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Evidence for cosmic ray modulation in temperature records from the South Atlantic Magnetic Anomaly region

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Abstract. Possible direct or indirect climatic effects related to solar variability and El Niño–Southern Oscillation (ENSO) were investigated in the southern Brazil region by means of the annual mean temperatures from four weather stations 2 degrees of latitude apart over the South Atlantic Magnetic Anomaly (SAMA) region. Four maximum temperature peaks are evident at all stations in 1940, 1958, 1977 and 2002. A spectral analysis indicates the occurrence of periodicities between 2 and 7 yr, most likely associated with ENSO, and periodicities of approximately 11 and 22 yr, normally associated with solar variability. Cross-wavelet analysis indicated that the signal associated with the 22 yr solar magnetic cycle was more persistent in the last decades, while the 11 yr sunspot cycle and ENSO periodicities were intermittent. Phase-angle analysis revealed that temperature variations and the 22 yr solar cycle were in anti-phase near the SAMA center. Results show an indirect indication of possible relationships between the variability of galactic cosmic rays and climate change on a regional scale.

Keywords. History of geophysics (solar–planetary relationships)

1 Introduction

Global warming and other climatic effects caused by anthropic action have been a subject of concern among investigators in the area of environmental sciences. However, geoscientists who study the evolution of the Earth know that in, its giga-year history, the planet has gone through several catastrophic episodes that brought drastic changes to the environment and affected all types of existing life. Therefore, it is certainly important that natural processes that may affect the climate are also investigated so that their effects can be evaluated.

This investigation studies the effects of solar activity as one of the possible natural climatic forcings. A possible correlation between sunspots and climatic variables has been proposed by several authors for over a century (see review article by Gray et al., 2010). However, this relation between solar activity and climate has been difficult to determine because the solar energy flux variation during a solar cycle is very small and insufficient to give rise to significant climate variations (Dickinson, 1975). Nevertheless, there were observational results that would favor the solar activity–climate correlation (e.g., Wilcox, 1975; Lassen and Friis-Christensen, 1995). An alternative and consistent explanation was proposed by Svensmark and Friis-Christensen (1997) and Svensmark (2007) by introducing the intermediate action of galactic cosmic rays (GCRs).

Solar activity variation has been historically associated with sunspot numbers, but other solar properties, such as the heliomagnetic field, also vary during solar cycles. The high solar magnetic field during solar maxima reduces the incidence of GCRs on the Earth to a minimum, whereas the maximum incidence would correspond to solar minima.

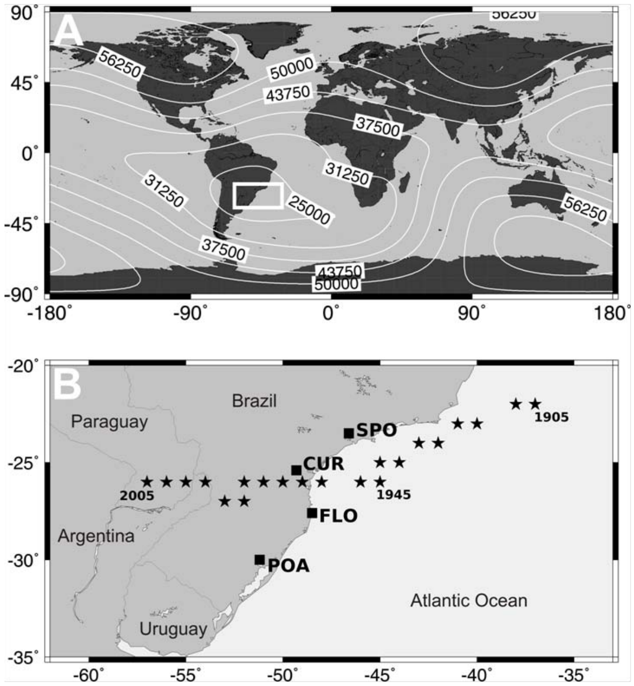

Fig. 1. (A) Global geomagnetic field intensity map computed from IGRF data for 2005. The study area is bounded by the white rectangle. **(B)** Enlarged map of the study area showing the locations of the weather stations (SPO, CUR, FLO and POA) and the SAMA center drift from 1905 to 2005 (black stars), computed every 5 yr.

