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THE STUDY OF SOLAR-TERRESTRIAL CONNECTIONS IN THE BRAZILIAN MAGNETIC ANOMALY REGION

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The influence of solar-terrestrial connections on climate was investigated at low latitudes near the equator in the Brazilian Magnetic Anomaly region (BMAr). Two kinds of correlations of rainfalls in Brazil were observed: 1. A significant short time scale and long time scale correlation takes place between index of geomagnetic activity Kp and rainfall level in the state of São Paulo. The effect of magnetic disturbances on climate is explained in terms of precipitation of charged particles ionizing the atmosphere; 2. The level of rainfalls in Fortaleza show correlation-anticorrelation with the 11, 22 year variations of sunspot numbers during the period of 1860-1990. The different modes of correlations, possibly, could be explained by the fact that one region (São Paulo) is connected with magnetic lines occupied by inner belt trapped particles and the other one is connected with the empty magnetic lines (Fortaleza). The correlations between the level of rainfalls and cosmic ray flux during Forbush decreases or solar flare flux were not found.

Key words: Rainfalls; Geomagnetic disturbance; Sunspot numbers.

ESTUDO DAS RELAÇÕES SOL-TERRA NA REGIÃO DA ANOMALIA MAGNÉTICA BRASILEIRA - *A influência da conexão sol-terra sobre o clima foi investigada para baixas latitudes, na região da Anomalia Magnética Brasileira (BMAr), próxima ao Equador. Foram encontradas duas formas de correlação com chuvas sobre o Brasil: 1. Uma correlação de curta e longa escala aparece entre o índice de atividade geomagnética* K_p *e nível de chuva no estado de São Paulo. O efeito dos distúrbios magnéticos sobre o clima é explicado em termos de precipitação de particulas carregadas que ionizam a atmosfera. 2. As chuvas em Fortaleza mostram correlação - anticorrelação com variações dos números de manchas solares (11 e 22 anos), durante o periodo de 1860-1990. Os diferentes modos de correlação são explicados pela conexão das regiões com linhas de campo magnético ocupadas por partículas aprisionadas no cinturão interno (São Paulo) e por linhas de campo magnético vazias (Fortaleza). Correlações de curtos periodos entre chuvas e a intensidade de raios cósmicos durante"Forbush decreases" ou erupções solares não foram encontradas.*

Palavras-chave: *Chuvas; Distúrbio magnético; Números de manchas solares.*

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INTRODUCTION

Investigations performed during the last few years have shown that solar activity affects the climate. The physical mechanisms of this influence are beginning to be formulated (Herman & Goldberg, 1986; Tinsley & Deen, 1991; Roederer, 1993). The connection of solar activity with meteorological parameters at high and middle latitudes is well known. In Tinsley & Deen (1991), the influence of solar activity is explained through the decrease of the MeV-GeV cosmic ray flux or appearance of solar flare fluxes ionizing the atmosphere. In its turn, the ionization can affect the nucleation of ice crystals in high-level clouds, and so on. This mechanism can work efficiently at high latitudes, because, in this region, cosmic ray particles with energy up to 1 GeV penetrate more easily due to the very low cut off rigidity.

The study of climate effects related to solar-terrestrial connections near the poles is extremely complex, because the polar areas are known to be "the kitchen of climate" and it is difficult to unravel the influence of cosmic ray particles on such a highly non-linear, chaotic and multiparameter system.

In the BMAr we have a more simple case for investigation of space-terrestrial connections. Here, near equator, the winds and clouds from the south pole are rarest. And here, above our heads, at the altitude of only 300 km, we have large fluxes of high energy protons and electrons trapped in the inner radiation belt (Galper et al., 1983; Voronov et al., 1986). Magnetic disturbances of sufficiently high amplitude can produce precipitation of these particles in the atmosphere. When dumped into the atmosphere, these particles produce a significant ionization that affects the conductivity, electric fields, and chemistry of the atmosphere (Baker et al., 1986).

