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Research Paper

Investigation of the Influence of Galactic Cosmic Rays on Clouds and Climate in Antarctica

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This paper studies the effects of galactic cosmic rays on clouds and snow-fall rates in Antarctica using nine years of data (2001-2009) covering the long deep solar minimum (2007-2009) for the first time. Measurements of the fair-weather air earth current (J_z) at the Indian Antarctic station Maitri (70º45'S, 11º43'E), and equivalent galactic cosmic ray (GCR) flux from the neutron monitor measurements made at the American station McMurdo (77º51'S, 166º40'E) are used for the study. Meteorological data from the Antarctic stations Maitri, Vostok (78º27'S,106º52'E), Scott Base (77º51'S, 166º46'E) and Antarctic Data base are also used. The results show that low level cloud coverage (pressure >680 hPa) is positively correlated to GCR flux with the maximum correlation (31%) being at the long solar minimum (2007-2009) when snow-fall increased by 14%. The observed link between cosmic rays and climate in Antarctica is discussed in terms of ion-aerosol clear-sky hypothesis and ion-aerosol near-cloud hypothesis. GCR enhanced the cloud formation, and the increased low level clouds have invigoration to reflect more heat back to space.

Keywords: **Global Electric Circuit; Cosmic Rays; Antarctic Cloud Anomalies; Cloud-Microphysics; Ion-mediated Nucleation**

Introduction

The studies to understand the effects of solar activity and cosmic rays on climate and weather have a long history (Wilson, 1920; Sarabhai, 1942; Rao *et al*., 1972; Harrison and Aplin, 2001; Rycroft *et al*., 2012). The total solar irradiance provides first order (variable) energy input to the lower atmosphere. The second and third order energy sources are solar ultraviolet radiations that vary by several percentages over a solar cycle (Frohlich and Lean, 1998) and cosmic rays (Carslaw *et al*., 2002). The cosmic ray effects on climate and weather comes through processes involving condensation nucleus abundances (Dickinson, 1975), thunderstorm electrification and thermodynamics (Markson and Muir, 1980), ice crystal formation (Tinsley and Deen, 1991; Tinsley 1996) etc. Cosmic rays of galactic and solar origin are difficult to differentiate. They are prime sources of ionization in the troposphere which is the main source region of climate and different kinds of weather including lightning clouds and snow-fall. The intensity of galactic cosmic rays (GCR) consisting mainly of high energy radiation of sub-atomic particles is known to decrease with increasing solar activity due to the heliospheric magnetic field (HMF) opposing the propagation of GCR (e.g., Achterberg, 1981; Potgieter, 2013). During solar active periods, highly irregular HMF causes sudden modulation of GCR flux, known as Forbush decrease. The GCRs are complex in nature, and their effects on earth's atmosphere are further complicated by the orientation of geomagnetic field. The intensity

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of solar cosmic rays (SCR) consisting of high energy protons (>0.1 GeV), heavier ions and relativistic electrons increase with increasing solar activity (e.g., Kamiyama, 1966; Roble, 1985; Tinsley, 1996; Papaioannou, 2011). At high latitudes where the geomagnetic field lines are open and nearly vertical to the earth's surface, SCRs can penetrate deep into the atmosphere, and strong transient changes of the fluxes of energetic particles can occur there due to solar flares and solar events (Schroter *et al*., 2006, Plainaki *et al*., 2007)

Both GCRs and SCRs have meteorological importance mainly because of their ionizing power (e.g., Sarabhai, 1942; Bazilevskaya, 2000; Rao, 2011; Mironova *et al*., 2015). GCRs cause ionization mainly in the lowest part of the atmosphere, where they ionize N_2, NO_X, HO_X, SO_X and O_3. SCRs cause ionization of O_2 and hydroxyl-radicals mainly at tropopuase and stratosphere altitudes (e.g., Calisto *et al*., 2011). The ionization rate varies from ~2 ions $cm^{-3}s^{-1}$ close to earth's near space to ~40 ions $cm^{-3}s^{-1}$ at tropopause (e.g., Carslaw *et al*., 2002). The ionization (or ions) and aerosols (or dust particles) lead to cloud formation by (1) acting as centers for aerosol nucleation (Svensmark *et al*., 2007, Kirkby *et al.,* 2011) for water vapor condensation and (2) modulating the atmospheric resistance for air-earth electric current flow through global electric circuit with ions aiding in ice nucleation (e.g., Markson and Muir, 1980; Rycroft *et al*., 2000; Tinsley, 2000; Harrison *et al*., 2012); processes (1) and (2) are known as clear-sky hypothesis and ion-aerosol near-cloud hypothesis respectively.

The role of ions and aerosols in acting as nuclei should enable the formation of more cloud condensation nuclei/ice nuclei (IN), under critical super-saturation, for activation for cloud formation, seems the link between cosmic rays and weather (e.g., Yu, 2002). A small change in aerosol number density seems to affect cloud properties because it modifies the rate of ice crystallization (e.g. Krissansen and Roger, 2013). This has been proposed to occur via the ion-assisted formation of ultra-fine aerosols which can grow to Cloud Condensation Nuclei (CCN) or through increased ice crystallization (e.g., Yu, 2002). Laboratory experiments seem to support this suggestion (e.g., Hansen *et al*., 1983). Modeling study showed that the changes in cloud condensation nuclei are small between solar minimum and solar maximum (Pierce and Adams, 2009). Usoskin and Kovaltsov, (2006) explored ionization rate which implies that, stronger than usual high energy particle fluxes are required for an appreciable change in the weather.

