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Variability of rainfall and temperature (1912–2008) parameters measured from Santa Maria (29°41′S, 53°48′W) and their connections with ENSO and solar activity

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ABSTRACT

In this work, we analyze the long term variability of rainfall and temperature (1912–2008) of Santa Maria (29°S, 53°W) and its possible connection with natural influences such as solar activity and ENSO. Temperature and rainfall present similar frequencies as revealed by spectral analyses. This analysis shows a large number of short periods between 2–8 years and periods of 11.8–12.3, 19.1–21.0, and 64.3–82.5 years. The cross correlation for rainfall and temperature versus Southern Oscillation Index (SOI) have higher cross-power around 2–8 yr. Rainfall and temperature versus sunspot number (Rz) showed higher cross-power around the 11-yr solar cycle period. A high and continuous cross correlation was observed for Rz-22 yr versus rainfall and temperature. Furthermore, the power between 22-yr solar cycle and meteorological parameters was higher than that obtained with the 11-yr solar cycle, suggesting that the effect of Hale cycle on climate may be stronger than the Schwabe cycle effect. These results indicate that the variability of rainfall and temperature is closely related to the variation of the Southern Oscillation Index and solar activity, and that the El Nino Southern Oscillation and solar activity probably play an important role in the climate system over Southern Brazil.

1. Introduction

Both natural and anthropogenic influences caused twentieth century climate change, but their relative roles and regional impacts are still under intense debate (Haigh, 2007; Joseph and Nigam, 2006; Lean and Rind, 2009; Pittock, 2009; Gray et al., 2011). In this context, it is fundamental to study the long term variability of climate in order to understand, which factors cause such variability. The climate of the Earth at a given time may be primarily characterized by its surface temperature and rainfall variations. To identify the causes of past change, thereby rendering forecasts for future decades, it is necessary to isolate and quantify the specific changes arising from both natural and anthropogenic influences (Benestad, 2003; Lean and Rind, 2008). The most cited natural phenomena affecting the long term variability of climate has been the El Niño.

Southern Oscillation and solar activity (Wang et al. 2000; Nuzhdina, 2002; Haigh, 2003; Raspopov et al., 2004; Souza Echer et al., 2008, 2009; Courtillot et al., 2010; Le Mouël et al., 2010).

The El Niño Southern Oscillation (ENSO) phenomenon is a result of complex interaction between the atmosphere and the hydrosphere in the tropical Pacific (Cane, 2005). The Southern Oscillation Index (SOI) is an index used to represent the ENSO phenomena (Petroni and Ausloos, 2008). This is a standardized index based in observations of sea level pressure between Darwin (12°27′S, 130°50′E) and Tahiti (17°37′S, 149°26′W). Negative values of the SOI indicate El Niño episodes and positive values are associated with La Niña episodes (Ausloos and Ivanova, 2001). El Niño, or warm phase of ENSO, is caused by the heating of water from the East Pacific (Andreoli and Kayano, 2005). On the other hand, at La Niña, or cold phase of ENSO, an anomalous cooling of superficial water has been observed at the Equator and in the

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Eastern Pacific Ocean. ENSO, which has its origin at the tropical Pacific Ocean, can cause climatic anomalies in different regions of the world (Dai and Wigley, 2000; Alexander et al., 2002; Barnett et al., 2002).

Southern Brazil is one of the extra-tropical regions most affected by El Niño and La Niña events (Grimm et al., 2000). Many observations suggested that the precipitation and temperature are the meteorological parameters most associated to ENSO (Alexander and Barnett, 1998). Positive rainfall anomalies are observed in El Niño years, and negative anomalies prevail in La Niña years (Prieto, 2007). Another study suggests that the temperature amplitude in Northern Uruguay is reduced in El Niño years, and the mean temperatures throughout the whole country have a tendency to be lower in La Niña years (Bidegain and Krecl, 1999).

Solar activity is related to the Sun's output, which varies on a wide range of time scales. Sunspot number is the longest directly measured solar activity index available and is representative of the general state of solar activity (Hoyt and Schatten, 1997). Analysis of sunspot number time series allowed the identification of the two main characteristic periodic variations of the solar activity: the 11-year sunspot cycle (Schwabe cycle) and the 22-year solar magnetic cycle (Hale cycle) (Lang, 2001; Usoskin and Mursula, 2003). While the Schwabe cycle is mainly related to the irradiance variations (Fröhlich, 2011) the Hale cycle is mainly related to the modulation of galactic cosmic rays (Singh et al., 2011). Changes in solar irradiance and in galactic cosmic ray flux are suggested to be the triggers of the mechanisms that relate solar activity and Earth's climate (Kirkby, 2008; Gray et al., 2011; Kilifarska, 2011; Singh et al., 2011). Several studies have indicated that solar activity may affect climate variations (Rind, 2002; Bard and Frank, 2006). The search for possible influences of solar activity on the different meteorological or climatological parameters is one key element that has been widely used to prove the Sun–climate connection. The literature contains an extensive history of this issue (Rigozo et al., 2004; Valev, 2006; Kilcik et al., 2008; Dobrica et al., 2009; Souza Echer et al., 2009; Le Mouël et al., 2010). Despite the scientific works supporting the view that meteorological phenomena must respond to variations of solar activity, this subject is far from being settled (Tsiropoula, 2003; Lockwood and Frohlich, 2007). Several analyses of these records are fraught with problems in the methods, have biased data selection, or have questionable statistical significance of the reported correlations. Quality research indicates that the relationship between solar activity and climate is very complicated and varies with time and probably also with geographic position (Kilcik et al., 2009). On the global scale, the correlation between sunspot number and meteorological parameters may be positive, negative, or even zero (Zhao et al., 2004). However, for South America, few studies on this issue have been reported (Rigozo et al., 2004; Gusev et al., 2004; Rampelotto et al., 2008).