For example, Campinas (23° **S**, 47° **W**) is situated at the south foot of the magnetic line L=1.16 at B=0.23 gauss. Maximum altitude of this line is ~ 400 km. The north foot of the line crosses the Earth surface at B=0.32 gauss. At the top of the magnetic field line L=1.16, there exists the above mentioned energetic electron flux of ~ 1 $cm^{-2}.s^{-1}.sr^{-1}$ with energy > 100 MeV and proton flux of ~ 300 $cm^{-2}.\ s^{-1}.\ sr^{-1}$ with energy >400 MeV. During magnetic disturbances the trapped particles presumably will precipitate to the south foot of the line where the magnitude of magnetic field is smaller. So it is appropriate to study a connection between the level of rainfalls and magnetic disturbances exactly here where one can expect precipitating particles to come into the atmosphere.

The particles can reach the deep layers of the atmosphere: < 20 km (electrons) and < 10 km (protons) which is the meteorologically sensed area. The energy contained in these components is 0.1 GeV $cm^{-2}.s^{-1}.sr^{-1}$ (electrons) and 100 GeV $cm^{-2}.s^{-1}.sr^{-1}$ (protons). Energy deposition in the inner belt proton fluxes is 1000 times higher than in the cosmic rays and solar flare fluxes on equatorial region. So their influence can be more pronounced than solar and cosmic rays near the Equator.

If precipitating particles have an influence on climate, we can expect to observe short and long time scale correlations in the level of rainfalls with the geomagnetic activity.

EXPERIMENTAL RESULTS

Fig. 1 shows the time dependence of K_p -index and level of rain in Campinas and in Ubajara (3° **S**, 41° **W**) during 1986. K_p-index is an indication of the geomagnetic disturbance level. One can see that with **a delay of 1-10 days**, almost every significant(>3.0) increase in K_p-index is accompanied by an increase in the rainfall level. The effect is especially seen at the time of the great geomagnetic storm of February 8 and 9, when the greatest level of rain in 1986 was registered nine days after the maximum of the storm. In Fig. 1, even the coincidence of the fine structure of K_p and rainfall variations is seen for some time intervals.

The year of 1986 corresponds to the minimum of 21/22nd Solar cycle and is the quietest one of the past years with the small numbers of magnetic storms. Consequently, the correlation is especially pronounced because there is no overlapping of disturbed periods.

If the connection of K_p-rainfall exists, is it carried out through the precipitation of radiation belt particles ? We observed some evidences of the process during the storm of February, 1986.

The measurements, performed on board of COSMOS-1686 satellite (altitude 350 km, inclination 51.6 degrees) showed that the large flux of relativistic electrons existing in the inner radiation belt was really subjected to significant variations during magnetic disturbances and precipitated in the atmosphere with several days delay.

The injection of subrelativistic electrons into the BMAr was observed during the magnetic storm of February, 1986 (Martin et al., 1995). Fast radial diffusion

