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Are changes of the geomagnetic field intensity related to changes of the tropical Pacific sea-level pressure during the last 50 years?

Luis Eduardo Antunes Vieira,[1] Ligia Alves da Silva,[1,2] and Fernando Luís Guarnieri[3]

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[1] The influence of solar variability into the lower atmospheric regions has been suggested on different atmospheric parameters in different time scales. However, a plausible mechanism to explain these observations remains unclear. Although it is widely accepted that the climate change over the past 50 years is attributed to human influence, we present the case that local climate change in the tropical Pacific may be due to changes in the Earth's magnetic field strength. The changes in the tropical Pacific circulation have been observed during the last 50 years, and they are attributed to the increase of the global surface temperature. However, a geomagnetic modulation of the net radiative flux in the southern tropical Pacific was recently suggested. Moreover, comparisons of long-term reconstructions of the Northern Hemisphere surface temperature and solar activity proxies indicated that the existence of a geomagnetic signal in climate data would support a direct link between solar variability and their effects on climate. Here we show that in the tropical Pacific the sea-level pressure, which is a component of the Walker circulation, could be related to the magnetospheric, ionospheric, and upper-atmosphere processes which may propagate downward to the lower atmosphere. Furthermore, we show that the changes in sea-level pressure and the Walker circulation are correlated to the westward drift of the magnetic anomaly. We compare the region averaged monthly values of the sea-level pressure in the tropical Pacific with those of the magnetic field intensity near the surface for the last 50 years. We find that the sea-level pressure in the tropical Pacific is increasing as the magnetic field intensity is decreasing. The correlation coefficient of the sea-level pressure 36-month running means versus the magnetic field intensity is 0.96. We anticipate our investigation to be a starting point for a more sophisticated investigation of the coupling between the space weather processes and lower atmosphere and ocean dynamics.

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1. Introduction

[2] Several observations suggest that the Earth's climate is changing. The most evident manifestation of these changes is the increase of the global surface temperature [*Intergovernmental Panel on Climate Change*, 2007]. The influence of solar variability on climate is an important research topic intending to estimate the natural contributions to climate change. The solar influence on the lower atmospheric regions has been strongly suggested on different atmospheric parameters in different time scales [e.g., *Bond et al.* 2001; *Usoskin et al.* 2005; *Solanki and Krivova*, 2003; *Labitzke and van Loon*, 1995; *Marsh and Svensmark*, 2000; *De Jager and Usoskin*, 2006, *Van Loon et al.*, 2007], but a plausible mechanism to explain these observations remains unclear.

[3] The main solar activity mechanisms proposed to explain these observations are (1) the variability of the total solar irradiance causing a change in the total energy input to the earth's atmosphere and consequent warming/cooling [*Solanki and Krivova*, 2003; *Krivova et al.*, 2003]; (2) the variability of the solar ultraviolet emission and its effects on the stratospheric ozone and thermal structure [*Haigh et al.*, 2005; *Matthes et al.*, 2004; *Cubasch and Voss*, 2000; *Haigh*, 2003; *Lean*, 2001]; (3) the cosmic ray effects on the cloud coverage [*Marsh and Svensmark*, 2000; *Svensmark and FriisChristensen*, 1997; *Carslaw et al.*, 2002; *Harrison and Carslaw*, 2003]; and (4) high-energy particle precipitation effects on mesospheric and stratospheric ozone and thermal structure [*Jackman et al.*, 2005, 2006; *Randall et al.*, 2005, 2006].

[4] The last two mechanisms depend on a combination of solar and geomagnetic modulation [see *Courtillot et al.*,

[1]Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany.
[2]Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil.
[3]Universidade do Vale do Paraíba, São José dos Campos, Brazil.

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2007 and references therein]. The main part of the geomagnetic field originates in the Earth's outer core [see *Olson and Amit*, 2006 and references therein]. According to the dynamo theory the geomagnetic field has a complex structure within the core. However, this dynamo generated field is relatively simple near the surface, consisting of a dipole inclined to the rotation axis that accounts for about 80% of the total and a nondipole part that accounts for the remainder. The dipole moment of Earth's magnetic field has decrease by nearly 9% over the past 150 years according to archeomagnetic measurements [*Olson and Amit*, 2006]. Maps of the geomagnetic field on the core-mantle boundary derived from ground-based and satellite measurements reveal that most of the present episode of dipole moment decrease originates in the southern hemisphere. The expansion of the Southern Hemisphere Magnetic Anomaly (SHMA), also known as South Atlantic Magnetic Anomaly (SAA), a low-intensity region in the geomagnetic field over South America and the adjacent oceans, is associated to the reduction of the dipole moment on the core-mantle boundary. Studies of the average drift rate indicates that the SHMA drifts westward at a rate of approximately 0.28° per year and northward approximately 0.08° per year [*Pinto et al.*, 1991; *Badhwar*, 1997]. As a consequence of the low-intensity magnetic field the precipitation of particles is higher then elsewhere at the same geographical latitudes [*Asikainen and Mursula*, 2005; *Pinto and Gonzalez*, 1989, 1986].