In this work spectral analysis was applied to centennial time series data of Santa Maria, Southern Brazil, in order to identify the main periodicities in rainfall and surface air temperature from historical records. These time series were also cross-correlated with possible natural factors that may influence the climate in this region.

2. Data and methodology of analysis

2.1. Datasets

The monthly rainfall and temperature from historical records were obtained for Santa Maria—RS (29°41′S, 53°48′W, 151 m a.s.l.), Southern Brazil from 1912 to 2008. We also used the Southern Oscillation Index (SOI) time series obtained from the United States National Geophysical Data Center (http://www.ngdc.noaa.gov). Rz is the longest solar activity index of sunspot number (Rz), which was first compiled by R. Wolf in the XIX century and is available as annual averages since 1700 (Eddy, 1976; Hoyt and Schatten, 1997). The annual averages of Rz were obtained from the Sunspot Index Data Center—SIDC. The time interval for Rz used in this study is 1912–2008. To study the 22-year (Rz22) solar magnetic cycle, we attributed to the Rz series positive and negative values during even and odd cycles, respectively.

2.2. Methodology of analysis

A spectral analysis by an iterative regression method was used to search for the most significant periodicities. This method (Análise por Regressão Iterativa de Séries Temporais—ARIST) is an iterative least square fit and uses a simple sine function with three unknown parameters, a_0=amplitude, a_1=angular frequency, and a_2=phase (Rigozo and Nordemann, 1998). The starting point of the method is the so called conditional function (Rigozo et al., 2005):

$$F = Y - a_0 \sin(a_1 t + a_2) \quad (1)$$

where Y is the signal (time series), t is the time and a_0, a_1, a_2 are the three unknown parameters to be determined. Every periodicity embedded in the time series corresponds to a set of values of the three parameters, which are determined one at a time by applying the iterative process to the original time series with the limiting condition of maintaining the angular frequency a_1 inside a restricted domain of the allowed interval of angular frequencies. For the determination of each parameter set, the maximum number of iterations used may be chosen between 50 and 200 (Rigozo and Nordemann, 1998). The advantage of the method is that it provides the standard deviation for each parameter, as determined from the statistical fluctuations and also, if desired, from the errors on every value of the time series. This allows a selection of the periodicities with amplitudes above 95% confidence.

The wavelet transform is a powerful tool for non-stationary signal analysis. It permits to identify the main periodicities in a time series and their evolution (Kumar and Foufoula-Georgiou, 1997; Torrence and Compo, 1998; Percival and Walden, 2000). The wavelet transform of a series of discrete data is defined as the convolution between the series and a scaled and translated version of the wavelet function chosen. By varying the wavelet time scale and translating the scaled versions of the wavelet, it is possible to build a graph showing the amplitudes versus frequency (or period) and how they vary with time.

In this work, a complex Morlet wavelet was used because it is most adequate to continuously detect variations of periodicities in geophysical signals. The Morlet wavelet is a plane wave modulated by a Gaussian function (Torrence and Compo, 1998):

$$\psi(0)_\eta = \pi^{-(1/4)} e^{i w_0 \eta} e^{-(\eta^2/2)} \quad (2)$$

X, Y being time series and $W_n^X(s)$, $W_n^Y(s)$ their wavelet transform, the wavelet cross spectrum (Torrence and Compo, 1998; Percival and Walden, 2000) is

$$W_n^{XY}(s) = W_n^X(s) W_n^{Y^*}(s) \quad (3)$$

where $W_n^{Y^*}(s)$ is the complex conjugate of $W_n^Y(s)$. The power is $|W_n^{XY}(s)|$. The wavelet cross power indicates the scale of high covariance between two time series (X, Y).

In this work, the cross-wavelet spectrum between every time series was calculated. The cross-wavelet power indicates the

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scales of higher covariance between two time series (Grinsted et al., 2004).

3. Results and discussion

Fig. 1 shows the annual temperature (a) and rainfall (b) series data collected at Santa Maria from 1912 to 2008. At this location temperature varies seasonally with the higher values for January (30.6 ± 0.9) °C and the lower for June (19.2 ± 1.8) °C (Fig. 2a). Precipitation has a constant profile throughout the year with a mean of 144.7 ± 11.4 mm (Fig. 2b).

