with SP events. Thus, the differing cloud response to FD and FD-SP events may preclude other solar mechanisms acting in isolation as an explanation of the results. However, it must be stressed that we have not examined cloud and NCEP anomalies explicitly sampled on the basis of other solar related variables.

Overall, given the weakness of the data over polar regions and the apparent inconsistencies in the ISCCP and NCEP temperature response it would be highly inappropriate to draw any firm conclusions on GCR-cloud processes from these results. Clearly, further work is required to provide a physical explanation of the observed ISCCP signal and surface temperature response.

Summary and Conclusions

The possible influence of GCR on clouds is a controversial issue. This study presents an update on previous findings on the possible effect of short-term changes in galactic cosmic ray flux associated with Forbush decrease (FD) events of GCR. FD events represent a relatively clean sampling basis for empirical studies into possible GCR-cloud association.

The study uses an extended set of FD events and ISCCP D1 cloud data over the period 1983-2000. The results confirm that the only field significant cloud anomaly structure is observed in the highest-level clouds at polar latitudes immediately prior to and following FD events, particularly notable over Antarctica. There remains considerable uncertainty about the quality of the data over polar latitudes, particularly the ISCCP cloud detection which is central to the observed cloud anomaly structure. In addition, FD events are associated with significant positive temperature anomalies in the same region as cloud decreases are observed. These findings are physically inconsistent if we assume the temperature anomalies are primarily a response to the radiative effect of cloud changes. Given the uncertainty in the ISCCP cloud retrievals and the observation of a physically inconsistent surface and tropospheric temperature response, the results provide very little clear evidence of a direct GCR-cloud association at short timescales. Our results highlight (a) the potential problems of data quality in the high latitude regions (b) the problems inherent in inferring cause and effect relationships from observational data alone (c) the need for further research to test competing hypotheses.

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Table titles

Table 1. Onset dates and magnitude of Forbush decreases in galactic cosmic ray flux (recorded at Mt. Washington neutron monitor) used in this study.

Figure captions

Figure 1. Zonal mean (averaged over 5 degree geomagnetic latitude bands) cloud proportion anomalies (relative to base period) for days –1 to 5 based on the sample of FD events (excluding SP events). Positive (negative) anomalies have solid (dotted) contours. The contour interval is 0.02, the zero contour is omitted and statistically significant anomalies (at 0.05 probability level) are shaded. (a) total cloud proportion anomalies for FD events over the period 1984-2000 (b) as (a) but for FD events occurring during the austral winter (April-September).

Figure 2. Mean anomalies at t=1 (relative to base period) on a 2.5-degree grid based on the sample of FD events (excluding SP events) over the austral winter (April-Sept) 1983-2000 period (a) Cloud level 1 proportion anomalies where only locally significant anomalies (at 0.05 probability level) are shown (b) NCEP surface temperature anomalies (K). Positive (negative) anomalies have solid (dotted) contours. The contour interval is 2K the zero contour is omitted and statistically significant anomalies (at 0.05 probability level) are shaded.

Event	FD date and magnitude	FD-SP date and magnitude
1	1984/05/04 (5.3%)	1985/04/25 (6.4%)
2	1984/07/03 (5.5%)	1986/02/06 (9.8%)
3	1984/09/12 (5.7%)	1986/03/08 (3.1%)
4	1986/11/03 (4.1%)	1988/01/04 (4.2%)
5	1987/05/24 (2.6%)	1988/08/24 (4.2%)
6	1987/08/24 (4.9%)	1988/10/09 (3.7%)
7	1988/02/20 (5.1%)	1988/12/17 (4.7%)
8	1988/07/20 (2.5%)	1989/01/04 (5.5%)
9	1989/02/11 (4.4%)	1989/03/12 (15.5%)
10	1989/08/19 (4.0%)	1989/03/26 (3.8%)
11	1989/08/28 (4.9%)	1989/08/09 (3.7%)
12	1989/09/18 (4.2%)	1989/09/04 (7.2%)
13	1990/05/17 (3.9%)	1989/10/20 (13%)
14	1991/03/12 (4.8%)	1989/11/17 (4.2%)
15	1991/04/24 (6.6%)	1989/11/28 (16%)
16	1991/08/18 (5.1%)	1990/03/18 (6.6%)
17	1991/11/07 (5.5%)	1990/04/07 (7.7%)
18	1992/02/25 (7%)	1991/01/30 (3.5%)
19	1992/09/08 (4.5%)	1991/03/24 (23.5%)
20	1993/02/19 (4.8%)	1991/05/28 (7.5%)
21	1993/10/22 (4.9%)	1991/06/11 (11.2%)
22	1994/04/16 (5.0%)	1991/06/30 (7.4%)
23	1994/06/17 (3.0%)	1991/07/08 (5.1%)
24	1998/04/03 (4.8%)	1991/10/27 (10.7%)
25	1999/01/12 (10.9%)	1992/05/09 (5.6%)
26	1999/08/16 (7.2%)	1992/10/31 (3.5%)
27	1999/10/07 (8.0%)	1994/02/20 (3.4%)
28	1999/12/06 (8.1%)	1998/04/23 (5.3%)
29	2000/02/04 (5.6%)	1998/08/21 (9.5%)
30	2000/05/01 (4.0%)	1998/09/24 (6.3%)
31	2000/05/20 (4.0%)	1998/11/08 (4.5%)
32	2000/07/09 (14.9%)	2000/06/03 (8.3%)
33		2000/09/15 (4.7%)
34		2000/10/14 (6.3%)
35		2000/11/26 (6.7%)