Through multiple interactions, GCR high-energy particles create a large number of ions that, when associated with aerosols, can favor condensation and the formation of low-altitude clouds. Therefore, cloud formation and their consequence on climatic variables can depend on the Sun's magnetic field, but the Earth's magnetic field is also variable and can reduce the GCR incidence. The simultaneous action of the heliomagnetic and the geomagnetic fields has been one of the difficulties in determining clear evidence of the effect of solar activity on climate variation (Dorman, 2012; Lockwood, 2012). Furthermore, there are many studies based on climatic and proxy data analysis that are in agreement with the GCR–climate relationship (e.g., Miyahara et al., 2008; Souza Echer et al., 2012; Svensmark, 2012) and other studies that disagree with this relationship (e.g., Wagner et al., 2001; Overholt et al., 2009; Erlykin and Wolfendale, 2011). Experimental results indicate that GCRs may play an important role in climate modulation (Enghoff et al., 2011; Kirkby et al., 2011; Pedersen et al., 2012).

In this research, we investigated the effect of solar activity on climate variation in the South Atlantic Magnetic Anomaly (SAMA) region where the geomagnetic field is exceptionally low and, therefore, where the influence of Earth's magnetic field on the GCR flux is much smaller and continuously decreasing (Smart and Shea, 2009). The SAMA time evolution has been investigated by Hartman and Pacca (2009) over the past few centuries, and they show that the anomaly center approached Rio de Janeiro near 1900 and then drifted southwest until reaching the coast of the state of Paraná near 1945, when the trajectory changed again to a westward drift. During the past century, the SAMA center has passed close to several Brazilian weather stations. Analyses of temperature time series from four Brazilian weather stations when the SAMA center was close to them will be shown.

Table 1. Information on the weather stations in this study.

Station	Code	Coordinates	Altitude
SPO	83 781	23.5° S, 46.6° W	792 m
CUR	83 842	25.4° S, 49.3° W	924 m
FLO	83 897	27.6° S, 48.5° W	2 m
POA	83 967	30° S, 51.2° W	47 m

2 Study area, data sets and methodology of analysis

Some authors relate cosmic rays to climate at specific regions of the planet (e.g., Pudovkin et al., 1997; Vieira and da Silva, 2006; Harrison and Ambaum, 2009). Spatially, GCR flux varies according to the geomagnetic field direction and intensity, with higher fluxes in the polar regions and lower fluxes at the Equator. Moreover, regions with weak geomagnetic intensities, such as the South Atlantic Magnetic Anomaly (SAMA), enable higher fluxes of particles (König et al., 1978; Smart and Shea, 2009). Currently, the SAMA covers part of the South Atlantic Ocean and the South American continent. The region has been strongly influenced by the SAMA since the early twentieth century. This geomagnetic anomaly ($<$ 25 000 nT) now covers half of South America and part of the South Atlantic (Fig. 1a). Its center moved from the Atlantic Ocean to Paraguay between 1905 and 2005, as shown in Fig. 1b, which also shows the locations of the four weather stations. Three stations (CUR, FLO and POA) are maintained by the Brazilian National Institute of Meteorology and one (SPO) by the University of São Paulo. The details of these stations are presented in Table 1.

The time evolution of geomagnetic field intensities, calculated from the International Geomagnetic Reference Field (IGRF), at each weather station location is shown in Fig. 2. The figure indicates that the geomagnetic intensity has been continuously decreasing. The intensities were very similar for all positions for the period between 1960 and 1990. Figure 2 also shows the distance between the weather stations and the SAMA center as a function of time. The minimum distance occurred in 1940 for SPO ($\sim$ 230 km), in 1960 for FLO ($\sim$ 165 km), in 1965 for CUR ($\sim$ 70 km), and in 1985 for POA ($\sim$ 340 km). The CUR weather station was the closest to the SAMA, followed by FLO and SPO.

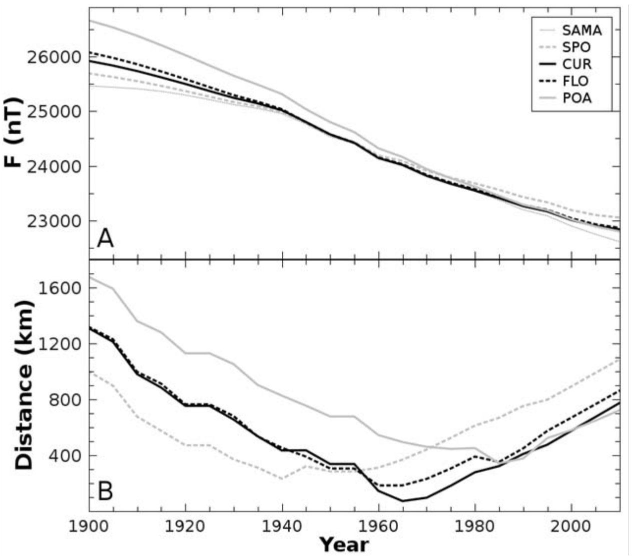

Fig. 2. (A) Time evolution of the geomagnetic field intensity at 5 yr resolution for the meteorological station positions and the SAMA center from 1900 to 2010. **(B)** Distance between each station and the SAMA center between 1900 and 2010.