Fig. 3 shows the ARIST spectra variability for the (a) temperature and (b) rainfall time series. For annual temperature, the significant periods are: 2.2, 3.1, 4.0, 4.8, 8.2, 11.8, 19.1, and 64.3 (years). In terms of annual precipitation, the significant periods are 2.3, 2.7, 5.2, 6.0, 9.0, 12.3, 21.0, and 82.5 (years).

Although temperature and rainfall present different absolute values and variability throughout the years, both time series have similar frequencies as revealed by spectral analyses. The analysis shows a large number of short periods between 2–6 years and periods of 11.8–12.3, 19.1–21.0, and 64.3–82.5 years. These results indicate that natural cyclic factors influence the long term variability of rainfall and temperature over southern Brazil. In order to find the causes of the periodicities observed in the temperature and rainfall from historical records, cross wavelets were performed between the meteorological data and the time series of ENSO and solar activity.

The linear correlation coefficients were calculated among the variables. The correlations were verified by the *t*-test. The linear correlation for Santa Maria's annual rainfall and SOI is $r=-0.49$, and the linear correlation for Santa Maria's annual temperature and SOI is $r=-0.36$. This indicates that during El Nino events, with a negative SOI, there is an increase in Santa Maria rainfall. The linear correlation between Santa Maria's annual meteorological parameters (temperature and rainfall) and sunspot number is very weak, with Rz $r<-0.10$ and with Rz22, $r=-0.19$.

The multiple linear correlations for 1912–2008 of rainfall=*f*(Rz, SOI) was $r^2=0.24$ and rainfall=*f*(Rz22, SOI) was $r^2=0.26$. In these results only 24% and 26% of the rainfall variability can be associated with a linear dependency to solar activity and ENSO. The multiple linear correlation for 1912–2008 for temperature=*f*(Rz, SOI) was $r^2=0.12$ and temperature=*f*(Rz22, SOI) was $r^2=0.13$. In these results only 12% of the

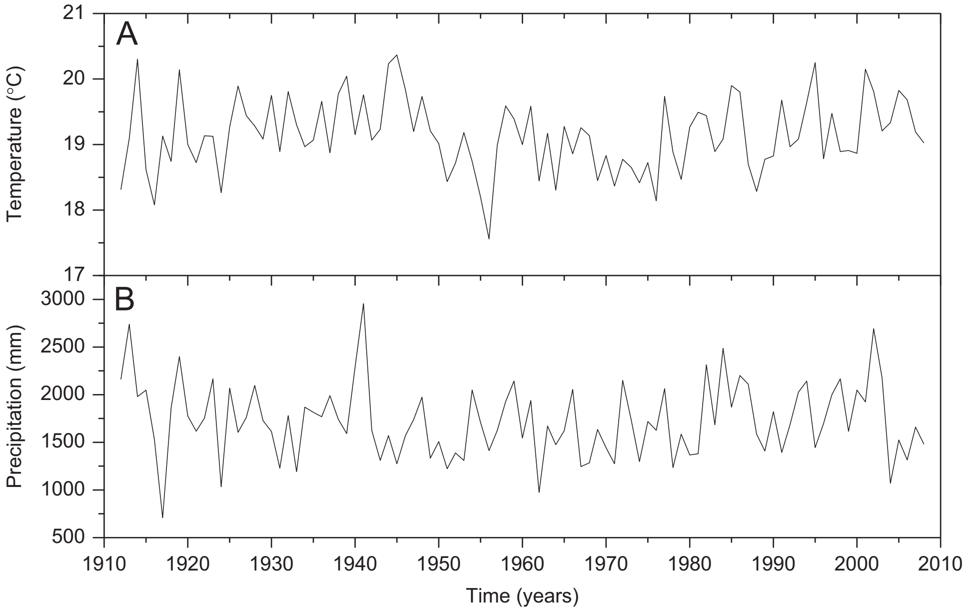

Fig. 1. Annual time series of temperature (A) and precipitation (rainfall) (B) in Santa Maria (29°41′S, 53°48′W) from 1912 to 2008.