The modeling studies of Lucas and Akimoto (2006) calculated aerosol nucleation rates. Aerosols can change the earth's radiation budget directly through scattering and absorption and indirectly by modifying cloud microphysics. Meteorological community has quantified the characteristics of aerosols to assess their effects on weather (e.g., Nakajima *et al*., 2001; Deshpande and Kamra, 2004; Curtius *et al*., 2006). In recent years, considerable progress has been made in understanding the chemical composition of Antarctic aerosols, and their microphysical properties and the factors that enable them to act as Cloud Condensation Nuclei (CCN) and Ice Nuclei (IN) (e.g., Koponen *et al*., 2003; Asmi *et al*., 2010). Clouds are condensed drops or ice crystals formed from atmospheric water vapor. Generally clouds are formed by the rising and lowering of air by convection, topography, convergence and frontal lifting in which cosmic rays seem to have third order (less) effect for the formation of CCN/ IN.

Important studies of the effects of cosmic rays on clouds have been reported (e.g., Svensmark, 1998; Rycroft *et al*., 2000; Harrison *et al*., 2012). Review articles presented by Tinsley (2000); Bazilevskaya, (2000); Carslaw *et al*., (2002); Smart and Shea, (2009) Marsh and Svensmark, (2000) noticed a good correlation between low level clouds and cosmic rays, and proposed that GCR and lower–tropospheric cloud coverage are positively correlated. Later, this hypothesis was supported by several other research groups (e.g. Carslaw *et al*., 2002; Kirkby, 2007; Harrison *et al*., 2012). The data from the Indian Antarctic station Maitri for short periods have been used earlier to study mainly the diurnal variation of air-earth current density and electric field. Siingh *et al*. (2013) reported the data for 12 days in January-February 2005. Deshpande and Kamra (2001) reported the data for 34 days in 1997. Panneerselvam *et al*. (2007b) analyzed the data in 2001-2004.

Using the rainfall data obtained from different locations in 1860-1917, Clayton (1923) reported a general decrease in the rainfall at solar maximum at mid-latitudes and to some extent at high latitudes while the rainfall increased at equatorial latitudes. In a study of the effects of solar variability on lower atmosphere, Dickinson (1975) suggested that noticeable changes in the lower atmosphere are possible through (i) changes in the distribution of clouds which is linked to solar activity and (ii) significant variations in the absorption of solar radiation or emission of infra-red radiation by the lower atmosphere and earth's surface. Kirkby (2007) reported that an increased GCR flux appears to be associated with a cooler climate and southerly shift of ITCZ (Inter Tropical Convergence Zone). The influence of ITCZ may imply significant changes of upper tropospheric water vapour in the tropics and sub-tropics potentially affecting both long wave absorption and availability of water vapour for cirrus clouds. Sourabh and Boss (2010) applied Fourier and wavelet analysis to the precipitation, temperature and sunspot number (solar activity) data from a number of locations in different continents during 1901-2000; they noticed periodicities of 9-11 years for sunspot number and 2-5 years for precipitation.

In this paper, we investigate the effects of cosmic rays on clouds and snow-fall rate in Antarctica using long data sets for nine years (2001-2009) covering the long deep solar minimum (2007-2009) for the first time. The study uses the atmospheric electrical and meteorological parameters measured mainly at the Indian station Maitri, and GCR flux measured at the American Antarctic station (McMurdo). The experiments at Maitri and data sources are described in section 2. The results are presented and discussed in sections 3 and 4.

Materials and Methods

The Indian Antarctic station Maitri (70º 45'S, 11º 43'E) is located in the Schirmacher oasis in the Dronning Maud Land (Fig. 1) and occupies an area of 35 km^2 at an altitude of 117 m above mean sea level (AMSL). Summer temperature at Maitri is –4 to –5ºC, and it falls below –25ºC in winter. Maitri station experiences moderate winds with a mean speed of 8m/s. At Maitri the surface is flat and void of obstructions; and the ice-covered surface has very high electrical conductivity. The surface can be considered as a plane plate of infinite electrical conductivity. The air-earth

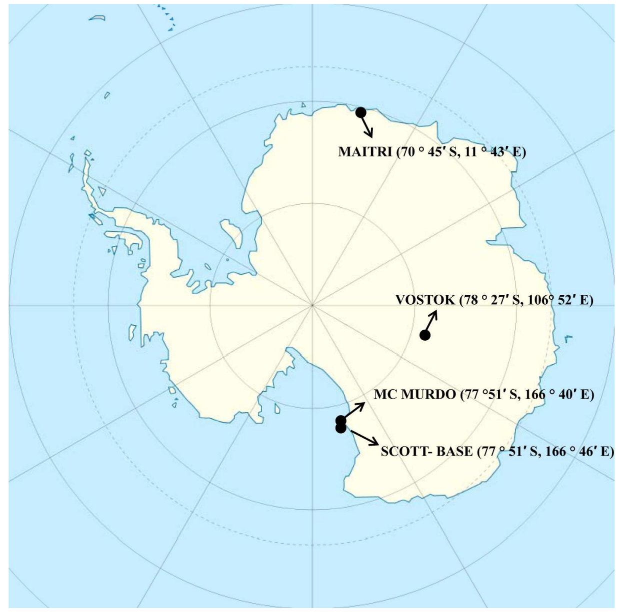

Fig. 1: Locations of Antarctic research stations Maitri (Indian), Vostok (Russian), Scott Base (New Zealand) and McMurdo (American) from where the data used

current and atmospheric electric potential measured at Maitri under specified meteorological fair-weather conditions are important proxies for studying the global electric circuit (GEC). The fair-weather days considered have full 24-hour observations. Fair-weather days are days without snowfall, wind speed less than 10 m s^{-1} and cloud coverage less than 3 octas at Maitri. Days with less than 24-hour observations are not considered.