Southern Brazil has a subtropical climate, with temperature and rainfall strongly affected by El Niño–Southern Oscillation (ENSO; Grimm et al., 2000; Barros et al., 2002). At longer timescales, solar activity variability can also affect temperature and rainfall patterns. A possible climatic modulation by solar activity at these timescales was suggested by Gusev et al. (2004) and Souza Echer et al. (2008). Spectral analysis of tree growth rings over the last centuries indicated climatic variations associated with ENSO on an interannual timescale and with solar activity on decadal to multidecadal timescales (Rigozo et al., 2003, 2004; Prestes et al., 2011). However, this external forcing has not been studied on the regional scale.

The time series of the annual average temperature relative to the 1961–1990 mean are shown in Fig. 3. Mean values for the 1961–1990 interval were 18.7 °C for SPO, 16.8 °C for CUR, 20.4 °C for FLO and 19.5 °C for POA. The time series of suggested climate forcings are shown in Fig. 4. The Southern Oscillation Index (SOI) (Fig. 4a) was obtained from the University of East Anglia website (http://www.cru.uea.ac.uk/). The SOI estimates the ENSO amplitude. Negative (positive) values are related to El Niño (La Niña) events. The sunspot number time series (Fig. 4b), represented in terms of Rz (Hoyt and Schatten, 1997), was obtained from the Solar Influences Data Analysis Center website (http://sidc.oma.be/). Neutron counts (Fig. 4c), an indicator of the GCR flux, were measured at the Climax Neutron Monitor. These data are available on the website of the Neutron Monitor Datasets of the University of New Hampshire for between 1953 and 2006. The Hale cycle (or "double sunspot cycle") (Fig. 4d) is the sunspot number multiplied by

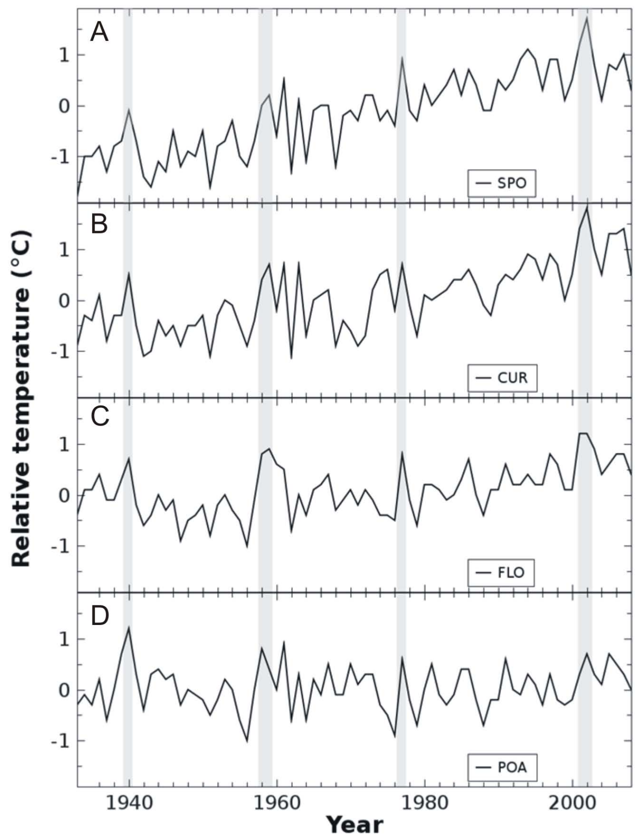

Fig. 3. Time series of the relative temperature between 1933 and 2008 for four Brazilian meteorological stations: SPO **(A)**, CUR **(B)**, FLO **(C)** and POA **(D)**. The shaded bands indicate simultaneous maximum temperature events.

−1 in odd cycles and is represented in terms of Rz22. GCR flux exhibits a clear effect from the 11 yr solar magnetic field modulation. Moreover, there is a 22 yr secondary modulation that depends on the Sun's magnetic field polarity (see Kudela, 2009). Neutron count curves in transitions from solar cycles 19 to 20 and 21 to 22 have a thin triangular shape. During transitions from cycles 20–21 and 22–23, the count curves become thick and squared.

