Geomagnetic modulation of clouds effects in the Southern Hemisphere Magnetic Anomaly through lower atmosphere cosmic ray effects

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[1] The study of the physical processes that drive the variability of the Earth's climate system is one of the most fascinating and challenging topics of research today. Perhaps the largest uncertainties in our ability to predict climate change are the cloud formation process and the interaction of clouds with radiation. Here we show that in the southern Pacific Ocean cloud effects on the net radiative flux in the atmosphere are related to the intensity of the Earth's magnetic field through lower atmosphere cosmic ray effects. In the inner region of the Southern Hemisphere Magnetic Anomaly (SHMA) it is observed a cooling effect of approximately 18 W/m^2 while in the outer region it is observed a heating effect of approximately 20 W/m^2. The variability in the inner region of the SHMA of the net radiative flux is correlated to galactic cosmic rays (GCRs) flux observed in Huancayo, Peru (r = 0.73). It is also observed in the correlation map that the correlation increases in the inner region of the SHMA. The geomagnetic modulation of cloud effects in the net radiative flux in the atmosphere in the SHMA is, therefore, unambiguously due to GCRs and/or highly energetic solar proton particles effects. **Citation:** Vieira, L. E. A., and L. A. da Silva (2006), Geomagnetic modulation of clouds effects in the Southern Hemisphere Magnetic Anomaly through lower atmosphere cosmic ray effects, *Geophys. Res. Lett.*, *33*, L14802, doi:10.1029/2006GL026389.

1. Introduction

[2] The solar activity, especially the 11-year cycle, has been observed to correlate with weather and climate anomalies. The level of water availability, local temperatures and precipitation rates are some of the phenomena which have been linked to the 11-year solar cycle of sunspot activity, but until now a plausible mechanism to explain some of these correlations has been missing [e.g., *Carslaw et al.*, 2002, and references therein].

[3] Recently, a correlation between the global average of low cloud cover and the flux of Galactic Cosmic Rays incident in the atmosphere has been observed [*Marsh and Svensmark*, 2000; *Svensmark*, 2000; *Svensmark and Friis Christensen*, 1997] using data derived by the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer*, 1991, 1999; *Schiffer and Rossow*, 1983, 1985] from 1983 to 1994. *Harrison and Stephenson* [2006] using ground based diffuse solar radiation data provide a new evidence for a nonlinear effect of galactic cosmic rays on clouds. They observed that across the UK, on days of high cosmic ray flux (above 3600×10^2 neutron counts h^{-1}) compared with low cosmic ray flux, the chance of an overcast day increases by (19 ± 4) % and the diffuse fraction, the ratio of diffuse to total solar radiation, increases by (2 ± 0.3) %. They also observed that during Forbush events simultaneous decreases occur in the diffuse fraction.

[4] Two mechanisms by which cosmic rays may affect cloud properties are currently under debate [e.g., *Carslaw et al.*, 2002; *Harrison and Carslaw*, 2003, and references therein]. The ion-aerosol clear-air mechanism is based on the assumption that the existence of ions enhances the beginning and growth of aerosol particles in the atmosphere. A fraction of these may eventually grow into cloud condensation nuclei. The ion-aerosol near-cloud mechanism is based on the assumption that the ion concentration is modified by the presence of cloud droplets over the ion concentrations found in particle-free clear air.

[5] *Farrar* [2000] argued that the cloud patters during the period in which it was observed the cloud-cosmic ray correlation was due to a cloud response to the 1986–1987 El Niño Event. The sea surface temperature (SST) is closely linked to the well-know El Niño-Southern Oscillation (ENSO) phenomenon, that is the primary global mode of climate variability in the 2–7 year time frame [*Cane*, 2005; *Mann et al.*, 2005]. El Niño is defined by SST anomalies in the eastern tropical Pacific, while the Southern Oscillation Index (SOI) is a measurement of the atmospheric circulation response in the Pacific-Indian Ocean.