[5] Recently, *Usoskin et al.* [2005] studied variations in the cosmic ray flux entering Earth's atmosphere due to a combination of solar modulation and geomagnetic shielding. The latter could add a long-term trend to the varying solar signal. They compared 1000-year reconstructions of sunspot numbers and cosmic ray flux, derived from cosmogenic isotope dates, with air temperature history in the Northern Hemisphere. They inferred higher temperatures during periods of intense solar activity. In addition, they report that three different statistical tests consistently indicate that the long-term trends in the temperature correlate better with cosmic rays than with sunspot numbers. This correlation suggests that the influence of the geomagnetic field strength, could explain why cosmic ray flux correlates better with the temperature rather than solar activity.

[6] Many interesting and significant atmospheric circulation features, such as the El Niño-Southern Oscillation (ENSO) phenomena, are observed in the equatorial and southern low-latitude regions of the Pacific Ocean [e.g., *Vincent*, 1994 and references therein]. An important aspect of the tropical circulation is the Walker Circulation, which is a large-scale zonal overturning of air across the equatorial Pacific Ocean [*Vecchi and Soden*, 2007; *Julian and Chervin*, 1978]. This circulation is fundamental to climate throughout the globe as its variations are closely linked to those of the ENSO [*Curtis et al.*, 2007].

[7] *Vieira and Da Silva* [2006] have shown that the effects produced by clouds on the net radiative flux over the southern Pacific Ocean are related to the intensity of the Earth's magnetic field. Over the inner region of the SHMA, a cooling effect of approximately 18 W/m^2 is observed, compared to a heating effect of approximately 20 W/m^2 over the outer region. They have also shown that the variability of the net radiative flux is correlated to cosmic ray flux in the inner region of the SHMA. The correlation was also observed to increase in the inner region of the magnetic anomaly. They have proposed that as the SHMA is drifting westward, a westward drift in the cloud coverage and their corresponding effects on the radiative flux will be observed. They suggested that the main consequences of the drift may be an increase in the area over the eastern Pacific with lower cloud coverage, resulting in a reduction of the cloud effects on the net radiative flux, and the corresponding changes in the atmospheric circulation.

[8] Changes on the atmospheric circulation over the Pacific have been attributed to the increase of the surface temperature [e.g., *Vecchi and Soden*, 2007 and references therein]. *Zhang and Song* [2006] recently observed a systematic weakening in the horizontal pressure gradient across the Pacific over the last 50 years. They compared the sea-level pressure (SLP) observed in the low-pressure center of the West Pacific, and the north and south subtropical high-pressure centers in the East Pacific. The reduction in the pressure gradient of the SLP was observed by ship-based measurements and reanalysis data. They argued that the weakening is consistent with simulations from general circulation models, when sea-surface temperatures (SSTs) are uniformly raised. They also argued that it is consistent with reductions of the large-scale subsidence over the eastern Pacific produced in the models.

[9] Our principal motivation is to study the relation of the westward drift of the magnetic anomaly and changes in the atmospheric circulation in the equatorial Pacific. In order to investigate this hypothesis, we based our analysis on the systematic changes in the horizontal pressure gradient across the Pacific over the last 50 years. We assume that the large-scale vertical circulation in the tropics is part of the atmospheric system and any trend in the vertical circulation should therefore accompany trends in other components of the system. The paper is structured as follows. In section 2 we present the data analysis and the results. In section 3 we discuss our results and present our conclusions.

2. Data Analysis and Results

[10] Figure 1 shows the sea-level pressure (SLP) climatology from 1948 to 2005. The SLP climatology was computed using reanalysis data from the National Center of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). It corresponds to the monthly SLP distributions averaged for the period from 1948 to 2008. The Walker circulation, which is an import feature of the tropical circulation [*Liu*, 1997], is seen at the surface as the northeast and southeast trade winds on the two sides of the Equator which transport westward air and water warmed by the incident solar irradiance. This circulation system is driven by the Coriolis force and pressure gradient forces directing from the high-pressure centers, north (HP-N) and south (HP-S) of the equator, to the low-pressure center in the Tropical Western Pacific (TWP) [*Zhang and Song*, 2006]. Surface air converges in the western Pacific to form the wet rising branch of atmospheric circulation, and diverges from the two centers of the subtropical highs to form its dry subsidence branch. The atmospheric circulation is closely related to cloud coverage and precipitation patterns in the southern Pacific region