Classical spectral analysis with iterative regression (ARIST – Análise por Regressão Iterativa de Séries Temporais) was used to identify cyclic variations in the temperature data. ARIST is based on the adjustment of observational data by means of a sine function with three unknown parameters (frequency, amplitude and phase). These parameters are computed in an iterative process, after which it is possible to determine periodicities that may be present in the time series and to select those with statistical significance (Rigozo and Nordemann, 1998; Rigozo et al., 2005).

To identify the common high covariance periodicities between temperature and climatic forcing time series, wavelet coherence (WTC) spectra based on the complex Morlet wavelet base function were computed (Torrence and Compo,

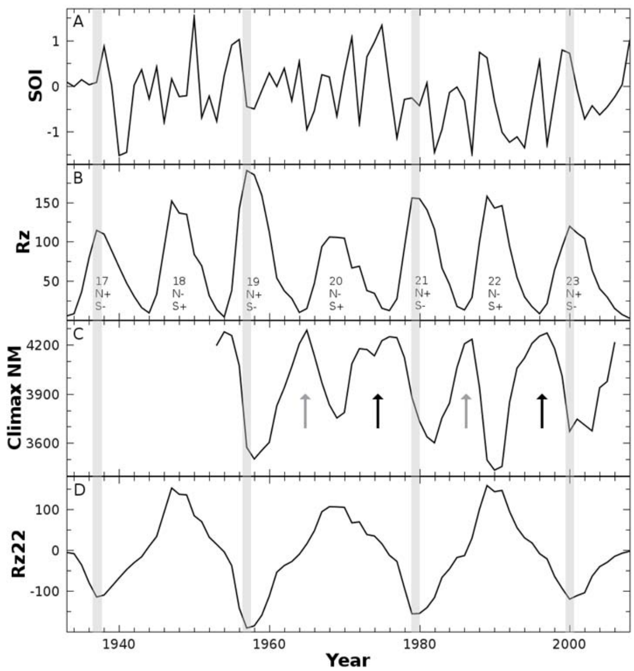

Fig. 4. Time evolution of the annual mean SOI index **(A)**, Rz time series **(B)**, neutron counts registered at the Climax Observatory **(C)**, and Rz22 time series **(D)**. The sunspot cycle number and the global solar magnetic field polarity are shown in **(B)**. The gray arrows (black arrows) in **(C)** indicate transitions from odd to even (even to odd) cycles. The shaded bands indicate the maxima of odd sunspot cycles.

1998). The WTC is quantified by a number between 0 and 1, which indicates the cross-correlation between analyzed time series in different spectral bands. For WTC spectra, the cone of influence (COI), the 95 % significance level and the relative phase angles were calculated according to the method of Grinsted et al. (2004). The COI is the limit of the spectral region where edge effects may be statistically important. The 95 % significance level region is a spectral area where the WTC values are not affected by a red noise process. This spectral region is calculated from a first-order autoregressive (AR1) process. The phase angles give indications about the linearity of a possible relationship between the two time series. Phase angles around 0° or around 180° indicate, for a linear relationship with the former, an in-phase relationship and the latter an anti-phase relationship. Other phase-angle configurations indicate a non-linear relationship.

3 Results

The temperature time series shown in Fig. 3 indicate a positive temperature trend for three of the four weather stations: 0.030 degrees yr^{-1} for SPO, 0.021 degrees yr^{-1} for CUR, and 0.011 degrees yr^{-1} for FLO. No significant trend has been observed for POA. However, strong interannual variability and four temperature maxima at SPO, CUR, FLO and POA in 1940, 1958–1959, 1977 and 2002 are indicated by the shaded bands in Fig. 3. The average time interval between these peaks is approximately 21 yr, which is very close to the Hale cycle. Furthermore, the mean annual temperature peaks occurred close to the maxima of odd solar cycles of positive (negative) polarity at the North (South) Pole in 1937, 1957, 1979 and 2000 (Fig. 4). The figure also shows that mean annual temperature maxima were nearly simultaneous to the cosmic ray minima that correspond to solar odd cycle maxima activity for 1958, 1982 and 2000–2003.

After removing the temperature trends, an iterative regression analysis was used to search for periodicities, and after 200 iterations, periodicities at interannual and decadal timescales were found over the 95 % confidence level (Table 2). Periodicities between 19 and 25 yr, 9 and 13 yr, and 2 and 7 yr are indications of the Hale, Schwabe and ENSO cycle influence, observed at all stations. The nearly 33 yr periodicity at FLO might be related to the Brückner solar cycle (Brückner, 1890; Prestes et al., 2011). The wavelet coherence power spectrum and the relative phase angles were calculated to investigate the time evolution of statistically significant periodic variations and the phase relationship between temperature and natural climatic forcing.