Table 1. Onset dates and magnitudes of Forbush decrease (FD) events and FD events coincident with solar proton bursts (FD-SP) used in this study

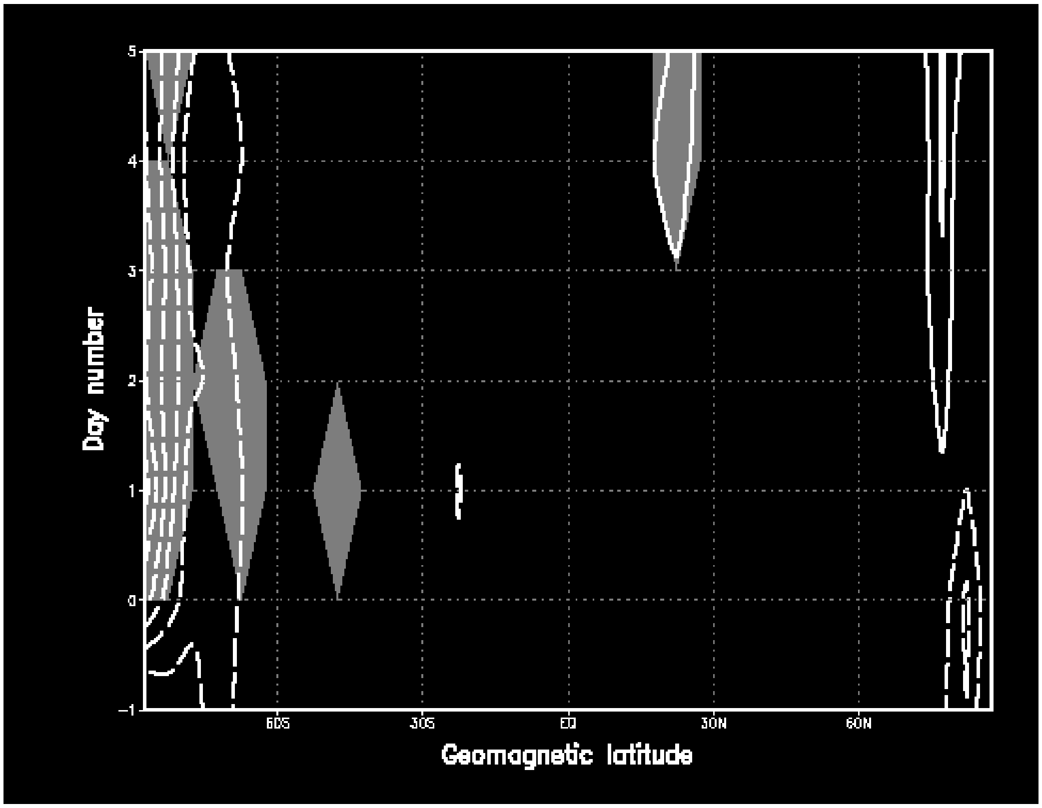