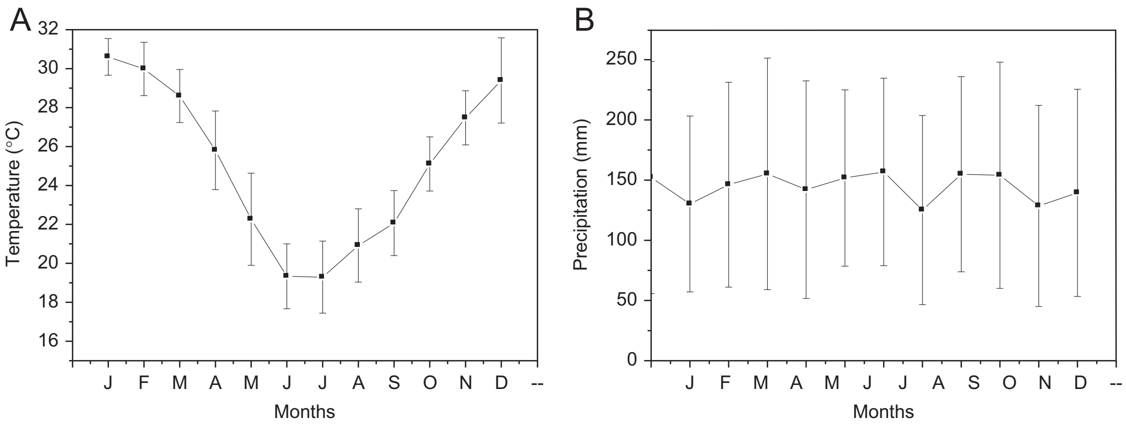

Fig. 2. Monthly mean seasonal variations of temperature (A) and precipitation (rainfall) (B) at Santa Maria (29°41′S, 53°48′W).

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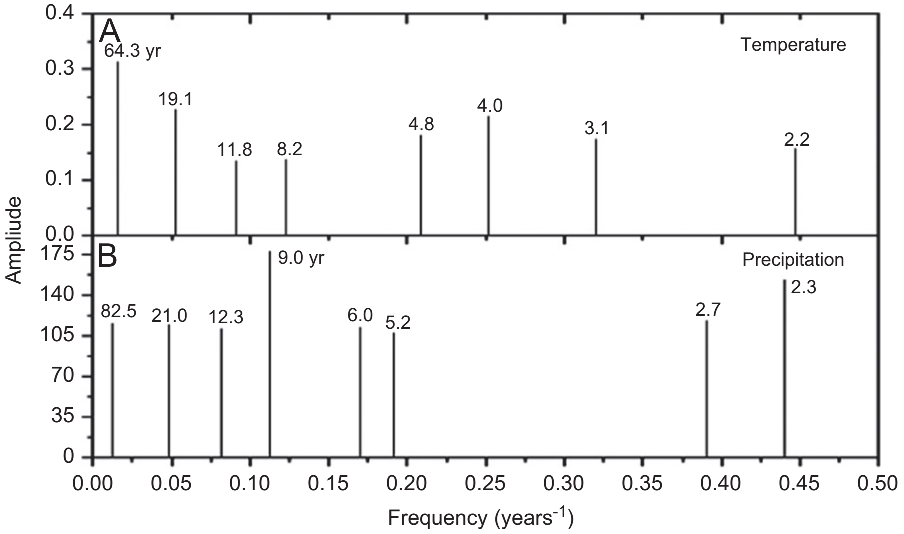

Fig. 3. Amplitude spectra for temperature (A) temperature and (B) precipitation (rainfall) above 95% confidence.

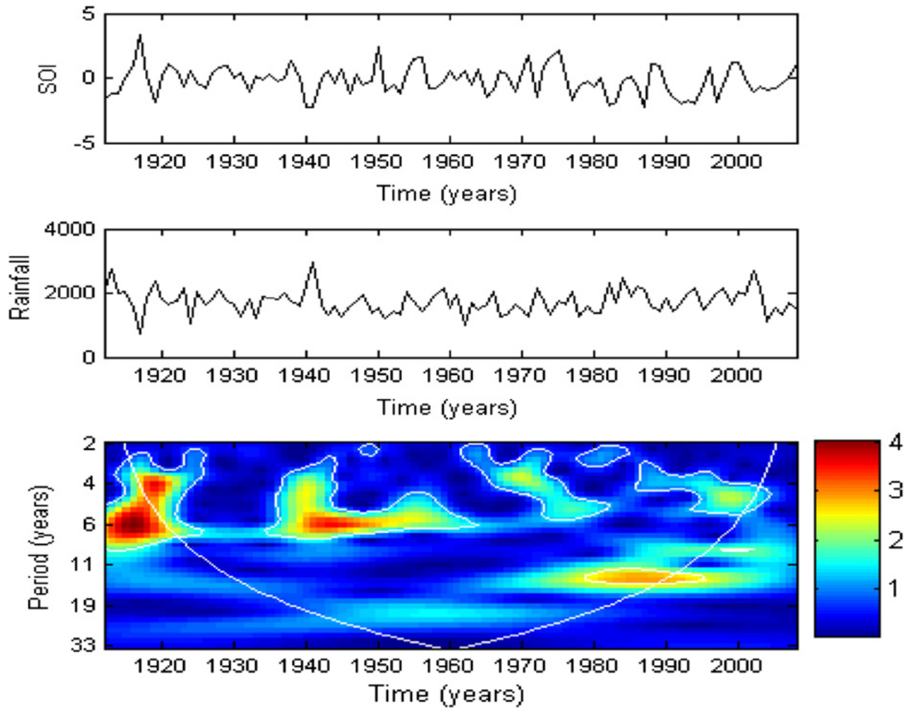

Fig. 4. The Morlet cross-wavelet map between SOI and rainfall, with cone of influence (parabolic curve) and significance levels contour for 95%. At right the legend indicates the cross-wavelet power.

temperature variability can be associated with a linear dependency to solar activity and ENSO. The correlation increased when Rz22 (to take into account the 22 yr cycle) is used instead of the normal Rz. These results are similar to results obtained by Souza Echer et al. (2008), which seem to indicate that the 22 yr magnetic cycle may have more influence on temperature and rainfall at Santa Maria than the 11 yr cycle.