At Maitri, air-earth current is measured using long wire antenna, and ambient electric field is measured using an Electric Field Monitor (EFM, http://www.boltek.com/). The signals from long wire antenna used for Maxwell current measurements and passive wire antenna used for electric potential measurements are fed through Teflon-insulated cables to a PC-based data acquisition system. The sensors are installed on bare land; and the sensors and insulations are cleaned at least once a day. High quality components which maintain their characteristics in subzero temperatures are used in all electronic circuitry. The atmospheric electricity measuring instrumentations used are long wire antenna, passive antenna and electric field mill, which are similar to the standard ones used (e.g., Ruhnke, 1969; Willett and Bailey, 1983; Tammet *et al.*, 1996; Harrison, 1997). Instruments are calibrated at the highly sophisticated electronic laboratories in India and described in Dhanorkar and Kamra (1997), Deshpande and Kamra (2001) and Panneerselvam *et al*. (2007a). An Automated Weather Station (AWS) is operated at Maitri for monitoring meteorological parameters. The *in-situ* winds are characterized by high directional constancy, namely the southeast. The sea level pressure is approximately 970 hPa, and overcast sky occurs mainly due to the influence of sub-polar low-pressure system. Antarctic clouds differ from the deep convective clouds of low latitudes. Snowflakes mainly form in clouds that contain both liquid drops and ice crystals. The ice crystals that are present within these clouds will grow rapidly until they are large enough to fall.

The atmospheric electric potential data and meteorological data obtained at Vostok (78º 27'S, 106º 52'E) (http://globalcircuit.phys.uh.edu) and Scott Base (77º 51'S, 166º 46'E)) are used for verification. Cloud coverage noted from the International Satellite Cloud Climatology Project (ISCCP) data base (http: isccp.gisa.nasa.gov) and cloud information and change-in-snowfall are obtained from Antarctic meteorological record (ftp://amrc.ssec.wisc.edu). The duration and number of blizzards, rate of snow fall and cloud coverage are also manually noted by the members of the Indian Scientific Expedition in Antarctica (ISEA) from time-to-time.

Neutron monitors are generally used for studying the variations in ground level GCR flux because they are sensitive indicators of primary GCRs with energies in the range 0.5-5 GeV. The ground level GCR flux data are obtained from the measurements made using the neutron monitors at the American Antarctic station McMurdo (77º51'S, 166º40'E) and available at (ftp.bartol.udel.edu). McMurdo's data are one of the sources and indicator of the ground level GCR flux at Antarctica. It provides a vital three dimensional perspective on the shower of equivalent Antarctic regional GCR count. The hourly time series of GCR flux during the period of study (2001-2009) are obtained and analyzed. Time-domain method is adopted to characterize the data series, in the same ways in which neutrons were observed.

Results

This section presents the observations and results. It inter-connects the series of measurements of fair weather air-earth current density (J_z) at Maitri, modulation of cosmic rays due to HMF, finally connects the putative GCR effect on clouds in Antarctica. Figure 2 shows the diurnal variation of half hourly average air-earth current density (J_z) in 2001-2009; vertical bars represent standard deviations at hourly intervals. The data are presented in three panels a, b and c corresponding to solar maximum phase (2001-2003), declining phase (2004-2006) and long deep minimum phase (2007-2009). As shown by panels a and b the air current density J_z on the whole decrease J_z by ~1.75 pA/m^2 from solar maximum to minimum and can be understood in terms of: (i) variation of the ionization by solar cosmic rays, solar energetic protons and bremmstrahlung electrons reaching the middle and lower polar atmosphere (Rishbeth and Garriott, 1969; Curtius *et al*., 2006; Schroter *et al*., 2006), and (ii) reduction in the solar wind-magnetosphere dynamo mechanism, discussed in section 4. The conduction current density however, peaks with respect to lightning at different times in different continents. The conduction current density peak increases from ~3.0 pA/m^2 in 2002 to 3.75 pA/m^2 in 2009 may be due lightning activity (enhancement of 17% in GCR flux noted).

Over the solar activity trend, J_z variation shows peaks at around specific UT hours corresponding to the thunderstorm times mainly in continents. For example, the prominent peak occurring at around 18:00-19:00 UT almost every year seems to correspond to the global lightning activity. The secondary peak at, around 20:00 UT, may be mainly due to a large contribution from South American thunder clouds. A flat peak during 08:00-09:00 UT in some years corresponds to the thunderstorm times in South East Asia/Australia maximizing at ~08:00 UT. Substantial peak in air-earth current happens with African thunderstorm contribution at 14:00-15:00 UT. The electrical storms occur mainly over the continents because the updraft intensities of clouds are higher in land than in ocean. The J_z variations have been studied earlier by a number of scientific groups (Israel, 1973; Deshpande and Kamra 2001; Harrison 2005; Rycroft *et al*., 2012; Siingh *et al*., 2013), as is discussed in section 4.

The number of fair-weather days of observations used is shown in Fig. 3. In general, 20 to 60 days of observations are available in all months except in the winter months of June and July when the observations are available for less than 10 days each. The difference in the number of days, however, does not seem to have any significant effect on the mean atmospheric current density as understood from the small standard deviations from average values (Fig. 2). The long duration (9 years) data presented for the first time, though not very large, seem valuable in understanding the geosciences of the remote continent. The satellite recorded meteorological fair-weather days, which provide information only of the cloud conditions, however, differ from those in Fig. 3.