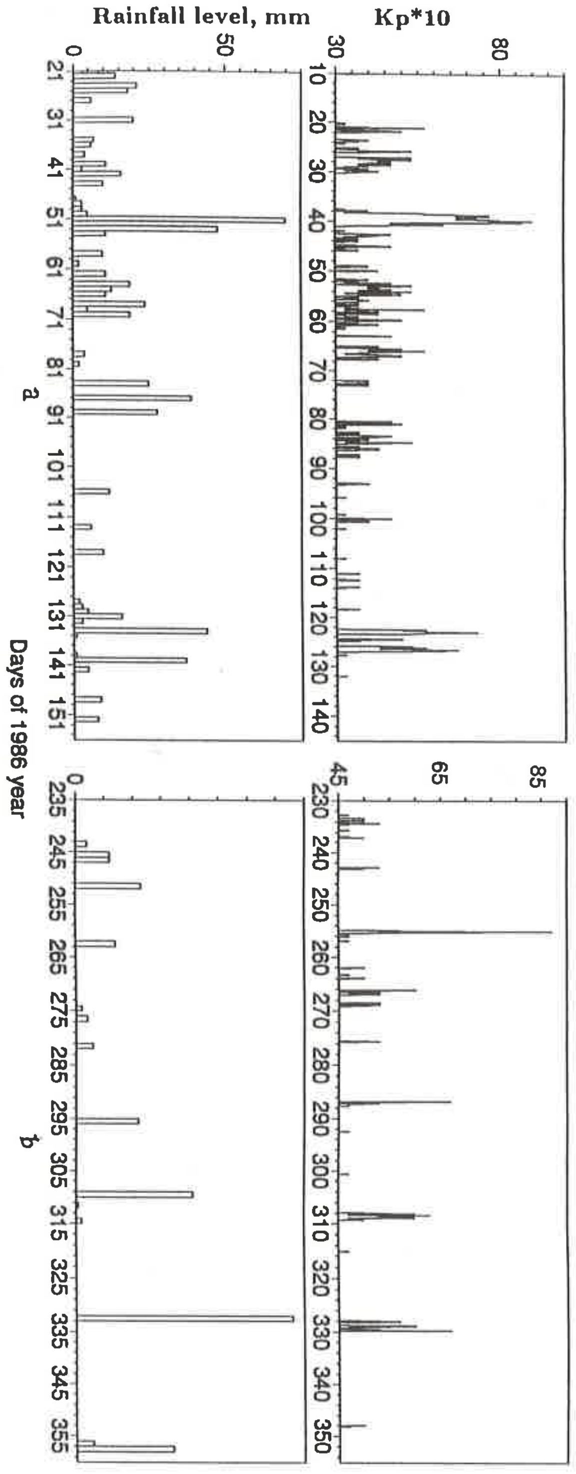

Figure 1 - Comparison of K_p and level of rainfall in
a) Campinas and
b) Ubajara during 1986.

Figura 1 *- Comparação entre* K_p *e o nível de chuva durante o ano de 1986 em:*
a) *Campinas e*
b) *Ubajara.*

pushed the injected flux into the magnetosphere to low *L*-shells of the BMAr during two weeks of recovery phase of the storm (see Fig. 3 in Martin et al., 1995). After this time, the new electron radiation belt with the greater flux was created on L=1.3 - 2.0. The electron fluxes of old inner radiation belt were thrown down into the atmosphere during several days of March 18-21, 1986. The greatest rainfall of the 1986 year was observed in March 19, 1986 at the meteostation of Campinas.

After the series of solar flares of March 19 - 22, 1991 in the regions N.6545 and 6555 (Solar Geoph. Data, 1991) the great magnitude of magnetic disturbances associated with the flares were registered by ground level magnetometers and great fluxes of the energetic solar flare particles were injected into magnetosphere. The São Paulo meteostation E3-070, on the March 22, 1991 showed the greatest rainfall of the year that was one of the 3 greatest rainfalls observed in the last 10 years.

These two examples of delayed coincidences of particle precipitation and rainfalls do not prove the existence of the connection, but they point out the possibility of the existence of the effect.

The relationship of K_p-rainfalls was investigated also on the long time scale base during the period of 1940-1990 using rainfall data from some São Paulo stations.

In Figs. 2 (1940-1964) and 3 (1973-1990), the long term variations of annual averaged rainfalls in Campinas, in meteostation D9-19 (mostly in the west part of the state of São Paulo, farthest from the ocean), the K_p-index and sunspot numbers are presented. One can see the clear double

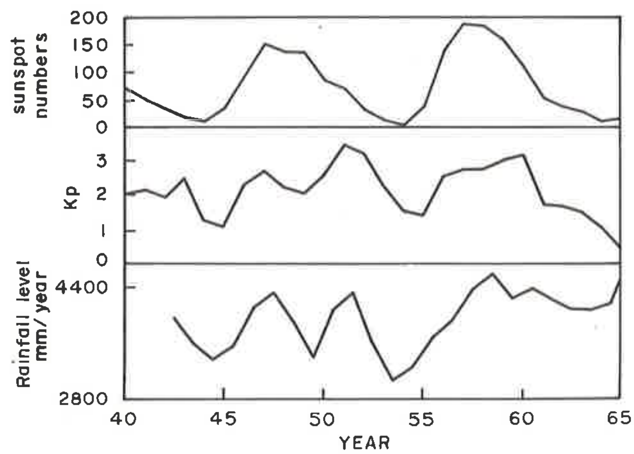

Figure 2 - The variations of rainfalls (Campinas), K_p-index and sunspot numbers in 1940-1964.