Fig. 4 shows the cross-wavelet spectra for SOI versus rainfall. The *Y* axis indicates the scale (in years). The *X* axis indicates the time in years, and the gray scale shows the power 1/2 (amplitude) in each band of the spectrum of frequency. The contour lines mark the periods with 95% significance. The parabolic curve delimits the cone of influence region. The analysis shows a large number of short periods between 2 and 8 years. The higher cross-power was around 1912–1925, 1935–1960, 1960–1980, and 1985–2005. In addition, there is continuous periodicity with high amplitude around 20 years, but this is not significant at the 95% confidence level.

Fig. 5 presents the cross-wavelet spectra for SOI versus temperature. This analysis demonstrates a high cross-power in the 2–8 year period with three main cross-powers around 1912–1925, 1935–1960, and 1972–2005. A continuous but moderate power signal with a frequency of 12–13 years was observed for the period 1980–2000. A slight signal of 19–21 years (not significant at the 95% confidence level) was also revealed around 1950–1970.

Figs. 6 and 7 show the cross-wavelet spectra for solar activity (represented in terms of Rz) versus rainfall and temperature, respectively. The cross-power of solar activity and rainfall was statistically significant in the 11 year signal after 1930, but it was

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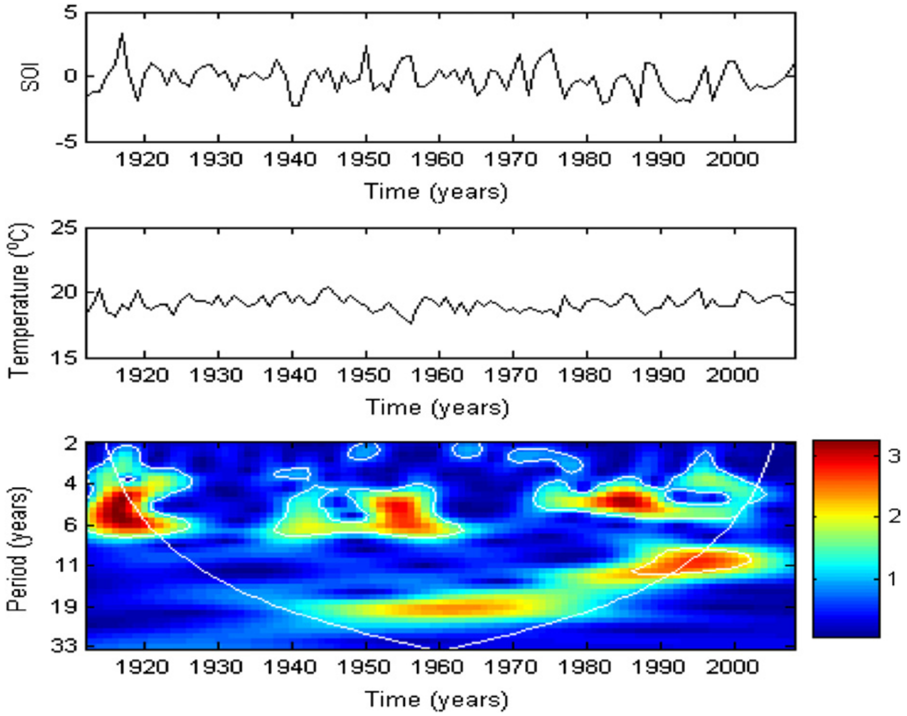

Fig. 5. The Morlet cross-wavelet map between SOI and temperature, with cone of influence (parabolic curve) and significance levels contour for 95%. On the right the legend indicates the cross-wavelet power.