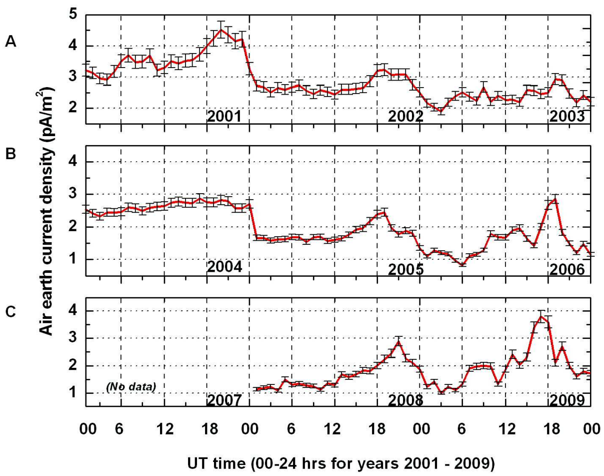

Fig. 2: Diurnal variation of half hourly average atmospheric air-earth current density (J_z) on fair weather days in 2001-2009 measured at Indian Antarctic station Maitri. Vertical bar indicates standard deviations at half-hourly intervals

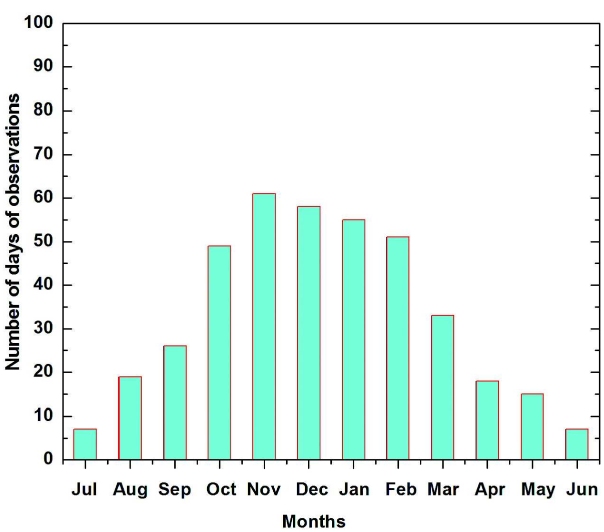

Fig. 3: Histograms of fair-weather days of observations at Maitri in different months during 2001-2009

Figure 4 shows the variation of GCR flux (10^3 counts/hour). The GCR flux increases with decreasing solar activity in 2001-2009, with the increase being slightly faster during the declining phase of solar activity (2004-2006). The flux increases from about 8.75 (x 10^3 counts/hour) in 2001 to 10 (x 10^3 counts/ hour) in early 2006. The flux then remains nearly steady (or increases by a small amount of 0.5 (x 10^3 counts/hour) during the long deep solar minimum (2007-2009). The observed increase of GCR flux seems positively correlated to thunder storm activity (conduction current) or low altitude clouds as discussed below. The correlation between GCR flux and low level clouds has also been noted in earlier studies (Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000; Kristjansson *et al.*, 2008), and is discussed in section 4.

In addition to the overall GCR flux variation described above, the GCR data (Fig. 4) showed large fluctuations during 2001-2006. In order to determine the periods (and causes) of the fluctuations, the data were subjected to wavelet analysis. Figure 5 shows the wavelet spectra of the data in 2001, 2003, 2008 and 2009. It may be noted that the data (Fig. 4) are not fully available for the year in 2001 and 2009. As shown (Fig. 5) the dominant periods are ~27 days and its sub-harmonic (13.5 days) in all years though the periods are centered during certain windows of the years. The spectra show that the dominant periods are stronger at higher levels of solar activity. The spectra seem to reveal that the GCR flux is could be modulated by solar wind periodicities. The dominant period is also broad (~40-15 days) especially in solar active years (2001 and 2003), which may be due to the occasional occurrence of coronal mass ejections (CME) and high speed solar wind streams (SWS). SWS interact with the background slow solar wind and produce CIRs (co-rotating interaction regions). The accelerated particles in CMEs and CIRs in turn modulate the GCR flux (Reames *et al.*, 1997). The Forbush decreases due to CMEs and corresponding decreases in low level clouds during this period are well-documented (Svensmark *et al.*, 2009). The satellite data suggest that the decrease of GCR flux is associated with a decrease in low altitude clouds, which are known to exert a global net radiative cooling effect (Kirkby, 2007; Harrison and Ambaum, 2010). The periodicities observed in the GCR time series and spectra (Figs. 4-5) agree well with that reported

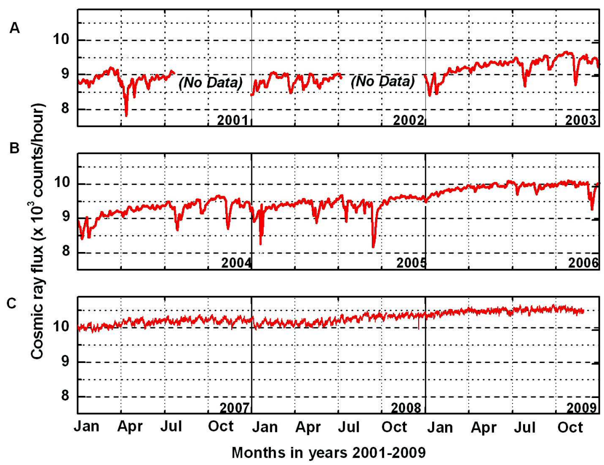

Fig. 4: Variation of hourly average counts of Galactic Cosmic Ray (GCR) flux in 2001-2009 measured at the American Antarctic station McMurdo. Months of the years are noted along the X-axis for convenience

earlier (Voiculescu and Usoskin, 2012).

The complexity of cloud microphysics results from both the different particle size and compositions in atmospheric clouds and the phase change of water molecules. Aerosol electrification in the atmosphere occurs from ion-aerosol attachment facilitated by ion transport in the electric field. The aerosol charge distribution can affect aerosol coagulation rates, which in turn may change the particle size distribution. Hence, the electric field caused by global electric circuit could affect aerosol charging by modifying the ion environment on the boundaries of the clouds where ion concentrations are profoundly high and the electric fields are enhanced.