[6] In the eastern Pacific a high variability is observed in atmospheric and oceanic parameters associated to ENSO phenomena. Coincidently, it is observed in the same region a decrease in the intensity of the geomagnetic field, the SHMA. The magnetic anomaly, also known as the South Atlantic Anomaly (SAA), is a region of low intensity magnetic field in the tropical region over the Pacific and Atlantic Oceans and the South America. It is caused by the eccentricity of the geomagnetic dipole and the presence of multipole perturbations that give rise to a series of phenomena in the southern hemisphere, that are important to the physics of the magnetosphere and ionosphere [*Asikainen and Mursula*, 2005; *Lin and Yeh*, 2005; *Pinto and Gonzalez*, 1989a, 1989b]. As a consequence of the temporal evolution of the flow in the Earth's core that sustains the geomagnetic field, it is observed a westward drift (approximately $0.2°$ yr^{-1}) of the SHMA [*Pinto et al.*, 1991]. The GCRs flux depends on the magnetic rigidity, and as expected, in the tropical region it is observed higher GCRs flux in the SHMA. GCRs are responsible for the ionization in the lower atmosphere below 35 km and are the principal source of ionization over the oceans [*Harrison and Carslaw*, 2003].

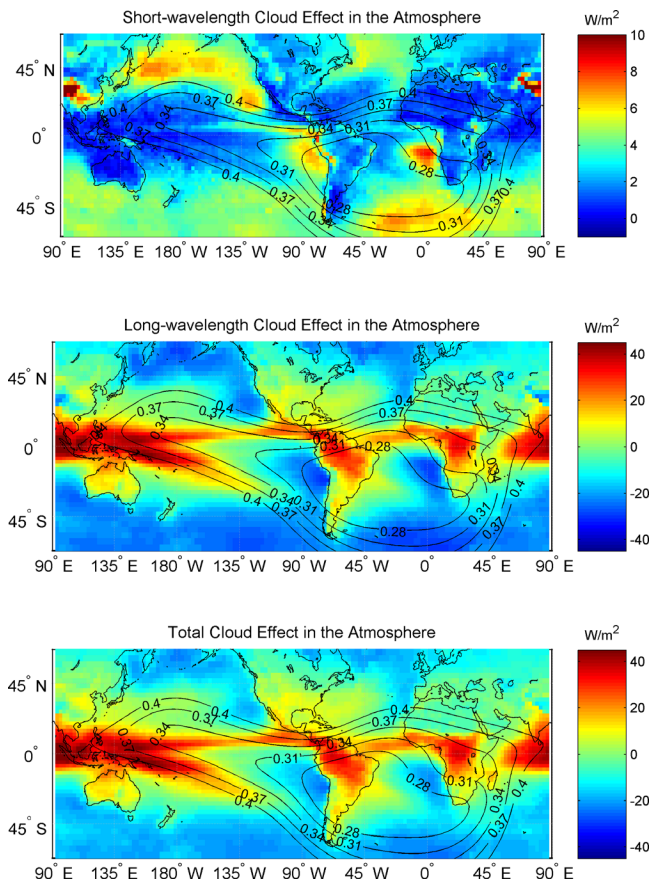[1]Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil.

Figure 1. Annual means of the short-wavelength, long-wavelength and total cloud effects on radiative fluxes in the atmosphere for the period July 1983 to June 2001. The superposed black lines show the iso-intensity contours of the geomagnetic field at ground for year 1990.

[7] Aerosols are thought to cool the planet's surface through increase scattering and cloud cover and re-radiation of solar energy to space. Clouds play an important role in the Earth's radiation budget through trapping outgoing radiation and reflecting incoming radiation [*Allen*, 2003; *Barnett et al.*, 2005]. The principal motivation of this paper is to explain the cloud effects on the radiative flux in the atmosphere in the region of the SHMA in terms of cosmic rays effects and/or highly energetic solar proton events.

2. Variability of Cloud Effects on the Radiative Flux in the SHMA

[8] In order to study the cloud effects on the radiative flux in the atmosphere in the region of SHMA we used the ISCCP D2 data. The variables used in this study are the cloud effects on net flux (the difference of upward and downward fluxes) with positive values indicating energy input or heating and negative values indicating energy loss or cooling. The short-wave fluxes (SW) are for wavelengths from 0.2 to 5 microns and the long-wave fluxes (LW) are for wavelengths from 5 to 200 microns. Even though the wavelength ranges overlap, radiation in SW comes solely from the Sun and in LW comes solely from Earth. *Zhang et*

al. [2004] described the calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP.

[9] Figure 1 shows the annual means of the SW, LW, and Total cloud effects on radiative flux in the atmosphere for the period July/1983 to June/2001. The superposed lines show the iso-intensity contours of the geomagnetic field at surface for year 1990, estimated using the International Geomagnetic Reference Model (IGRF). The low intensity magnetic region over the South America and adjoin oceans is the SHMA. Observe in the middle and bottom panel that the "tongue" in the intensity of the magnetic field is quite coincident with a region of intense negative forcing in the eastern Pacific, which is surrounded by a region of intense positive forcing.