Figura 2 *- Variações de chuvas (Campinas),* K_p *índice e número de manchas solares no periodo de 1940-1964.*

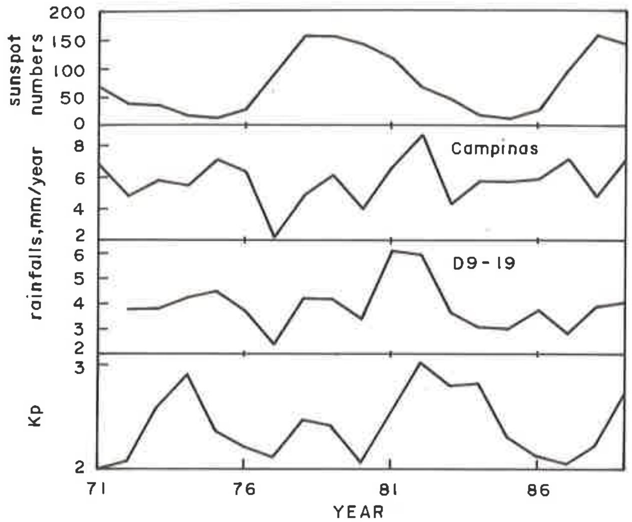

Figure 3 - The variations of rainfalls (Campinas, one of SP meteostations), K_p-index and sunspot numbers in 1971-1990.

Figura 3 - *Variações de chuvas (Campinas, estação meteorológica D9-19 do Estado de São Paulo), K_p índice e número de manchas solares no período de 1971 a 1990.*

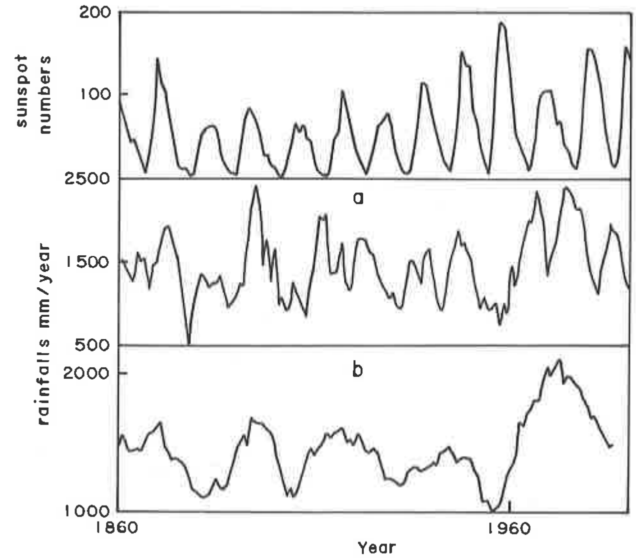

Figure 4 - The 3 **(a)** and 11 **(b)** year running averaged rainfalls in Fortaleza and sunspot numbers beginning from 1860 up to 1990.

Figura 4 - *Precipitações médias contínuas de chuva em Fortaleza (CE), em períodos de 3 anos **(a)** e de 11 anos **(b)** e número de manchas solares, começando de 1860 até 1990.*

peak structure of rainfall variations similar to the K_p-index variations. The rainfall variations better correspond to K_p-index variations than to sunspot numbers at the São Paulo meteostations. Only during the 20 solar cycle (1964 - 1975), weakest of the last 6 cycles, a correlation of rainfalls and K_p-index is absent. The clear anticorrelation between rainfalls and sunspot numbers is observed in most of Brazil, during the 20 solar cycle.

Our observations show that the K_p-rainfall correlation is more pronounced in regions connected with magnetic lines occupied by trapped particles.