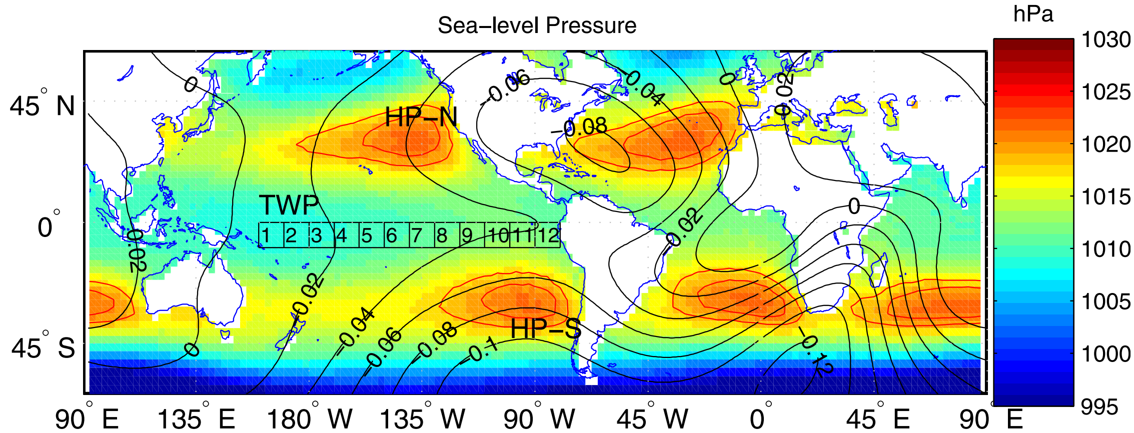

Figure 1. Sea-level pressure climatology from 1948 to 2005. The superimposed black lines show the difference between the geomagnetic field intensity near the surface between the years 1948 and 2005. The 12 regions analyzed in the tropical Pacific are indicated.

[e.g., *Curtis et al.*, 2007]. Two important large-scale features that occur in the Pacific SHMA region are: the Intertropical Convergence Zone (ITCZ), and the South Pacific Convergence Zone (SPCZ).

[11] In this work, we used monthly SLP reanalysis data from 1948 to 2005 in order to examine the hypothesis that changes in the configuration of the geomagnetic field could be associated to changes in the atmospheric circulation. The SLP has been used as a proxy for diagnosing the Walker circulation [e.g., *Trenberth*, 1990]. The reanalysis data set for the Southern Hemisphere (SH) produced large root mean square errors around the true observations when it is compared to the Northern Hemisphere. It occurs because of fewer land-based observations in the SH [see *Kistler et al.*, 2001 for a detailed discussion about the error analysis of the reanalysis data set]. For this reason, we restricted the analysis to the tropical region.

[12] In order to analyze the SLP evolution in the eastern Pacific we calculated the monthly average of the SLP and the magnetic field intensity in 12 regions of 10° by 10° from 160° E to 80° W and from the equator to 10° S (see Figure 1). Figure 2 shows the time series for the regions 5–8 from 1948 to 2005. In order to remove partially the effects of ENSO and volcanic aerosols, as well as seasonal effects, we computed 36-month running means (black lines). The least squares best fit linear regression was performed and the results are shown in the figure and the specific parameters of the fit are given in Table 1. The 12 regions show an increasing trend of the SLP. However, it is noticeable that the increasing rate is not uniform in all regions.

[13] Figure 3 shows the statistical parameters of the SLP over the defined regions. We choose to present the statistical parameters using the Box Plot representation [*McGill et al.*, 1978], which is a graphical approach for examining one or more data sets. Each box has lines at the lower quartile, median, and upper quartile value. The lines extending from each end of the box show the extent of the rest of the data. Points beyond the lines are displayed using the symbol '+'. We note that the mean values of the SLP increase systematically from region 1 to 10 and decrease from region 10 to 12.

[14] Before we compare directly the trends in the SLP and trends in the magnetic field strength, we have to verify the hypothesis that there is no true difference between the means of each pair of regions. If there is no true difference between the means, it could be argued that comparisons between trends in the SLP and any parameter (geophysical or not) could lead to the same result. We performed a *t*-test to verify this hypothesis at the confidence level of 95%. We observed that the regions 3–7 show statistically independent mean values when compared to other regions. Regions 1–2 are in the western Pacific. From this analysis, we note that there is no true difference between these regions, and, consequently, there is not significant gradient between then. It occurs because these regions are in the ascending branch of the Walker Circulation. Regions 8–12 are close to South America cost which affects the easterly winds in the tropical Pacific.

[15] The first and second panels of Figure 4 show the geomagnetic field intensity (B) near the surface (10 km) for years 1940 and 2000 estimated using the *International Geomagnetic Reference Field* (IGRF) model. The bottom panel shows the magnetic field the 12 regions from 1948 to 2005. The westward drift of the magnetic anomaly and its expansion in the southern hemisphere is clearly noticeable. It is also important to note that the magnetic field strength near the surface is changing at different rates across the tropical Pacific. Higher rates are observed in the inner region of the magnetic anomaly, close to South America. For comparison, the difference between the geomagnetic field intensity near the surface between the years 1948 and 2005 is compared to the SLP climatology (see Figure 1). The changes in the magnetic field intensity are observable in both hemispheres. Significant changes over the south pacific, near the high-pressure center, and over North America and western Atlantic are evident.