[10] These patterns are due to a reduction in the high and middle cloud amount in the tropical eastern Pacific and an increase in the low cloud amount. The cloud patterns in the eastern Pacific are classically explained as a consequence of the large scale atmospheric circulation and the atmosphere-ocean coupling. The patterns in the Atlantic are more complex and seem to be biased by meteorological systems over the South America. In this study, we analyze just the patterns in the eastern Pacific, which are associated to the ENSO phenomena.

[11] To analyze the cloud effects on the radiative flux in the eastern Pacific we calculated the monthly average of the parameters in six regions of the southern Pacific (40°S to 0°) from January/1984 to December/2000. The regions were defined according to the surface total magnetic field intensity (see Figure 2). We defined the cloud anomalies effects on SW, LW and Total net radiative fluxes as the deviations of monthly mean values of components.

[12] Figure 3 shows from top to bottom the statistical analysis of the cloud effects on SW, LW, and Total net fluxes in the defined regions. Each box has lines at the lower quartile, median, and upper quartile value. The whiskers are lines extending from each end of the box to show the extent of the rest of the data. Outliers are data with values beyond the ends of the whiskers. If there is no data outside the whisker, a cross is placed at the bottom whisker. We performed a t-test to verify the hypothesis that there is no true difference between the means in the inner region of the SHMA (regions 4−6) and the surrounding region (region 3). We concluded that LW and Total net flux in the inner region of the SHMA are significantly different from the surrounding region at p = 0.001. It is observed in the LW and in the Total net fluxes a heating effect in the outer regions of the SHMA (regions 1−3) and a cooling effect in the inner region of the SHMA (regions 4−6). In the SW net flux it is observed a gradual increase in the heating effect toward the inner region of the SHMA.

3. Correlation of the Cloud Effects and the GCRs

[13] To analyze the cosmic ray modulation in the cloud effects we used monthly values of cosmic ray data from Huancayo, Peru, located at 12°S and 75°W at an altitude of 3400 m and a cutoff rigidity equals to 12.92 GeV. We normalize the cosmic ray data to the mean value from 1953 to 2000.

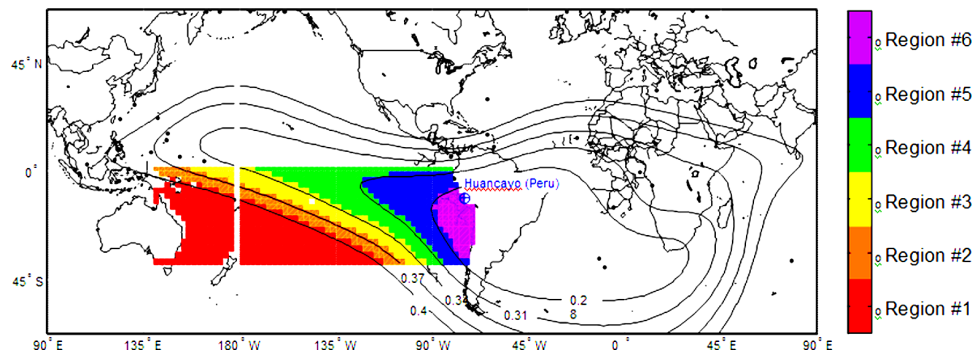[14] Figure 4 shows the anomalies of cloud effects on SW (red lines) and LW (green lines) net flux for each region.

Figure 2. Regions in the southern Pacific defined according to the total magnetic field intensity (B): Region #1 (B > 0.40 Gauss); Region #2 (0.37 < B ≤ 0.40 Gauss); Region #3 (0.34 < B ≤ 0.37 Gauss); Region #4 (0.31 < B ≤ 0.34 Gauss); Region #5 (0.28 < B ≤ 0.31 Gauss); and Region #6 (B ≤ 0.28 Gauss). The regions were defined between 140°E and 70°W. The superposed lines show the iso-intensity contours of the surface geomagnetic field for year 1990. (1 Gauss = 10^5 nT).

Superimposed it is shown the cosmic ray data (blue lines). Note that SW net fluxes anomalies does not follow the behavior of the GCRs, while the LW net fluxes anomalies in Regions 4–6 follow quite well the behavior of cosmic rays.