For example, in Fortaleza (4° **S**, 39° **W**), situated on the L=1.054, which is an empty magnetic tube, one can see the other kind of correlation (Fig. 4). The positive correlation of sunspot numbers and rainfalls (Fig. 4a) was observed during the 1860-1900 years (3 solar cycles: 11, 12, and 13 cycles) and 1933-1954 years (2 cycles: 17 and 18 cycles). The negative correlation was observed during 1900-1933 years (3 cycles: 14, 15 and 16) and 1954-1990 years (3 cycles: 19, 20, and 21 cycles). As far as sunspot numbers mainly anticorrelate with the cosmic ray flux, a negative correlation of sunspot numbers with rainfalls could be interpreted as a positive correlation of the level of rainfalls with the cosmic ray flux. The positive and negative phases of the correlation interchange several times during the long time interval from 1860 up to 1990.

Such an effect was observed long ago in the North America (King, 1975): at high northern latitudes (70 - 80 deg) the 11-year solar cycle was positively correlated with the annual rainfall level; at latitudes between 60 and 70 deg **N** the opposite behavior occurred while at still lower latitudes (50 - 60 deg) a negative correlation existed before about 1915 A.D. and positive one after that.

Some climate events have a 22-year periodicity, which is connected somehow with the 22-year solar magnetic cycle. The strongest droughts in High Plains (USA) follow the 22-year cycle of sunspot numbers, according to Roberts (1973). The regularity was used for forecasting the droughts of 1974-77. We investigated the 22-year periodicity of the level of rainfalls in Fortaleza and São Paulo regions. After a 11-year running average one can see the 22-year periodicity of level of rainfalls in Fig. 4b. The phenomenon is clearly observed in Fortaleza during 5 periods (22-years) from 1860 to 1990. During the 11-16 solar cycles (from 1860 until 1930), the maxima of rainfalls correspond to the maxima of sunspot numbers of odd solar cycles 11, 13, 15 and minima of rainfalls correspond to maxima of 12, 14, 16 solar cycles. During the 17 solar cycle the phase of the 22-

year periodicity is changed to the opposite and the sunspot number maxima of odd cycles 19 and 21 correspond to the minima of rainfall.

The effect is absent (excluding years 1957-1977) in rainfalls of SP stations.

Double peak structures of rainfall variations and K_p-rainfall correlation were not observed in Fortaleza.

There must exist a mechanism of solar-terrestrial connection which corresponds to long term variations. Now, it is known that these connections sometimes are carried out by solar or cosmic rays at the middle and high latitudes (Tinsley & Deen, 1991). In that case, we could look for the influence of Forbush decreases of cosmic rays and the high energy solar flare particles with a higher rigidity than the cutoff rigidity on the level of rain in BMAr.

We selected 17 greatest Forbush decreases from 1956-1985, which coincided with the rainy season in the state of São Paulo (January-April, October-December). The amplitudes of Forbush decreases observed by Washington neutron monitor (R=6.7 GV) in units of count rate per hour (the amplitudes more than 100 counts/h were selected only) are presented in Tab. 1 (Tinsley & Deen, 1991). In the left column of Tab. 1 there are the key days when Forbush decreases began, according to Tinsley & Deen (1991). Also, in Tab. 1 we put the relative amplitudes of Forbush decreases observed by Huancayo monitor (R=13 GV) (Pyle, 1994) at the same days: it is seen that the amplitudes are mostly > 3%.

We performed the method of superposed epochs for rainfalls of 15 meteostations of the state of São Paulo, plotting the 20 days before and 20 days after key days of the above mentioned Forbush decreases. Statistically proved Forbush effect does not appear in the rainfall data of the region.