[16] In the Southern Hemisphere the largest changes in the particle flux in the ionosphere and in the upper and middle atmosphere should occur in the region where the changes in the magnetic field are the largest, generally below 30o S latitude. This region encompasses the anticyclonic system associated with the high-pressure center in the south Pacific (HP-S in Figure 1) which is one of the drivers

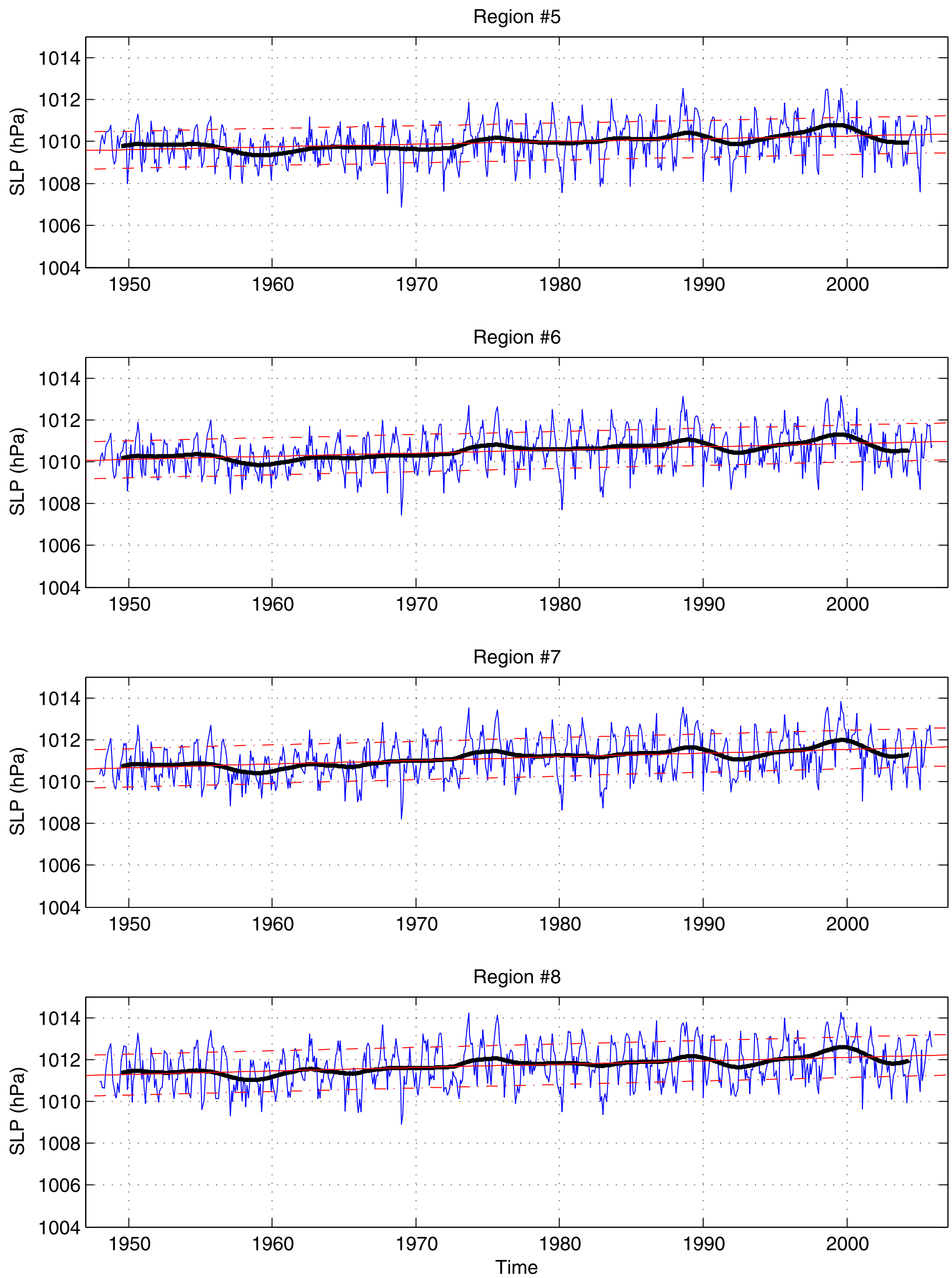

Figure 2. The monthly SLP averages estimated for regions 5–8 (blue lines) and 36-month running means (black lines). The continuous red lines show the linear models, and the dotted lines show the 1-sigma error.

of the easterly winds in the tropical Pacific. If the changes in the magnetic field influence tropospheric climate, we would also expect to detect changes in the SLP and circulation in the regions where the changes in the magnetic field are the largest. Unfortunately, as stated in the above, the quality of the reanalysis data is not as high as in the tropics, and we are thus unable to use this data set to test our hypothesis in the regions of large magnetic field change.