The WTC between the temperature time series and Rz22 is shown in Fig. 5. High and persistent coherence (higher than 0.8) was observed for approximately 22 yr periodicities at all four locations. Part of the signal is outside of the COI. Other intermittent and statistically low coherent periodicities, between 4 and 8 yr, are also apparent. They occurred at SPO between 1942 and 1960, at CUR between 1942 and 1970, at FLO between 1943 and 1965, and at POA between 1942 and 1962. Other intermittent features with periods less than 4 years are apparent between 1970 and 1980 (at all stations) and near 1990 (for FLO and POA). Black arrows in Fig. 5 indicate the phase angles between the time series. For periodicities of approximately 22 yr, the arrows tend to point to the left for SPO, CUR and FLO, indicating a possible linear (anti-phase) relationship between the Hale cycle and the temperature variations. However, for POA, the arrows point up, indicating a non-linear relationship. For the intermittent periodicities (4–8 yr), the arrows point up, suggesting a non-linear relationship. For significant periodicities of less than 4 yr, the arrows tend to point to the right, indicating a linear relationship. Similar out-of-phase phase-angle relations, at different stations and at the same time, can be an indication of a similar non-linear relationship. Notably, the wavelet coherence spectral features are very similar for all weather stations.

Figure 6 shows the wavelet coherence spectrum between temperature and Rz. The 11 yr cycle signal was statistically significant until 1960 for SPO, after 1985 for CUR, until 1971 for FLO, and after 1950 for POA. The phase-angle analysis indicates a linear relationship between the Schwabe cycle and temperature in SPO (until 1960), FLO (until 1971)

Table 2. Statistically significant periods in the temperature data for each station.

Station	Periods (amplitude in °C)			
	2–7 yr	9–13 yr	19–25 yr	32–34 yr
SPO	2.3 (0.14), 2.9 (0.14), 4 (0.16), 4.4 (0.17), 6.1 (0.19)	9 (0.15), 10.9 (0.14)	19.8 (0.15)	
CUR	2.1 (0.22), 4.1 (0.17), 4.7 (0.22), 5.2 (0.15)	9.1 (0.21)	21.2 (0.18)	
FLO	4.1 (0.16), 4.5 (0.14), 5.2 (0.18), 6.3 (0.18)	11 (0.14)	21.7 (0.22)	33.4 (0.2)
POA	2 (0.16), 3.4 (0.14), 4.1 (0.19), 4.7 (0.22), 6.5 (0.18)	10.7 (0.19)	21.2 (0.16)	

and POA (until approximately 1971). After 1985, the phase angles tend to point down for CUR and POA. Between 1950 and 1960, a 4–6 yr periodicity occurred in CUR, FLO and POA, with the arrows pointing down. Near 1980, a periodicity of less than 4 yr was detected in all stations, with the arrows pointing to the left. Thus, the coherence features between temperature and the 11 yr solar cycle are not similar for all stations.

The relationship between temperature variations and the SOI index computed by the WTC spectrum is shown in Fig. 7. Very similar features common to all locations are observed before 1945 and between 1955 and 1980, with cycles between 4 and 8 yr and characterized by arrows pointing to the left. After 1990, features with periods less than 4 yr and with arrows pointing to the left are observed in SPO and CUR. After 1980, similar spectral features are detected in FLO and POA. Between 1982 and 1997, periodicities of 4–7 yr with arrows pointing down are observed. For periodicities less than 4 yr after 1995 and between 7 and 11 yr after 1985, the arrows point to the left. At CUR, periodicities longer than 11 yr with arrows pointing down are also observed. An analysis of SOI versus temperature wavelet coherence indicates that ENSO is an important climatic forcing in the southern Brazil region. Small spectral feature differences were noted between the southernmost and the northernmost stations.

4 Discussion

ENSO periodicities in the temperature data were intermittent over time, but some similar features were observed in more than one location using wavelet coherence and phase-angle analysis. The most interesting feature was observed in all stations with similar spectral characteristics before 1945 (4–7 yr periods), in the 1955–1980 interval (4–7 yr periods) and after 1995 (<4 yr periods). Around 1940, 1958, 1977 and 2002, the SOI index exhibited negative excursions (Fig. 4) associated with a strong El Niño episode that might have caused the four simultaneous maxima in the mean annual temperature. However, other strong El Niño episodes have not produced simultaneous statistically significant periodic variations or maxima temperature peaks simultaneously at the four locations. This observation indicates that the ENSO modulation varies locally in the Brazilian subtropical region. The most statistically significant coherence spectrum signal, with cycles between 4 and 7, occurred between 1955 and 1965. Similar spectral features were also observed in Fig. 6. McCracken et al. (2002) and Usoskin et al. (2006) have associated an intermittent periodicity of 5.5 yr either directly or indirectly to solar activity. This cycle is present in the geomagnetic field variations and in Earth's rotation variations (Djurovic and Pâquet, 1996).