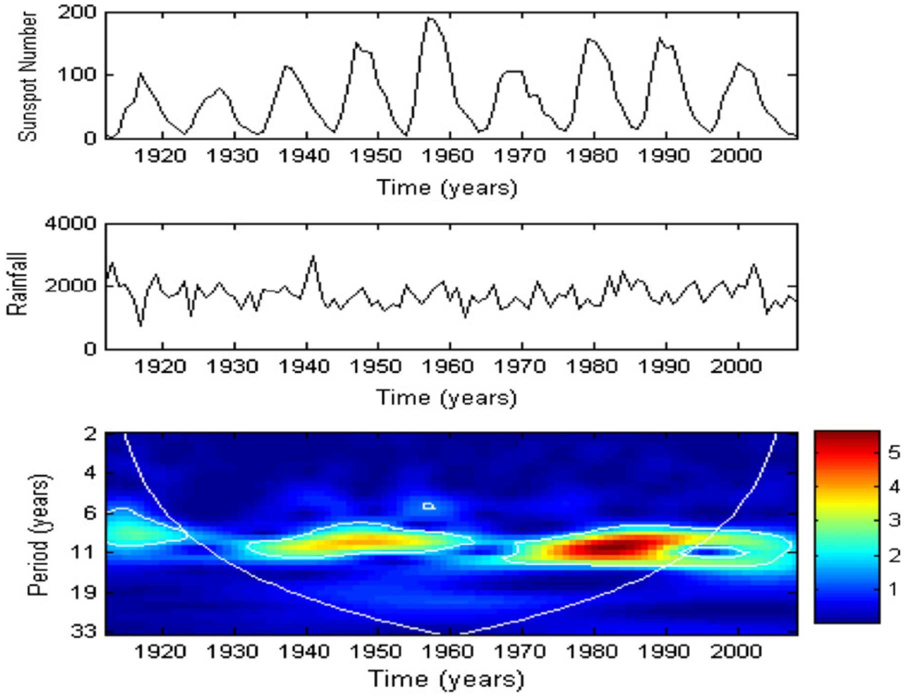

Fig. 6. The Morlet cross-wavelet map between solar activity (represented in terms of Rz) and rainfall, with cone of influence (parabolic curve) and significance levels contour for 95%. On the right the legend indicates the cross-wavelet power.

intermitted around 1960–1970 (see Fig. 6). A continuous signal was observed after 1935 when the relationship between solar activity and temperature was analyzed (see Fig. 7). The signal was slight around 1970–1980. It is worth to note that during 1955–1965 a weak solar cycle was observed and may explain the intermitted period observed in the cross-analyses with the meteorological parameters. These results are supported by recent evidences which demonstrate a strong relationship between solar activity and tree ring growth (Rigozo et al., 2008; Prestes et al., 2011; Wang and Zhang, 2011). The results from Figs. 6 and 7 indicate that temperature and rainfall may respond similarly to solar forcing, although in a different time lag.

Figs. 8 and 9 show the cross-wavelet spectra for the 22 year solar cycle versus rainfall and temperature, respectively. A high and continuous cross correlation between Rz-22 yr and meteorological parameters was observed. The cross-power of Figs. 8 and

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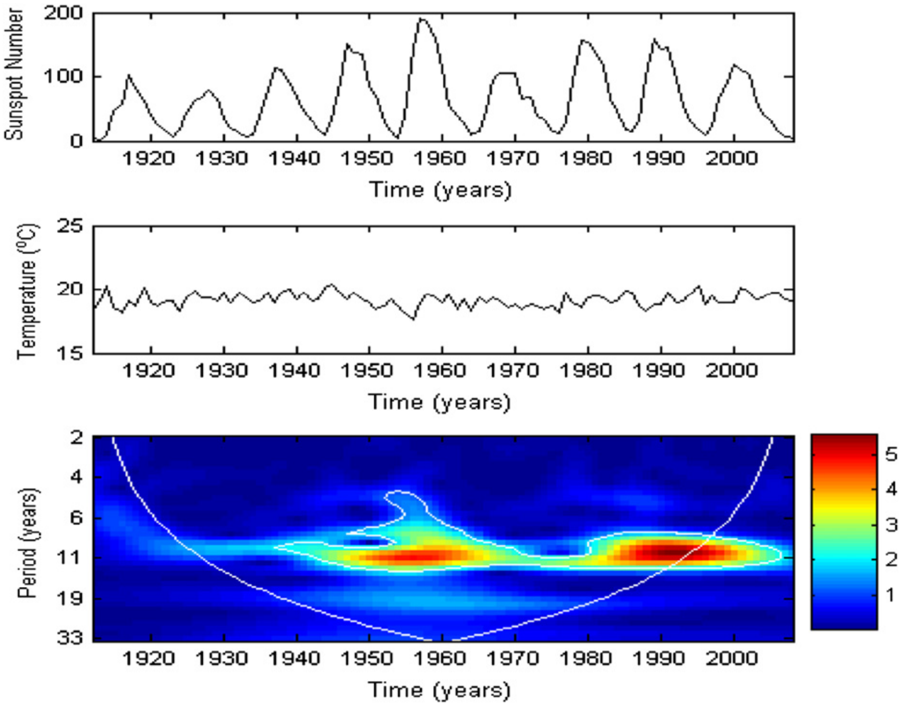

Fig. 7. The Morlet cross-wavelet map between solar activity (represented in terms of Rz) and temperature, with cone of influence (parabolic curve) and significance levels contour for 95%. On the right the legend indicates the cross-wavelet power.