[17] Figure 5a shows a composition of the scatterplots of the SLP versus B for the 12 regions. The black continuous line shows the linear fitting for the whole data set, estimated using the least square fit method. The dotted black lines show the 1-sigma model error. The frequency distribution of the Model Error is shown in the upper right panel. The Model Error is defined as the difference between the raw data and the linear fit and it is a measure of the quality of the linear fit. The distribution follows approximately a Gaussian distribution. Table 2 shows the linear fit parameters estimated for each of the 12 regions from SLP versus B scatterplots.

[18] We also performed a one-way analysis of covariance models. The slopes obtained from the linear models were tested for the individual regions using the Tukey-Kramer significant difference criterion, and we concluded that the

Table 1. Linear Models Estimated for the 12 Regions[a]

Region	Slope	Intercept
1	0.00003027	986.95
2	0.00002314	992.22
3	0.00002538	990.85
4	0.00002978	987.99
5	0.00003551	984.32
6	0.00004134	980.67
7	0.00004767	976.71
8	0.00004548	978.89
9	0.00003743	985.17
10	0.00003280	988.75
11	0.00002698	992.86
12	0.00003750	984.69

[a]SLP = Slope × Time + Intercept. The serial date number represents the whole and fractional number of days from a specific date and time, where the serial number 1 corresponds to 1 Jan 0000 00:00:00. (The year 0000 is merely a reference point and is not intended to be interpreted as a real year in time.)

slopes of the linear fitting for regions 3–9 have no significant difference. Figure 5c shows the composite scatterplot of SLP versus B for regions 3–9. The black lines represent the 36-month running mean. The continuous blue line shows the best linear fit for regions 3–9 data, and the dotted blue lines the 1-sigma error. The time dependence is obtained observing that SLP increases and B decreases from 1948 to 2005. The correlation coefficient estimated for the SLP versus B using raw data and the 36-month running means are equal to 0.71 and 0.96, respectively. The SLP increases as B decreases from 1948 to 2005, which matches the SHMA westward drift.

3. Discussion and Conclusions

[19] We have compared the region averaged monthly values of the sea-level pressure in the tropical Pacific to those of the magnetic field intensity near the surface from 1948 to 2005. We find that the sea-level pressure in the tropical Pacific is increasing as the magnetic anomaly is drifting westward.

[20] The 12 regions analyzed across the tropical Pacific show an increase in the SLP. However, as presented in Table 1, the increase is not uniform. The rate in which the SLP change increases from regions 2 to 7. From region 7 to 11 the rate decreases. This analysis supports the conclusion that the forcing in the tropical Pacific is not uniformly distributed. In agreement with the sea-level pressure climatology, we observed also that the regions 3–7 show statistically independent mean values when compared to other regions (see Figure 3).

[21] The westward drift of the SHMA is caused by changes in the current systems produced by the Earth's core. As the magnetospheric, ionospheric and upper atmospheric processes are controlled by the Earth's magnetic field configuration, any changes to this configuration affects the space weather processes. One can see in the third panel of Figure 4 that the magnetic field estimated across the Pacific is decreasing as the SHMA is drifting westward. It is also noticeable that the magnetic field intensity is decreasing at different rates. The rate increases in the eastern tropical Pacific (inner region of the magnetic anomaly). In the western Pacific, the magnetic field intensity is decreasing at a much lower rate.

[22] Comparing directly changes in both quantities, we find that the sea-level pressure is increasing as the magnetic field is decreasing. This relation is stronger if comparing just regions 3–9. The linear negative correlation found between the sea-level pressure and the magnetic field in the tropical Pacific is valid for the period of time we analyzed. It is known that the Earth's magnetic field has reversed over time, and at least for some period, the magnetic field is quite weak. If there is a negative correlation in changes in the magnetic field and the sea-level pressure, the inescapable conclusion is that the pressure will approach infinity when the magnetic field becomes quite weak, which is impossible. As the magnetic anomaly is a region of low-intensity magnetic field over South America and the adjacent oceans, a future investigation of changes in the atmospheric circulation over the entire region of the magnetic anomaly is necessary to understand if