The cloud type and change-in-show-fall data are analyzed. The data obtained from different Antarctic bases (section 2) are averaged for each month in 2001-2009, separately for high level clouds (cloud pressure cp, <440 hPa, above 3 km height) and low level clouds (cp >680 hPa, below ~3 km height). Figures 6A-6C show the monthly average of cloud type and snowfall data in 2001-2003, 2004-2006 and 2007-2009 respectively. Top panels correspond to change-in-snow fall and bottom panels give cloud type with red and green histograms representing high and low level clouds.

A striking observation (Figs. 6A-6C) is that the amounts of high level (red histograms) and low level (green histograms) clouds are generally increased by 8% and 23% respectively with decreasing solar activity. Extensive amount of low level clouds are observed at solar minimum as shown in Fig. 6C. The yearly average amount of low level and high level clouds reduce by 3% and 1%, during the declining phase. The monthly snow-fall rate (top panels), however, does not show clear solar activity dependence though the snow-fall rate is lowest at declining phase (2004-2006, Fig. 6B) and 1% higher towards the end of the long deep solar minimum in early 2009 (Fig. 6C).

Table 1 provides statistical evidence for high levels of GCR flux enhancing the formation of low level clouds, (r = 0.31, in Table 1, it shows a third order relation between GCR and low level clouds). For example, Figure 6c shows most extensive low level cloud coverage at the long deep solar minimum (2007-2009, green histograms) when GCR flux is highest (Fig. 4). 280 days of low level cloud condition per year were noticed during this period (2007-2009), and snow fall rate was maximum in 2009. In the (2004-2006) years the high level cloud coverage reduced 6% and low level cloud decreased to 4% while snowfall rate reduced to 2% (Table 1) discussed in section 4.

The data in Fig. 6B show scatter in both cloud coverage and snowfall rate. For example, the snowfall rate shows high values in 2005 and low values in 2006, and an extensive heterogeneous cloud coverage was noticed during 2004-2006 (Fig. 6B). The correlation coefficient indicates that the changes in cosmic rays flux may tertiary importance for the changes in the amount of cloud coverage. The cloud data may also have some uncertainties because cloud observation is not easy and has shortcomings. Weather station observations (on land) are contaminated by the presence of widespread and migrated ocean clouds.

Weather satellite observations are better though drifting and decaying orbits plague the data. Study was also carried out for the number of high-cloud days per month and low-cloud days per month and monthly snowfall per month against monthly mean GCR flux (X-axis) in 2001-2003, 2004-2006 and 2007-2009. For each case, the correlation coefficient (r), coefficient of determination (r^2) and t-test statistics values are determined above the significance level and listed in Table 1. Table 1 allows us to see how the correlations are between cosmic rays and low level clouds/change-in-snowfall data during extended

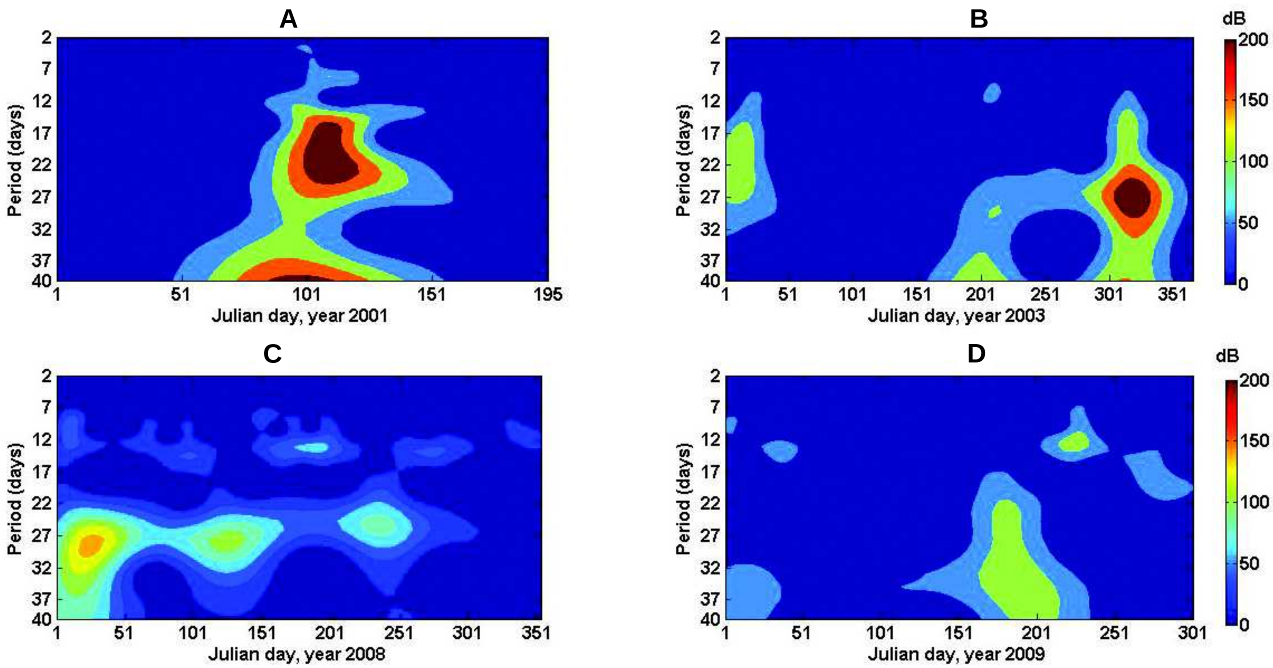

Fig. 5: Wavelet spectra of the GCR data in 2001, 2003, 2008 and 2009

minimum period. Table gives a correlation of 0.31 and 0.14 for the low level clouds and for change-in-snowfall in 2007-2009 are the highest correlations noted. An interesting point is that the correlations and t-test in 2007-2009 are higher than those in 2001-2003 and 2004-2006. The test shows that the changes in low level cloud cover with cosmic rays provide a small/ convincing link.