The 11 yr cycle is less persistent than the ENSO signal. Furthermore, there is no noticeable common standard relationship for all locations in terms of the time-series phase angles. This intermittence of the 11 yr signal was also observed by Souza Echer et al. (2008) and by Rampelotto et al. (2012) and might be related to a non-linear local climatic response to solar variations. However, the most striking factor affecting the temperature records for the investigated locations appears to be the 22 yr solar cycle, as indicated by the temperature maxima, the ARIST spectral analysis and the high amplitudes in the wavelet coherence spectrum, which agrees with previous work by Souza Echer et al. (2008) and Rampeloto et al. (2012). In general, the 22 yr cycle present in the climatic data is associated with solar activity variation and more specifically to a cosmic-ray-related climate modulation mechanism (Kirkby, 2007).

The 22 yr cycle is a remarkable characteristic of the galactic cosmic ray flux, modulated by the Hale solar magnetic cycle (Usoskin et al., 2001). As shown in Fig. 4, odd cosmic ray cycles are longer than even cosmic ray cycles. During transitions from odd to even cycles, the maximum of cosmic ray flux appears as a clear peak, while for transitions from even to odd cycles, the maximum of cosmic ray flux persists for a longer time period. This observation suggests that during transitions from an even to odd solar cycle, the flux of cosmic ray on Earth's atmosphere is higher than in transitions from even to odd cycles. Furthermore, Usoskin et al. (2001) showed the existence of a time lag between solar activity variations and the consequent cosmic ray variations. During odd cycles, the time lag is long, while during even cycles, the time lag is short or negative.

Temperature peaks occurring in 1940, 1958–1959, 1977 and 2001–2002 were in phase with the maximum of the odd sunspot cycles (1937, 1957, 1979 and 2000, respectively).

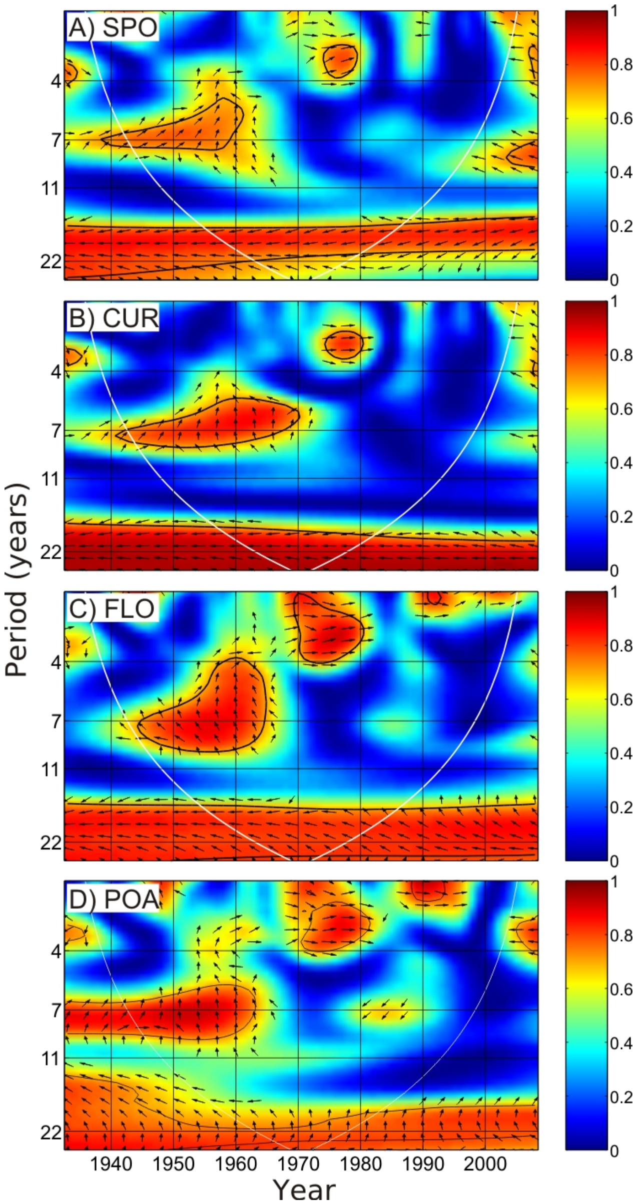

Fig. 5. Wavelet coherence spectrum between temperature data and the Rz22 time series computed for SPO **(A)**, CUR **(B)**, FLO **(C)**, and POA **(D)**. Coherence values are indicted by colors. The white line indicates the COI, below which edge effects may be important. The black lines are the limit of the 95 % confidence level for red noise. Black arrows represent the phase angle between two investigated time series.