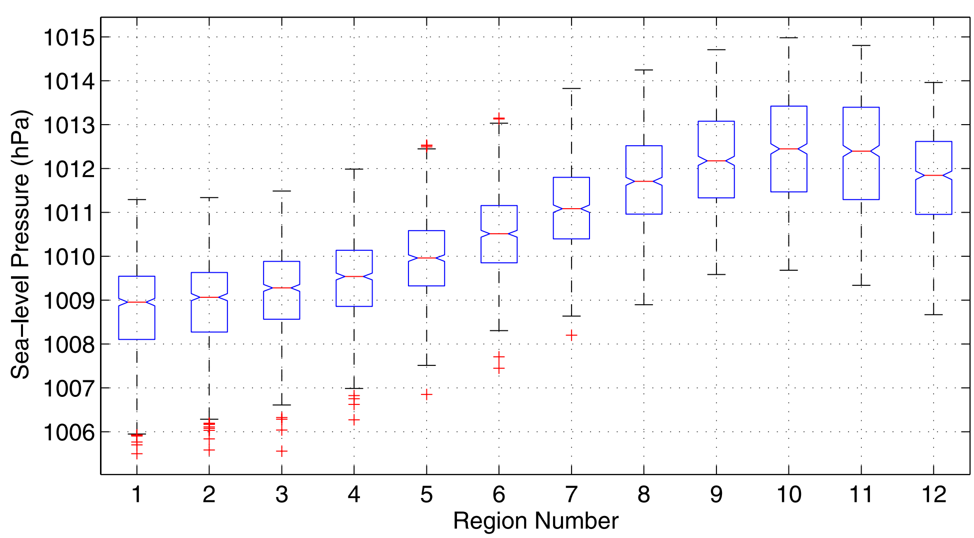

Figure 3. The statistical parameters of the SLP for the defined regions from January/1948 to December/2005.

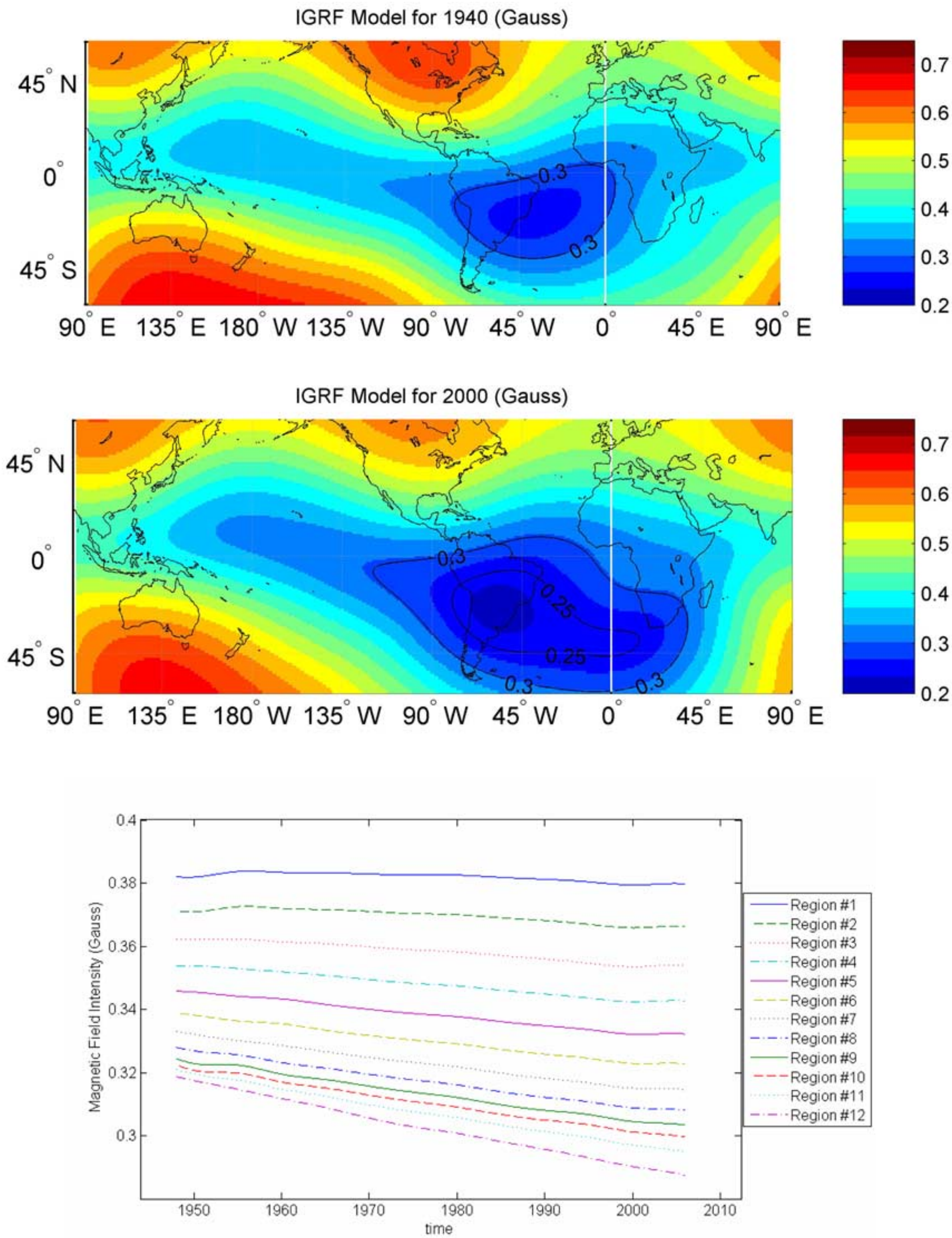

Figure 4. The first and second panels show the magnetic field intensity for years 1940 and 2000 at the surface which was estimated using the International Geomagnetic Reference Field (IGRF) model and the difference of the magnetic field intensity between years 2000 and 1940. The third panel shows the region averaged magnetic field intensity for years 1940–2005 at the surface, estimated using the IGRF model.

physical processes exist that are responsible for the linear correlation found in the tropical Pacific.