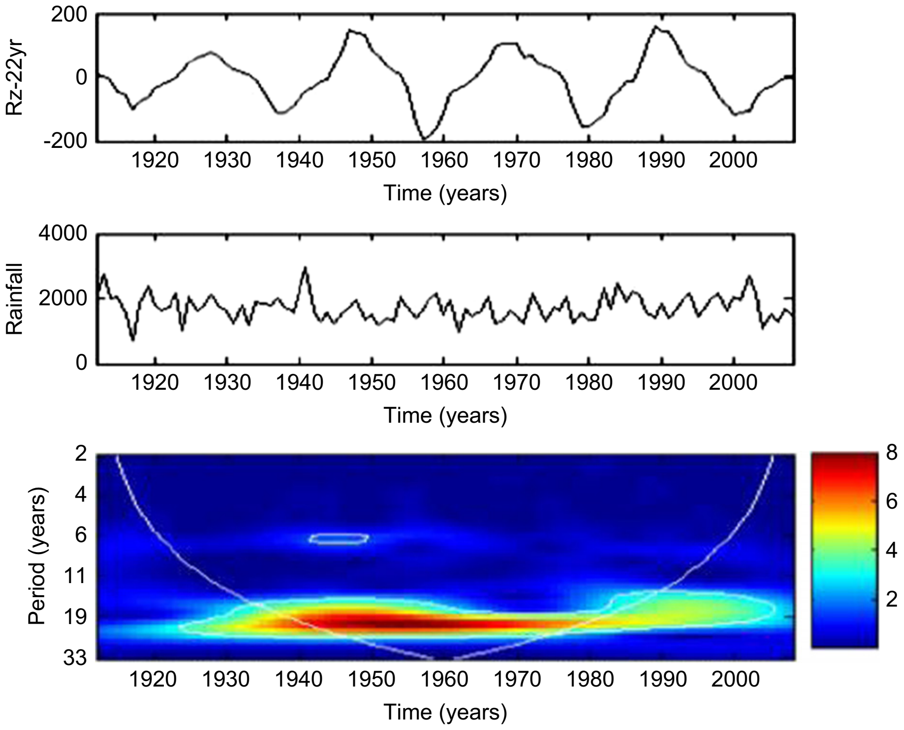

Fig. 8. The Morlet cross-wavelet map between solar activity (represented in terms of Rz-22) and rainfall, with cone of influence (parabolic curve) and significance levels contour for 95%. On the right the legend indicates the cross-wavelet power.

9 was higher than that obtained in Figs. 6 and 7, indicating that the effect of the 22 year solar cycle on climate may be stronger than the 11 year solar cycle. The relationship between Rz-22 yr versus temperature was higher than Rz-22 yr versus rainfall.

These results are in relative agreement with classical spectral analyses, which have showed a peak around 11, and 25 year as well as several peaks between 2 and 6 years. Souza Echer et al. (2008) showed that similar phenomena could influence Pelotas' rainfall variability. This study indicated that Pelotas' rainfall is predominantly affected by ENSO and that cosmic rays also possibly influence the 22 year period. We have found the same results in Santa Maria's meteorological parameters (rainfall and temperature). Rainfall in Santa Maria seems to depend more on ENSO than other phenomena. ENSO is known to have a strong

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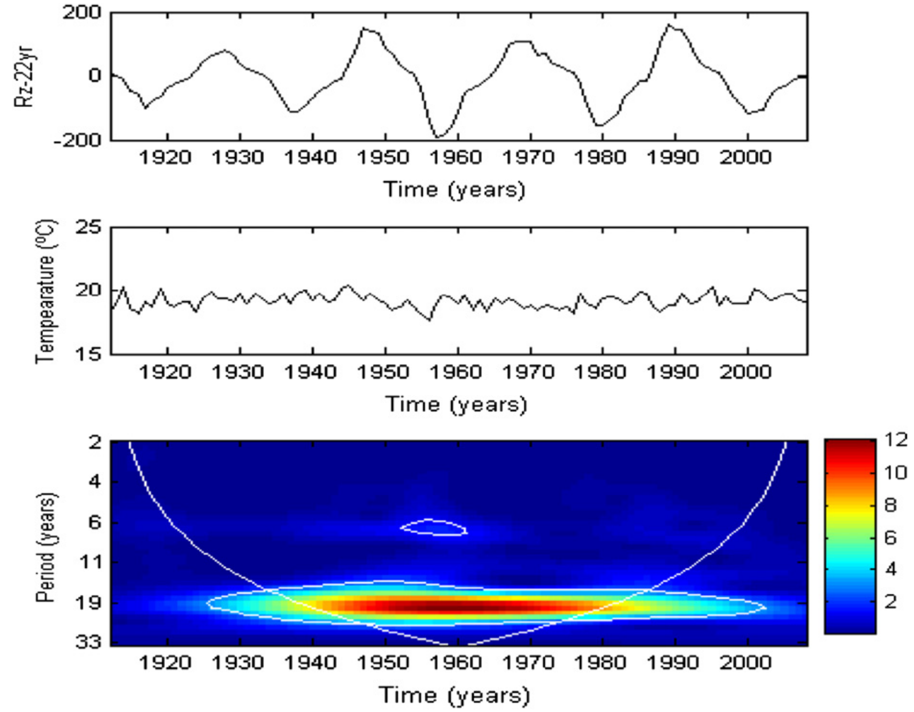

Fig. 9. The Morlet cross-wavelet map between solar activity (represented in terms of Rz-22) and temperature, with cone of influence (parabolic curve) and significance levels contour for 95%. At right the legend indicates the cross-wavelet power.

impact on the climate of South America (Neelin and Latif, 1998), and in Southern Brazil El Niño events are usually followed by stronger precipitation (Dai and Wigley, 2000). The present study seems to corroborate this relationship.