Discussion

The fair weather atmospheric electric current density (J_z) and meteorological parameters measured at the Indian Antarctic station Maitri for nine years (2001-2009) covering the long deep solar minimum are presented. The data together with meteorological data from other Antarctic stations and equivalent GCR flux measured at the American Antarctic station (McMurdo) are used to study the possible effects of GCR flux on Antarctic climate. The main observations are discussed.

Current Density

The current density (Fig. 2) increases with increasing solar activity from 2001 to 2009, and base line reduced to half at the value of about 1.25pA/m^2 during the long deep solar minimum (2007-2009). In 2001, the cause may be higher flux of energetic protons (>0.1GeV) and relativistic electrons and frequent solar flares are maximum. At high latitudes, solar maximum, where the geomagnetic field lines are open to the auroral zone during solar disturbances and nearly vertical to the earth's surface, ionization increases up to stratospheric height. The contribution of solar wind-magnetosphere dynamo considerably increases during the solar maximum period in the global electric circuit (Roble, 1985; Anil Kumar *et al*., 2009). The variation of J_z in specific UT hours in 2009 can be understood in terms of 17% increase in GCR. The current density also (Fig. 2) undergoes the well-known diurnal variation (Wilson, 1920; Torreson *et al*., 1946) with primary maximum at around 18:00-19:00 UT in almost all years and minimum at around 03:00 UT. The diurnal variation studied earlier (Deshpande and Kamra 2001; Harrison, 2005) has been explained in terms of Wilson's classical hypothesis (Wilson, 1920) based on the observations of Maud and Carnegie survey ships (Torreson *et al*., 1946). Later ionospheric dynamo mechanism and solar wind-magnetosphere dynamo mechanism are added to the hypothesis of global electric circuit.

The current density variations (Fig. 2A) can be understood more closely in terms of a strong dependence of thunderstorm dynamo (Israel, 1973); solar wind–magnetosphere and ionosphere dynamo

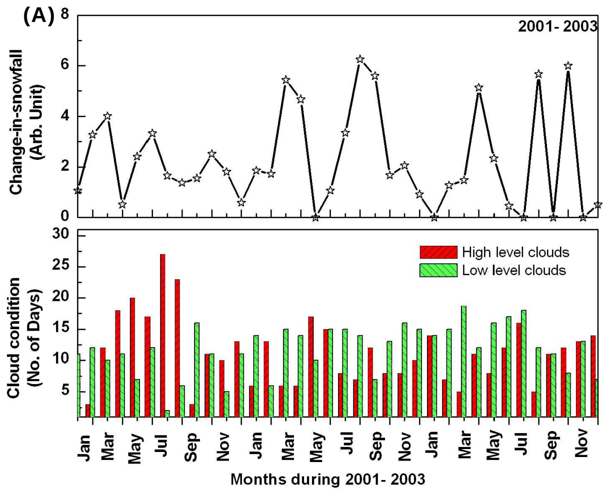

Fig. 6A: Monthly average cloud type (bottom) and change-in-snowfall rate (top) from January 2001 to December 2003. Cloud coverage means the area covered by clouds and change-in-snowfall indicates the snow fall average

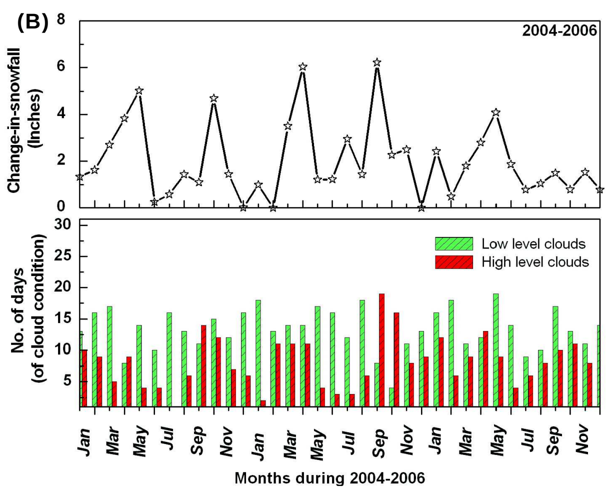

Fig. 6B: Monthly average cloud type (bottom) and change-in-snowfall rate (top) from January 2004 to December 2006

may also contributed to GEC as in Fig. 2A (Weimer, 2005; Anil Kumar *et al*., 2009; Tinsley 1996, Rycroft *et al*., 2012). In an earlier work, Panneerselvam *et al*., (2007b) mathematically differentiated later contributions from Maitri observations. It is well known that the current density J_z is proportional to the overhead ionospheric potential (V_i). To verify how J_z near the Earth's surface responds to the changes in V_i, Tinsley *et al.*, (1998) analyzed the values of E_z (proxy of J_z) and V_i measured at the South Pole during 1982-1986. They found a good correlation between the two parameters even during periods of irregular

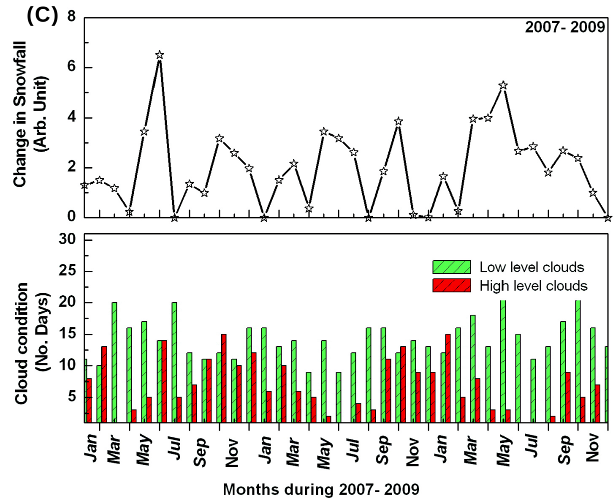

Fig. 6C: Monthly average cloud type (bottom) and change-in-snowfall rate (top) from January 2007 to December 2009

variations in low latitude thunderstorm activity. Recently, Rycroft *et al*. (2012) also showed that J_z is modulated by solar processes both on 11 year and shorter time scales.