[23] The correlation found suggests the possibility that the changes in the magnetosphere, ionosphere and upper atmosphere during last 50 years may have been mapped downward to the middle and lower atmosphere and Pacific Ocean. Hence our analysis arrives at the usual problem facing researchers in this area – how do these processes in the high atmosphere cause an amplification of energy on the order of 10^5 to 10^6 needed to influence the troposphere? From the data analyzed here it is not possible to answer this question and it is still a fundamental issue to be resolved.

[24] However, it is plausible that the observed changes in the SLP to be related to changes in the ozone abundance in

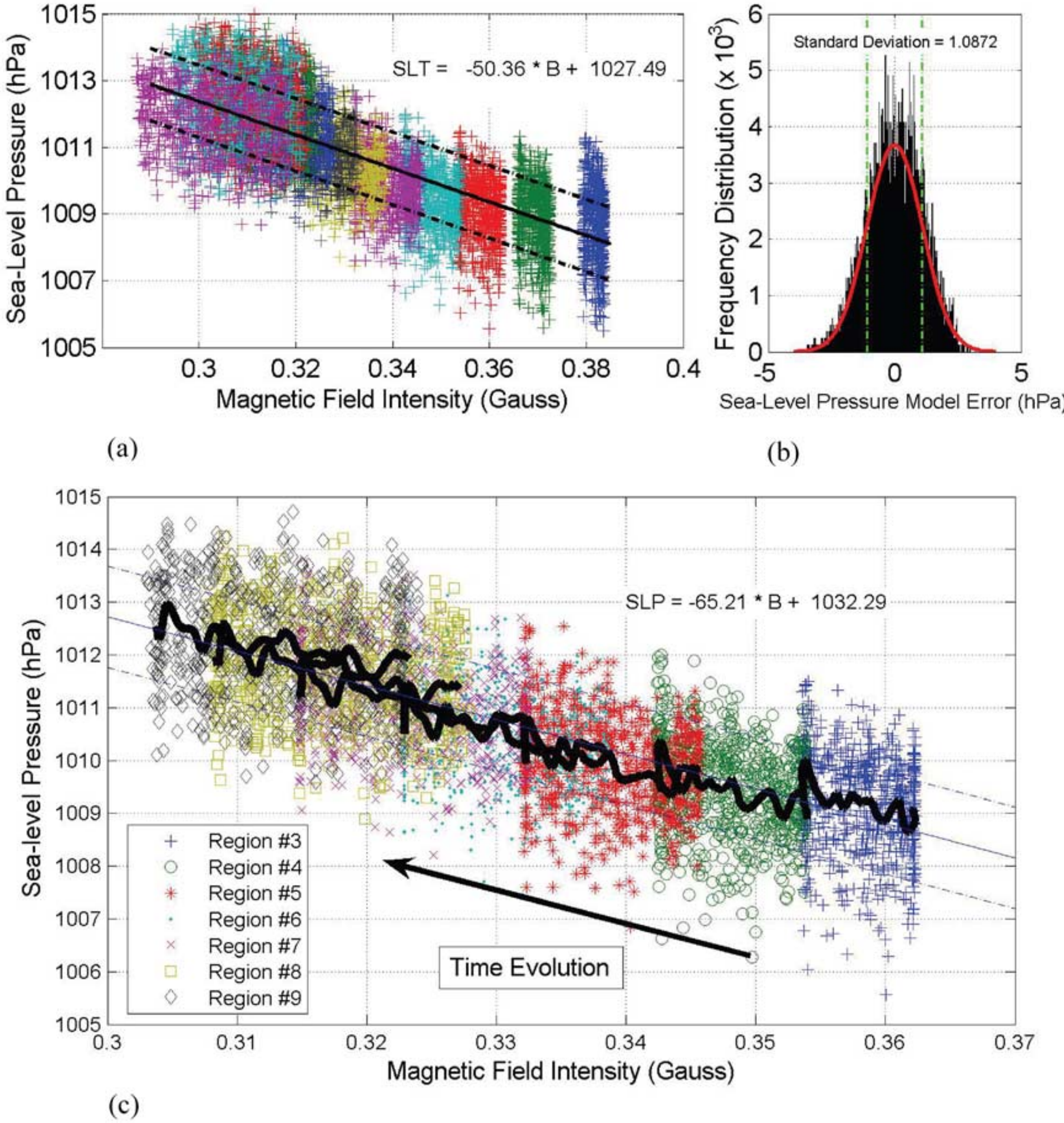

Figure 5. (a) Scatterplot of the sea-level pressure versus the magnetic field intensity. The black line shows the line of best fit for the whole data set. The dotted black lines show the 1-sigma model error. (b) Frequency distribution of the model error. (c) Scatterplot of the sea-level pressure versus the magnetic field intensity for regions 3–9. The continuous blue line shows the line of best fit, and the dotted blue lines show the 1-sigma error. The black lines are the 36-month running means for regions 3–9. The slopes for these regions are not significantly different at the confidence level of 95%.