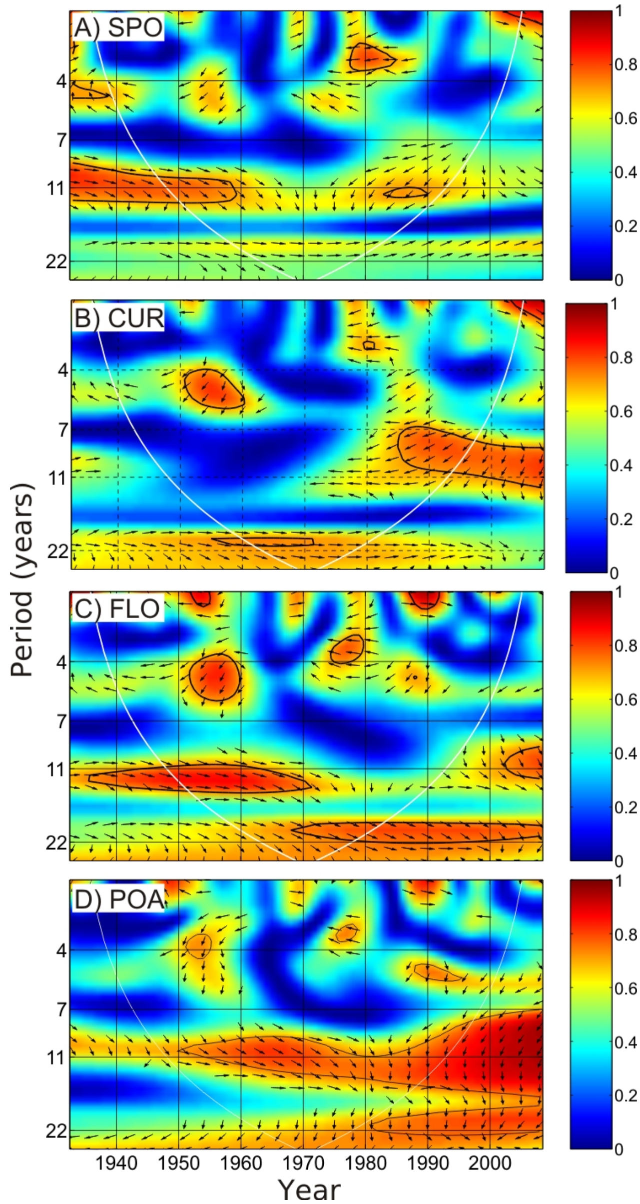

Fig. 6. Similar to Fig. 5, but considered for the wavelet coherence spectrum between the temperature data and the Rz time series computed for SPO **(A)**, CUR **(B)**, FLO **(C)**, and POA **(D)**.

In addition, the last three temperature maxima occurred near the minima of neutron counts (1958, 1982 and 2000–2003). The observed 1940, 1958–1959 and 2001–2002 temperature maxima occurred after the 1937, 1957 and 2002 odd cycle maxima respectively, and after or at the same time as the 1958 and 2000–2002 neutron count maxima. However, the 1977 temperature maximum occurred before the 1979 odd solar cycle maximum and the 1982 neutron count maximum. Curiously, it was for the solar cycle 20–21 transition (∼ 1974) that Usoskin et al. (2001) found the longest negative time lag between solar activity and neutron count variations, indicating that the cosmic ray maximum occurred before the solar activity minimum.