The data from Maitri for short durations have been reported earlier by other scientists. Singh *et al*. (2013) reported the data for 12 days in January-February 2005 and showed that the diurnal variation of Maxwell current density and electric field has a peak between 18:00 UT and 20:00 UT. Deshpande and Kamra (2001) reported the data for 34 days in 1997, and the difference of their results from the Carnegie field curve (Ksemir, 1972) is attributed to the seasonal and longitudinal distribution of thunderstorm activity. Panneerselvam *et al*., (2007) analyzed the data in 2001-2004 and stressed that apart from day-to-day variations there are diurnal, seasonal and inter-annual variations in electric potential and currents. Anil Kumar *et al*. (2008, 2009) studied the air-earth current measurements during the geomagnetic storms in 2004-2006 to study the role of solar wind-magnetosphere-ionosphere interactions.

The current density variations, J_z (Fig. 2C) can be understood more closely in terms of a strong dependence expected from thunderstorm contribution. The large clear increases of J_z at 08:00 UT, 14:00 UT, 16:00 UT and 20:00 UT corresponds to peak thunderstorm times in south East Asia, Africa, Europe and America. These current variations can be understood more closely in terms of a strong dependence expected from thunderstorm dynamo (Israel, 1973). It has a clear GCR flux influence as per the statistical analysis provided in Table 1.

Cosmic Ray Flux

The GCR flux (Fig. 4) increases with decreasing solar activity (in 2001-2009), and undergoes fluctuations of mainly mean 27 days period (Fig. 5). The relation between GCR flux and solar activity can be understood closely in terms of the ponderomotive force due to Alfven waves. The waves re-distribute the field and energy of space plasmas in such a way that HMF flux expands and pushes off the GCR flux with increasing solar wind velocity (Achterberg, 1981; Potgieter 2013). Using the data during Satellite Cloud Climatology Project (ISCCP) in 1983-1999, Kristjansson *et al*. (2002) reported that GCR flux varies inversely with solar activity. Using the long span of neutron monitor data from 1965 to 1997 recorded at the South Pole/Antarctica, Bieber *et al*. (2007) reported that the GCR flux decreased by 8% in 32 years.

As mentioned in section 1, both GCRs and SCRs have meteorological importance mainly because of their ionizing power (Sarabhai, 1942; Rao *et al*., 1972; Bazilevskaya, 2000; Rao, 2011; Mironova *et al*., 2015). GCRs cause ionization mainly in the lowest part of the atmosphere while SCRs cause ionization mainly at tropopuase and stratosphere altitudes (Calisto *et al*., 2011). Certain SCRs associated with solar flares are highly energetic. These cosmic rays particles increase the charging of air and lead to the formation of cluster ions with large number of hydrogen-bonded hydrates that can then coalesce with other air particles. The ionization produced by GCRs helps in the formation of clouds.

Clouds and Snow-Fall

The data is presented to provide a connection between clouds (Table 1) and GCR flux. The amount of high level cloud is less than of low level cloud with decreasing solar activity (Fig. 6A-6C) or with increasing GCR flux (Fig. 4). The correlation of low level clouds increased from 0.07 to 0.31 between the two levels of solar activity (2001) and at the end of long deep solar minimum (2009) respectively when the GCR fluxes are also lowest and highest.

The present observations are found to generally agree with those earlier reports (Svensmark and Friis-Christensen, 1997; Tinsley, 2000; Marsh and Svensmark, 2000; Carslaw *et al*., 2002; Kirkby, 2007; Kristjansson *et al*., 2008; Voiculescu and Usoskin, 2012; Harrison *et al*., 2012) though earlier studies are mainly for other periods and locations. For example, in a general global study using the ISCCP data in 1983-1994, Marsh and Svensmark (2000) reported a high and statistically significant correlation between GCR flux and low level clouds. Using the time series data in 1984-2009, Voiculescu and Usoskin (2012) found the low level clouds varying in phase with cosmic rays induced ionization (CRII) in some areas (south Pacific and south Atlantic oceans, western Indian Ocean, Continental East Asia and northern high latitudes), and the response of clouds to CRII is positive and persistent over the entire time interval in some key areas such as high latitude Pacific.

Table 1: Measured relationship (Linear correlation) that exist between GCR , Cloud distribution and change-in-snow fall from monthly average values of 2001-2009

Solar activity	Mean GCR flux (Counts/hour)	R & R^2 with meteorological parameters			T-test value		
		LLC	HLC	CSF	LLC	HLC	CSF
High 8.5 x 10^3 (2001-2003)		0.07 0.0049	0.070.13 0.0049	8.65 0.0169	15.75.71		
Moderate	9.4 x 10^3	0.04 0.0016	0.06 0.0036	0.11 0.0121	12.30	14.09	7.39
Long deep solar minimum (2007-2009)	10.6 x 10^3	0.31 0.0961	0.15 0.0225	0.14 0.0096	24.9	9.58	7.54

R-Correlation Coefficient with GCR & R^2 values are below R Values; LLC - low level clouds, HLC - high level clouds, CSF - change in snow-fall

Effects on Climate

As mentioned, the data (Fig. 2-6) seem to provide link between cosmic rays and climate and weather. The science of the link of low level clouds and cosmic ray flux has been reasonably discussed earlier too (Harrison, 2000; Harrison and Aplin, 2001), though the involved microphysical processes need further studies.