the magnetic anomaly region through energetic particle precipitation. As ozone absorbs electromagnetic radiation, changes in ozone concentrations alter Earth's radiative balance by modifying both incoming solar radiation and outgoing terrestrial radiation [e.g., *Lean et al.*, 2005]. In this way, ozone controls solar energy deposition in the stratosphere and its variations alter both the vertical temperature gradient in the stratosphere, from the equator to the poles. These changes are assumed to propagate downward through a chain of feedbacks involving thermal and dynamical processes [*Arnold and Robinson*, 2001; *Boville*, 1984; *Haigh*, 2003; *Polvani and Kushner*, 2002].

[25] New analyses show a correlation between the lower stratosphere temperature and the magnetic field configuration in the south hemisphere [L. Da Silva et al., Longitudinal anomaly in the lower stratospheric temperature in southern hemisphere: Effects of particle precipitation in the southern hemisphere magnetic anomaly?, submitted to *Geophysical Research Letters*, 2008]. It was noted that during the austral winter and spring, in the subtropical region (below 30°S), the reduction of the lower stratosphere temperature occurs systematically in the magnetic anomaly area. However, from this analysis it is not possible to distinguish if these effects could be related to particle precipitation in the lower stratosphere or, most probably, in the lower mesosphere/upper stratosphere and than propagating downward. *Pinto et al.* [1990] estimated that the ozone depletion due to electron precipitation at 70–80 km

Table 2. Comparison Between the Linear Models for the 12 Regions[a]

Term		Estimate	Standard Error	T	Prob > |T|
Intercept		1028.2472	1.2706	809.2539	0.0000
Differences	1	22.5560	10.1067	2.2318	0.0257
	2	7.7433	6.1318	1.2628	0.2067
	3	2.1209	4.3729	0.4850	0.6277
	4	−0.7664	3.4751	−0.2206	0.8254
	5	−0.7146	2.9828	−0.2396	0.8107
	6	−0.3281	2.6431	−0.1241	0.9012
	7	0.1041	2.3904	0.0435	0.9653
	8	−1.6458	2.2358	−0.7361	0.4617
	9	−4.5346	2.1545	−2.1047	0.0354
	10	−6.4739	2.0685	−3.1298	0.0018
	11	−9.2430	1.9130	−4.8316	0.0000
	12	−8.8179	1.7290	−5.0999	0.0000
Slope		−51.0703	3.4836	−14.6603	0.0000
Differences	1	−58.8923	26.4806	−2.2240	0.0262
	2	−22.1631	16.5982	−1.3353	0.1818
	3	−8.0627	12.1859	−0.6616	0.5082
	4	−0.6189	9.9269	−0.0623	0.9503
	5	−0.8515	8.7009	−0.0979	0.9220
	6	−1.6684	7.8398	−0.2128	0.8315
	7	−2.2896	7.1744	−0.3191	0.7496
	8	4.1731	6.7649	0.6169	0.5373
	9	14.2861	6.5558	2.1792	0.0293
	10	20.9932	6.3074	3.3283	0.0009
	11	29.3664	5.8131	5.0517	0.0000
	12	25.7277	5.2102	4.9379	0.0000

[a]SLP = Slope × B + Intercept.

in the SHMA region during large geomagnetic storms can be as much as 30%. We speculate that the patterns of the atmospheric circulation, cloud coverage and SST distribution associated with the Walker circulation could be an indicative of the influence of space weather processes in the atmospheric dynamics through changes in the composition and thermal structure.

[26] Summarizing, we investigated the hypothesis that the in the tropical Pacific the sea-level pressure, which is a component of the Walker circulation, could be related to the magnetospheric, ionospheric and upper-atmosphere processes which may propagate downward to the lower atmosphere. We compared the region averaged monthly values of the sea-level pressure in the tropical Pacific to those of the magnetic field intensity near the surface for the last 50 years. We found that the sea-level pressure in the tropical Pacific is increasing as the magnetic field intensity is decreasing. Assuming that trends in the sea-level pressures should accompany trends in other components of the system, we conclude that the westward drift of the magnetic anomaly may be related to changes in the tropical atmospheric circulation.

[27] **Acknowledgments.** The authors would like to acknowledge FAPESP (projects 02/12723-2, 03/11194-9, and 07/11192-9) and CNPq (project 202142/2007-8) for the financial support.

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L. A. da Silva, Instituto Nacional de Pesquisas Espaciais 12227-010 São José dos Campos, Brazil. (dasilva@mps.mpg.de)

F. L. Guarnieri, Universidade do Vale do Paraíba, São José dos Campos, Brazil. (guarnieri@univap.br)

L. E. A. Vieira, Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Strasse, 2, Katlenburg-Lindau, D-37191, Germany. (vieira@mps.mpg.de)