It is known that the energies of the solar flare protons are in the range of 1 - 100 MeV and their spectra are almost exponential with the characteristic energy ~30 MeV. But several of the great solar flares such as February 23, 1956; October 6, 1960; August 4, 1972; October 19-24, 1989; February 16, 1984 and some others have the rigid spectra with significant fluxes of > 10 GV protons.

key days	Wash. (1/h)	Huanc. (%)
09.11.56	120	3
22.01.57	257	3.2
10.03.57	120	-
21.10.57	130	5.2
25.03.58	119	5.3
31.03.60	152	4.4
06.10.60	110	3.5
13.11.60	505	4.7
15.11.60	256	2
29.10.68	164	5.1
24.03.69	106	4.8
07.11.70	101	3.4
31.10.72	118	3.2
15.02.78	221	-
08.03.78	125	3.3
06.02.80	99	-
04.02.83	134	3

Table 1 - Forbush decreases observed in Washington and Huancayo during the same days.
Tabela 1 *- Decréscimos de Forbush observados em Washington e Huancayo durante os mesmos dias.*

Date	Amplitude (%)
28.02.42	-
23.02.56	-
28.01.67	16.8
25.02.69	11.0
22.11.77	25.3
12.10.81	11.4
07.12.82	19.2
16.02.84	50.0
19.10.89	51.6
22.10.89	18.8
24.10.89	90.1
15.01.91	16.4

Table 2 - Amplitudes of ground level events.
Tabela 2 *- Amplitudes dos eventos observados na superfície terrestre.*

To find out the solar flare events with high energy proton fluxes we used the data of the neutron monitor of south hemisphere Sanae which registers the solar cosmic ray ground level events (GLE) with the rigidity of 2-5 GV, from 1966 until now (Stoker et al., 1993). We selected only those GLE which have amplitudes more than 10 % and saw that all above mentioned solar flares are present in Tab. 2.

We used the data concerning only rainy months: January-March and October-December and added to it 2 well known flares with the hard proton spectra of February 28, 1942 and February 23, 1956. Thus, the whole list of solar flare events includes 12 flares in which we could expect large flux of > 10 GV protons. We researched the possible influence of solar flare protons, using the method of superposed epochs for rainfall level of 15 meteostations of the state of São Paulo, plotting the 20 days before and 20 days after key days of selected flares shown in Tab. 2. Middlesquare deviation of the result is equal to ~ 50 %.

Any effect that overcomes the error limits was not observed here. We performed the same analysis for 4 great flares with the increase of > 25 %: November 22, 1977; February 16, 1984; October 19, 1989; October 24, 1989 and also without statistically proved results. We also used data of the equatorial neutron monitor Huancayo. The Huancayo Neutron Monitor responds to galactic and solar cosmic ray nuclei with rigidity >13 GV (vertical incidence). The monitor has registered increases from only two solar particle events from Tab. 2. These were February 23, 1956 and September 29, 1989, with increases of 20 % and 30 % (est.) respectively. No other increases have been detected. These two solar flares did not show any relationship with the level of rainfalls.

Probably, the flare proton fluxes are not significant to produce enough ionization to stimulate rainfalls near the Equator and the mechanism of sun-rains connections occurs through the interactions of solar wind plasma with the ionosphere.

SUMMARY

This study found significant short term correlations between index of geomagnetic activity K_p and rainfalls in Campinas, during 1986. An effect of magnetic disturbances on climate parameters can be, possibly, explained in terms of precipitation of charged particles ionizing the atmosphere. Energy deposition in the inner belt particle fluxes is 1000 times higher than in the cosmic rays and solar flare fluxes at the low latitudes. Several samples show the probability of particle precipitation-rainfall relationships.

Two kinds of long term correlations of rainfalls exist in Brazil: the rainfalls in São Paulo region show better long term correlation with K_p-index than with sunspot numbers during the 18, 19 and 21 solar cycles; the rainfalls in Fortaleza show correlation-anticorrelation with the 11-, 22-year variations of sunspot numbers during the 1860-1990 period.

The existence of positive long term correlation of rainfalls with cosmic rays (or negative one with sunspot numbers) demonstrates the influence of cosmic rays to the climate. But the mechanism of positive correlation of rains with sunspot numbers can not be explained directly by solar flare proton effects on the atmosphere. This mechanism must be researched further. Also, the reason for the change of phase of correlation remains unknown.

The short term variations of rains were researched for data from 15 meteostations of the state of São Paulo during 12 solar flares with rigid proton spectra and during 17 greatest Forbush decreases in the equatorial region. The effects were not found to be statistically significant.

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