Cosmic rays cause ionization at tropospheric altitudes; and the presence of charged particles (and aerosols) lead to condensation of water vapour and relative humidity enable to form clouds (Raes *et al.,* 1986; Tinsley and Deen 1991; Harrison 2000). The charged particles act as centers of radius '*r*' that help overcome the excess pressure (*P*) inside water vapour (of surface tension *T*) to start the process of condensation. The involved process can be understood from excess pressure $P(= 2T/r)$ tending to infinity when there is no particle (or when radius *r* becomes zero), and hence condensation becomes unlikely due to the excessive outward pressure. The ionization also reduces the atmospheric (columnar) resistance or enhances the mild ionosphere-earth current flow (via GEC); this also enhances the coalescence of small water drops into large drops (Mason, 1971). The process of condensation and electroscavenging lead to formation of drops under super-saturation. Currently, two hypotheses are prevailing (Carslaw *et al*., 2002). The central theme of the 'ion-aerosol clear-sky hypothesis' is that cosmic rays affect ion concentrations in the atmosphere. Aerosol nucleation (the formation of ~1 nm particles in the atmosphere) is generally enhanced by the presence of ions (Spracklen *et al*., 2008; Wang and Penner, 2009; Yu and Luo 2009). The particles formed through nucleation may grow through condensation of sulfuric acid and organic vapors to sizes where they can act as CCN (Kirkby *et al*., 2011) and, if, CCN are exposed to relative humilities above 100%, cloud will form on them. Thus, a change in cosmic rays could potentially affect the number of cloud drops, which in turn may affect the amount of sunlight reflected by a cloud, the formation of precipitation and cloud lifetime (Carslaw *et al*., 2002).

The second one 'ion-aerosol near-cloud hypothesis' is connected with the global electric circuit mechanism via vertical current developed by increased ionization due to cosmic rays, as suggested by Tinsley and Deen (1991); Tinsley (1996); Tinsley (2000); Harrison (2000); Harrison and Aplin (2001), Svensmark *et al*. (2007). In this case thunderstorm creates a charge separation with positive ions at the top of the cloud and negative ions at the bottom (this negative charge gets discharged through lightning to the ground). The positive charge at the top of the cloud moves through the conductive upper atmosphere to the ionosphere giving the ionosphere a positive charge. The difference in charge between the ionosphere and the Earth's surface drives an electric current from the ionosphere to the surface. The resistance of the atmosphere to current flow depends on the ion concentrations. Thus, when more cosmic rays enter the atmosphere, electricity flows more quickly through the atmosphere.

This may have an effect on the cloud properties by enhancing the collision rate between cloud droplets and aerosols. Often, in the clouds, liquid water drops will exist even when temperatures are well below 0ºC (freezing point of water). Collisions between the charged aerosols with these super cooled cloud droplets may enable the freezing of these droplets, which could lead to cloud invigoration due to the heat released from freezing or enhanced precipitation. These effects, however, are all still very uncertain.

The quantitative analyses prove that the observed cosmic ray flux correlates with the cloud cover and snowfall. The month mean variability in GCR, cloud cover and snowfall are less correlated during solar maximum, while during solar minimum period correlation is higher. It's impossible to speculate if any such changes are statistically significant in declining phase. A couple of quantitative analyses r^2 and t-teat values are also provided the same result (Table 1) for the period. On each solar epoch the correlation coefficient (r), the coefficient of determination (r^2) and t-test statistics are noted. The plot 6(A)-6(C) and Table 1 allow us to see how the correlation increases between the cosmic rays and the low level clouds from solar active period to extended minimum period. The mean monthly variability t-test provides the inference that the high/low cloud cover are significantly different in the 2007-2009 period than from the 2001-2003 period.

As described, the formation of clouds depends on the ionization at tropospheric heights mainly by GCRs. Marsh and Svensmark (2000) noticed a good correlation of low level clouds with cosmic rays. Harrison *et al*. (2012) reported that the base height of low level clouds vary with cosmic ray conditions. As shown by the present data (Fig. 4) the GCR flux undergoes long term and short term variations, and hence the rate of ionization and cloud formation could also undergo similar variations, which is also shown by the data (Fig. 6), especially for low level clouds. During the long deep solar minimum (2007-2009) the GCR flux increased to the peak level of 10500 counts/hour on average (Fig. 4), and paved the way for wide-spread low level cloud formation (Fig. 6C), which might have exerted a net cooling effect as reported for earlier periods based on temperature variation (Carslaw *et al*., 2002).

Clouds are important in Earth's radiative balance. In the balance between absorption and emission of heat in the form of long-wave infrared radiation, low level clouds cool while high level clouds heat the earth's surface. However, low clouds are much more wide-spread than high level clouds and re-radiate larger amount of heat back to space. On the other hand, low level clouds have a stronger cooling effect due to the combination of a higher albedo and higher cloud temperature. As discussed, the study performed using the long duration (9 years) data sets seem to support that cosmic rays have a small link on Earth's climate and weather at Antarctica.

Conclusions

The study of fair weather atmospheric electric current density (J_z) and meteorological parameters measured at the Indian Antarctic station Maitri together with the equivalent GCR flux obtained from the American Antarctic station McMurdo for nine years (2001-2009) covering the long deep solar minimum (2007-2009) has been carried out for the first time. The correlations and t-test increase with decreasing solar activity and highest correlation and t-teat are at the low deep solar minimum. This study indicates that the low level clouds increased from 7% to 31% in accordance with the variation GCR flux during extended solar minimum. It indicates that GCR has a small link that can affect the weather and climate at Antarctica.

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