[15] The correlation map of GCRs and anomalies of LW cloud effects on radiative fluxes is shown in Figure 5. The correlation coefficients, r, are calculated from a 12-month running mean for each region. The correlation coefficients are statistically significant at the level of 99.9%. It is remarkable that the correlation increases as the total magnetic field intensity decrease, that is, the correlation increases in the inner region of the SHMA. The reduction of high and middle cloud amount in the region of the SHMA leads to a reduction in the LW net fluxes in the atmosphere, that is, a reduction in the outgoing radiation trapping. Similar pattern in the LW net flux in the SHMA is also observed in the top of atmosphere data. The reduction

of cloud amount also leads to a decrease of the reflection of the incoming radiation.

4. Discussion

[16] On basis of the analysis present here, the cloud effects on radiative fluxes in the SHMA seem to be explained in terms of cosmic ray effects. The basic explanation is that the cosmic ray energy spectrum is modulated by the geomagnetic field and the ionizing potential of the
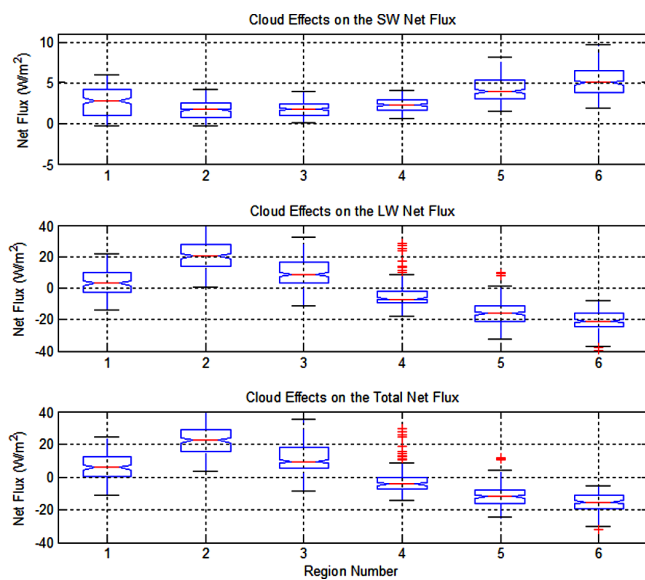

Figure 3. Statistical analysis of the cloud effects on (top) SW, (middle) LW and (bottom) Total Net Fluxes in the defined regions from January/1984 to December/2004.
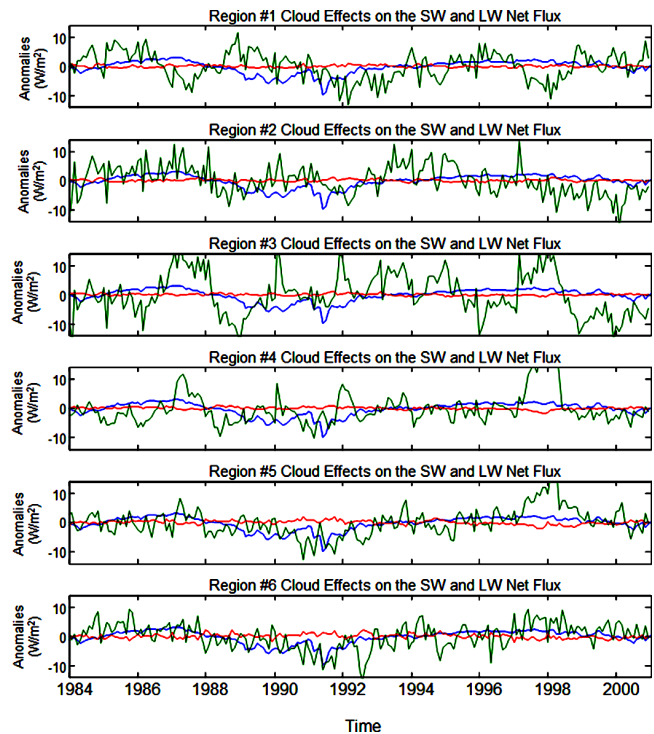