This relationship between temperature maximum and cosmic ray minimum activity is in agreement with the cosmic-ray–cloud-climate modulation mechanism because periods of lower cosmic rays would be associated with lower cloud coverage and consequently with maximum temperature events. Another interesting feature in agreement with

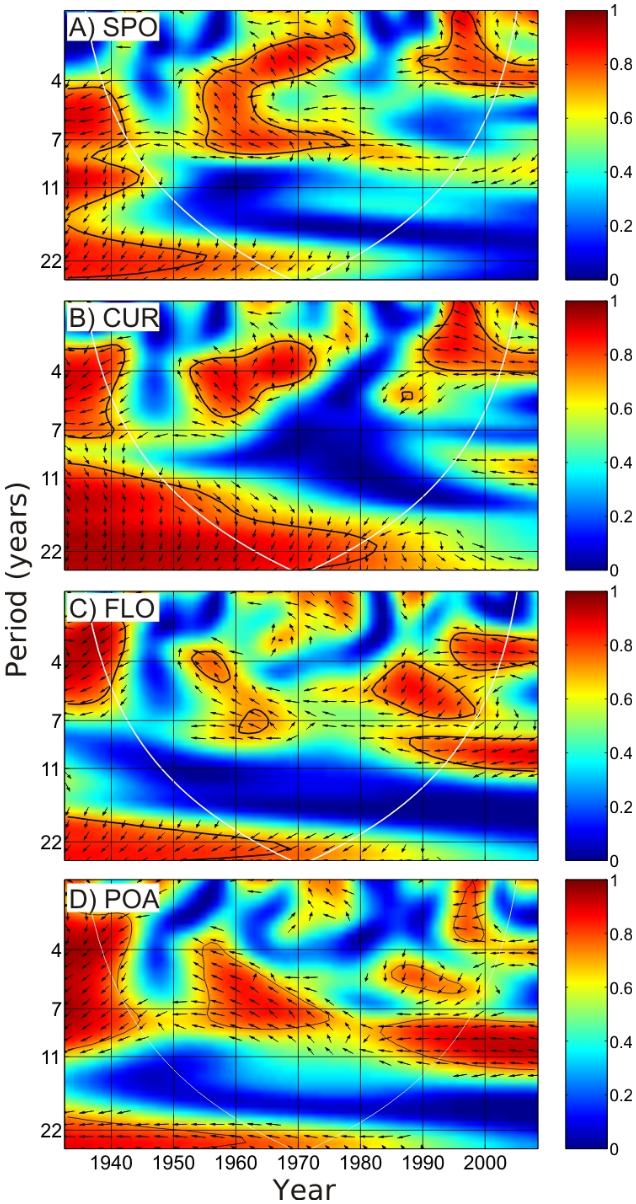

Fig. 7. Similar to Fig. 5, but considered for the wavelet coherence spectrum between the temperature data and the SOI index time series computed for SPO **(A)**, CUR **(B)**, FLO (C), and POA **(D)**.

the cosmic-ray–climate relationship is that the phase-angle relations between temperature and the 22 yr solar cycle are similar for SPO, CUR an FLO, although it is different for POA. Figure 2 shows that the SAMA was closer to SPO, CUR and FLO positions compared to POA. The 22 yr solar magnetic cycle is also present in POA's temperature data, but with a phase difference between the time series. A possible explanation for this phase difference is that a geomagnetic field being closer to the SAMA center results in a weaker field and higher precipitation of electrically charged particles. Therefore, the Hale cycle modulation is strongly evidenced in the region that surrounds the locations of Earth's lowest magnetic field intensity.

5 Conclusions

The regional impact of natural climatic forcings (solar variability, galactic cosmic rays and ENSO) on temperature variations has been discussed for the Brazilian subtropical region with a SAMA-heavy influence since the beginning of the twentieth century. Spectral analysis results indicate that the influences of ENSO and the Schwabe solar cycle are intermittent in time and exhibit different characteristics for different locations in southern Brazil. Modulation of the ENSO and the Schwabe solar cycle signals can appear with different characteristics in distinct locations and under distinct meteorological variables (Grimm et al., 2000; Barros et al., 2002; Haigh, 2007; Gray et al., 2010).

The Hale solar magnetic cycle signal was persistent during the entire period for all analyzed locations, in agreement with Souza Echer et al. (2008) and Rampelotto et al. (2012), who used data from a single location. The four temperature maxima in the time interval between 1933 and 2008 occurred simultaneously at all weather stations, which are separated by 2 degrees of latitude. The time of occurrence of these maxima nearly coincides with the maxima of solar odd cycles and consequently with the minima of the galactic cosmic ray odd cycles.

Results of the present work are an indirect statistical indication for a possible cosmic-ray–climate mechanism at a regional scale. This conclusion is supported by the influence of SAMA, as possibly indicated by the phase-angle analysis, which allows for easier entry of electrically charged particles (König et al., 1978; Vieira and da Silva, 2006). Future work will continue this line of study with additional data from other climatic variables and from other weather stations installed in this region. Furthermore, displacement of few years between some cosmic ray minima in odd cycles and temperature maxima should be investigated in more detail in future work.

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