Figure 1a

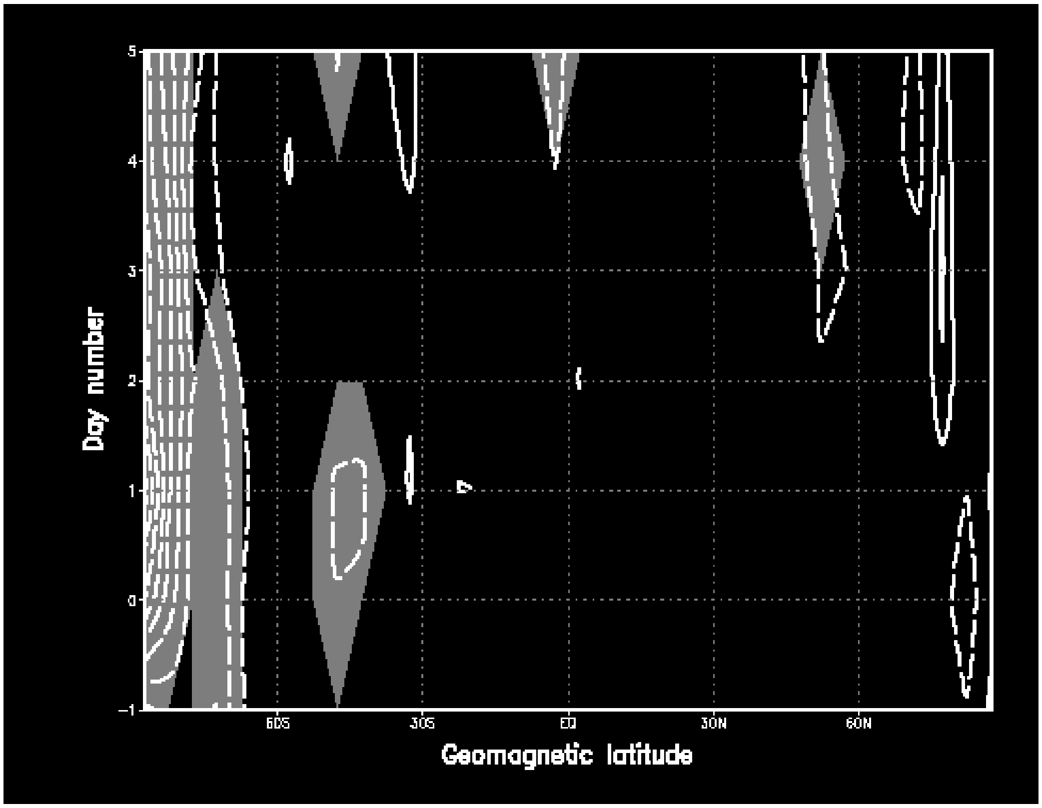

Figure 1b

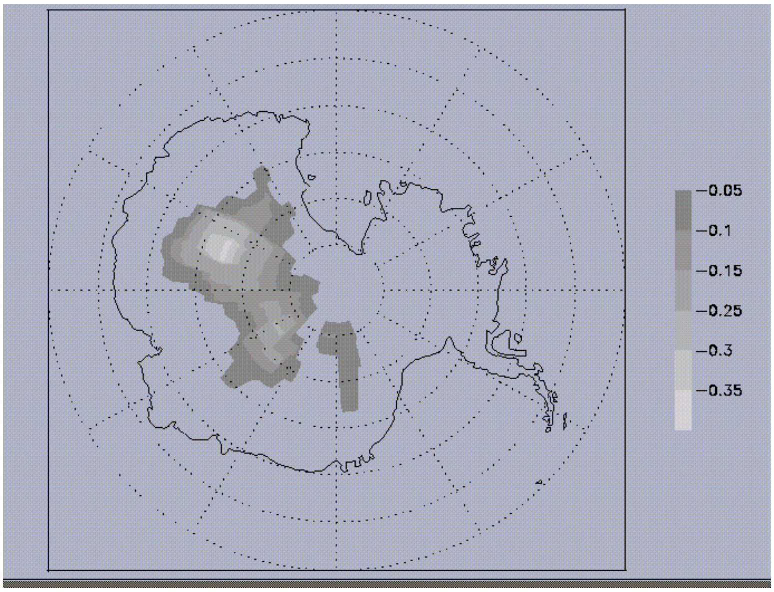

Figure 2a

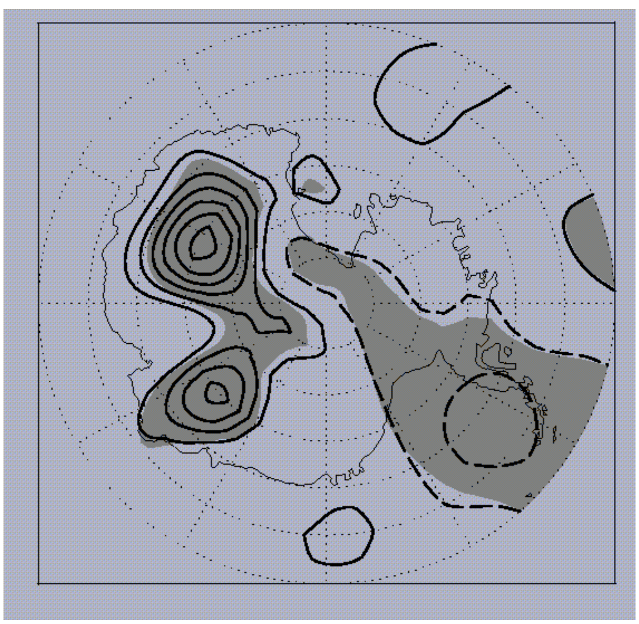

Figure 2b.