Figure 4. From top to bottom are shown the anomalies in the SW (red lines) and LW (green lines) Net Fluxes for the defined regions. Superposed is shown the cosmic ray data observed at Huancayo (blue lines). Notice that the SW Net Flux does not follow the behavior of the cosmic rays, while LW Net Flux anomalies in Regions 4–6 follow quite well the behavior of cosmic rays.
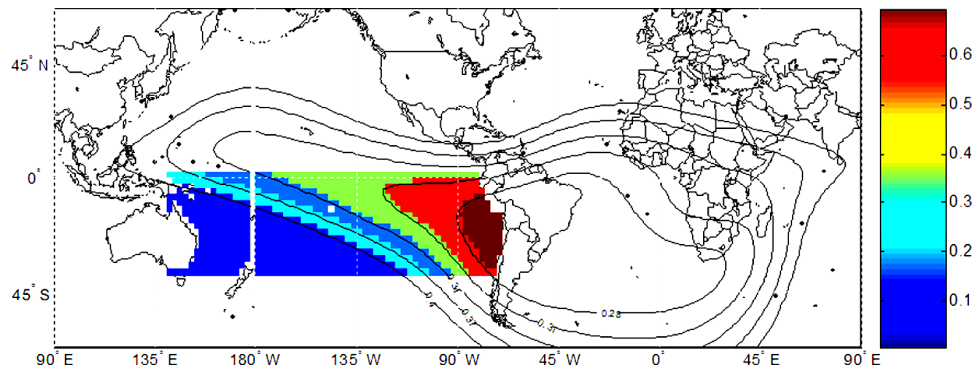
Figure 5. Correlation map of Galactic Cosmic Rays and anomalies of the LW Cloud Effects on Radiative Flux. The correlation coefficients, r, are calculated from a 12-month running mean for each region. The correlation coefficients are statistically significant at the level of 99.9%. Note that the correlation increases as the total magnetic field intensity decreases.

cosmic rays depend in a complicated way on the local atmosphere composition and the energy of the primary and secondary cosmic ray particles. The region where the geomagnetic reduction in cosmic rays is least, the cosmic ray effect on clouds appears greatest.

[17] At this point, it is not possible to establish the physical mechanisms that drive the atmospheric and oceanic variability in the SHMA. However, plausible indirect physical mechanisms have been outlined recent through which ions could influence clouds at natural atmospheric water supersaturations, such as by electric charge effects on aerosol-cloud microphysics. It seems also that, in agreement with the suggestion of *Carslaw et al.* [2002], the marine air in the eastern Pacific might provide a suitable environment for the formation of new particles from ions, as clear air is one of the requirements for the nucleation of new aerosol particles to occur.

[18] A third mechanism to be investigated is the ozone depletion in the upper stratosphere in the SHMA region due to highly energetic protons observed during solar proton events (SPEs) caused by large solar storms. Highly energetic protons associated to SPEs produce ionizations, excitations, dissociations, and dissociative ionization of the background constituents, which lead to the production of odd hydrogen (HOx) and odd nitrogen (NOy). *Jackman et al.* [2005] reported that during the October–November 2003 large solar storms it was observed a short-term ozone depletion of 40% in the Southern Hemisphere polar lower mesosphere, probably a result of the HOx increases. They also observed ozone depletions of 5–8% in the southern polar upper stratosphere lasting days beyond the events, most likely a result of the NOy enhancements. These observations illustrate the substantial impact of solar protons on the polar neutral atmosphere.

[19] The impact of changes in the solar ultra-violet emission on ozone levels in the stratosphere has been considered as a candidate to explain the influence of solar activity on climate [*Haigh*, 2003]. The variations in solar irradiance and ozone levels in the stratosphere may lead to small but significant changes in global weather patterns. Changes in the level of ozone in the stratosphere modify the radiative flux at the top of the atmosphere (known as "radiative forcing") and hence cause changes in the weather and climate patterns, including cloud coverage.

[20] Whilst ozone changes in radiative forcing, energetic particles and cosmic rays have all been suggested to link solar changes with climate, they are by no means alternative explanations. It is quite conceivable that they could all occur, but to different extents in different regions. However because of the geomagnetic influence, the SHMA observations strongly suggest a charged particle effect.

[21] The association of the cloud effects on the radiative fluxes in the atmosphere and the SHMA give rise to a new interpretation of the observed climate changes. As the SHMA is a dynamic feature of the Earth's magnetic field and is drifting westward, it is expected a westward drift of the cloud effects on the radiative flux. The main consequence of the drift of the SHMA could be an increase in the area over the Pacific with an intense negative forcing that could increase the variability of the SST and atmospheric circulation associated to ENSO phenomena. It is also expected to observe a westward drift of meteorological systems over the South America and adjoin oceans, including the Caribbean basin where tropical storms are intensified.

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