Although there are an extensive scientific literature supporting the view that meteorological phenomena must respond to variations of solar activity, this subject is far from being settled. At present there are two general models on the sun–climate relationship, one based in irradiance variations and the other one based on galactic cosmic ray–cloud cover (Gray et al., 2011).

Variations in solar irradiance may affect climate in two ways. First, changes in total solar irradiance (TSI) can directly impact the surface through ocean heat uptake and sea surface temperature (SST) changes, which affect evaporation and low-level humidity in the atmosphere (van Loon et al., 2007; Meehl et al., 2008). The second way involves changes in stratospheric temperatures and winds due to changes in UV irradiance (Haigh et al., 2005); this region of the atmosphere has the potential to affect the troposphere and hence the surface climate (Haigh, 1999; Matthes et al., 2006). Although there are studies indicating that both proposed mechanisms are operating (Rind et al., 2008; Meehl et al., 2009), Roy and Haigh (2010) suggest that the most probable solar influence is by the effect of changes in the stratosphere resulting in expansion of the Hadley cell and poleward shift of the subtropical jets.

Another model recently proposed to explain the sun–climate relationship links galactic cosmic ray flux variations to the global cloud coverage (Svensmark and Friis-Christensen, 1997; Svensmark, 2007; Kirkby, 2008). According to this model, cosmic ray flux (directly modulated of solar activity) stimulate ionization in the atmosphere, which leads to more nucleation and thus more aerosol particles; these particles serve as cloud condensation nuclei and thus enhance cloud formation (Laken et al., 2010).

While the studies of solar influence on climate via changes in solar irradiance are relatively well advanced, the galactic cosmic ray cloud model have only just begun to be quantified (Gray et al., 2011). However, initial experimental results are favorable to the cosmic ray–cloud mechanisms (Kirkby et al., 2011). Nevertheless, both approaches indicate that the mechanisms involved are not a direct effect of solar activity on rainfall and temperature parameters. In both cases, the solar forcing is likely to be weak. However, even a very weak forcing can cause a significant climate effect if it is present over a long time or if there are nonlinear responses giving amplifying feedbacks (Meehl et al., 2009).

Furthermore, it is important to point out that although solar activity presents a global influence on Earth's climate, in a regional scale, its effect may be variable. In fact, a number of quality studies indicate that the sun–climate relationship varies with time and probably also with geographic position. Depending on the location, the correlation between solar and meteorological data may be positive, negative, or even zero (Zhao et al., 2004). It can be explained by the fact that, although temporal variations of solar irradiance and galactic cosmic ray flux effects are similar, its amplitudes are dependent on geographical position and altitude (Smart and Shea, 2009; Kandel and Viollier, 2010). Furthermore, regional peculiarities of the climate make difficult to determine the relative contribution of the different natural phenomena that are suggested to explain the variability of rainfall and temperature in a specific place (Peixoto and Oort, 1992), among them the El Niño Southern Oscillation (ENSO) and the quasi-biennial oscillation (QBO). ENSO is known to play an important role in the climate system over Southern Brazil. The QBO influences not only the wind and thermal structure at the equator, but also the stratospheric warming and the transport of trace gases, such as ozone, to Polar Regions (Baldwin et al., 2001), which may change the variability of rainfall and temperature. Furthermore, non-linear coupling among Sun–QBO (Labitzke, 2005), QBO–ENSO (Hocke, 2009), or possible Sun–ENSO (Emile-Geay et al., 2007; White and Liu, 2008), may have significant effects on climate over the region investigated.

4. Conclusion

The Earth's climate is affected by several factors acting in different temporal and spatial scales. In this work, we analyzed

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the long term variability of rainfall and temperature (1912–2008) from Santa Maria (29°S, 53°W) and its possible connection with natural influences such as solar activity and ENSO. Temperature and rainfall time series present similar frequencies as revealed by spectral analyses. Our results indicate that in low frequencies, the 22-yr solar cycle is an important factor in the climate modulation during the analyzed period. Superimposed to the Hale cycle, the Schwabe cycle is also statistically significant; however its influence is intermittent. In terms of high frequencies (2–8 years), ENSO is the main influence on temperature and rainfall variability, especially during El Nino events. Furthermore, possible non-linear effects of Sun variability and natural phenomena (QBO–ENSO) may contribute significantly to the regional meteorological variability and should be investigated further. The results presented in this study, performed by qualified methodology, provide the basis for future detailed investigations of hypothetical mechanisms able to explain the observed correlations.

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