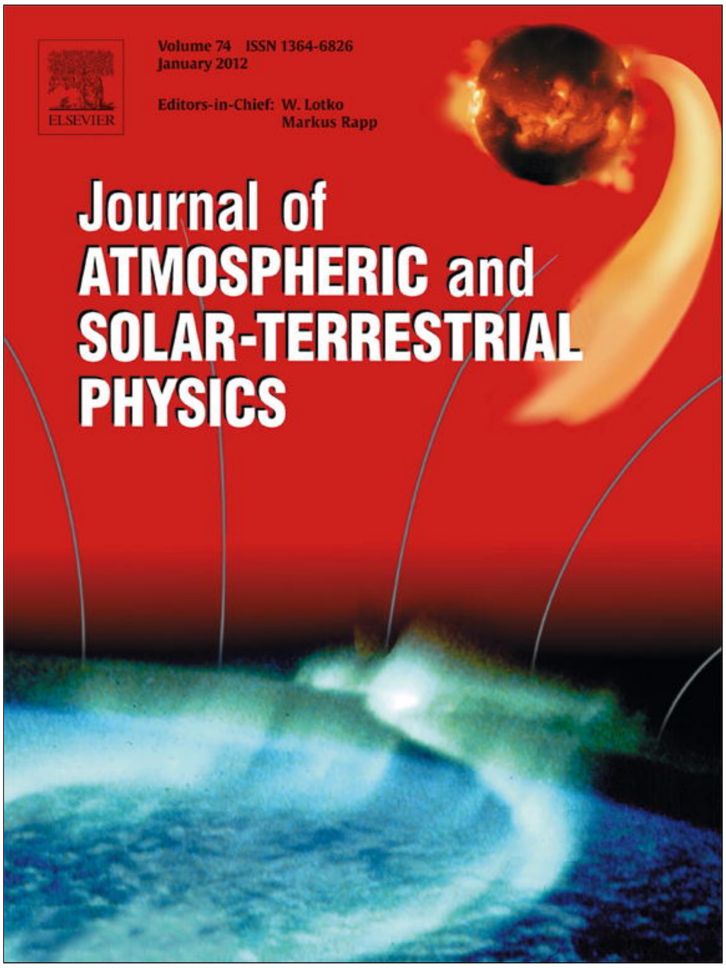
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The relationship between thunderstorm and solar activity for Brazil from 1951 to 2009

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ABSTRACT

The goal of this article is to investigate the influence of solar activity on thunderstorm activity in Brazil. For this purpose, thunder day data from seven cities in Brazil from 1951 to 2009 are analyzed with the wavelet method for the first time. To identify the 11-year solar cycle in thunder day data, a new quantity is defined. It is named TD1 and represents the power in 1-year in a wavelet spectrum of monthly thunder day data. The wavelet analysis of TD1 values shows more clear the 11-year periodicity than when it is applied directly to annual thunder day data, as it has been normally investigated in the literature. The use of this new quantity is shown to enhance the capability to identify the 11-year periodicity in thunderstorm data. Wavelet analysis of TD1 indicates that six out seven cities investigated exhibit periodicities near 11 years, three of them significant at a 1% significance level ($p<0.01$). Furthermore, wavelet coherence analysis demonstrated that the 11-year periodicity of TD1 and solar activity are correlated with an anti-phase behavior, three of them (the same cities with periodicities with 1% significance level) significant at a 5% significance level ($p<0.05$). The results are compared with those obtained from the same data set but using annual thunder day data. Finally, the results are compared with previous results obtained for other regions and a discussion about possible mechanisms to explain them is done. The existence of periodicities around 11 years in six out of seven cities and their anti-phase behavior with respect to 11-year solar cycle suggest a global mechanism probably related to a solar magnetic shielding effect acting on galactic cosmic rays as an explanation for the relationship of thunderstorm and solar activity, although more studies are necessary to clarify its physical origin.

1. Introduction

Variations in solar irradiance are recognized as a fundamental forcing factor in the climate system (Kristjánsson et al., 2002). Although the solar irradiance varies by about 0.1% over the 11-year solar cycle, persistent claims have been made of 11-year signals in various meteorological time series, e.g. sea surface temperature (White et al., 1997) and cloudiness over North America (Udelhofen and Cess, 2001). Despite efforts since the beginning of the nineteenth century to establish a connection between solar activity and thunderstorm activity, this relationship has not been fully understood yet (Brooks, 1934; Rycroft et al., 2000).

Fritz (1878) was one of the first scientists to investigate the long-term variability of thunder day data in association with solar activity. He used thunderstorm frequencies from Europe and North-America between 1755 and 1875 and correlated them with relative sunspot numbers. The results were not conclusive. At some stations he found a positive correlation, at others a negative one. Brooks (1934) made a very comprehensive study of the variation of the annual frequency of thunderstorms in relation to sunspots. It was motivated by the analysis made by Septer (1926) for Siberia who found a high ($R=0.88$) in-phase correlation of the thunderstorm variations and the relative sunspot number. After analyzing a large number of stations in many different places (almost all outside the tropics), Brooks (1934) found a large variation in the correlation of thunderstorm variations and relative sunspot number (R varying from −016 to 0.36) and of phase-difference of thunderstorm activity and sunspots (in 72% of the cases there were an in-phase correlation and in 28% an anti-phase correlation). Myrbach (1935) used a 124-year series of annual thunder day observations in Austria to investigate the relationship of thunderstorm activity and solar activity. He concluded that they were anti-phase correlated with the maximum in the thunder day data occurring just after the solar minimum and its minimum coinciding with the solar maximum. After that, controversial results have been reported indicating in-phase or anti-phase correlations, although there is no basis to expect that the

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relationship between thunderstorm and solar activities would be identical for all regions (Kleymenova, 1967). Kleymenova (1967) reported a global analysis of the relationship between thunderstorm and solar activity at different locations, indicating that in some regions the thunderstorm activity varied in anti-phase with the solar activity, while in others it varied in phase. For example, he found that the thunderstorm activity in North America showed a pronounced anti-phase dependence on solar activity. All over Africa, there was also an anti-phase pattern. Only in China and Germany the number of thunder days varied in phase with the solar activity, although the periods under consideration for these countries were short (about one solar cycle). Kleymenova (1967) also revised the results of Septer (1926) for Siberia and found that his conclusion about the phase behavior was incorrect and concluded that, in general, there was an anti-phase relationship between thunderstorm and solar activities, in agreement with the conclusions obtained previously by Bezold (1884), Myrbach (1935), Sen (1963) and Egeland et al. (1965). It is worth reporting, however, that no detailed information about the data used in the study was presented by Kleymenova (1967). Also, no data for South America was included in that analysis of Kleymenova (1967). Another interesting result was obtained by Aniol (1952), who studied the mean thunderstorm frequency in southern Germany between 1881 and 1950 and its relation to relative sunspot number. He found an insignificant correlation coefficient of −0.02 between both quantities for the whole record. However, when the thunder day data were analyzed for different periods, a change in the correlation sign was evident around 1920; for the years 1889–1913 the correlation coefficient was −0.55, while for the period 1923–1944 it was 0.74. This result suggests that the relationship between thunderstorm and solar activities may change with time. Stringfellow (1974) reported a significant positive correlation between an index for the mean lightning incidence in Britain and sunspot number between 1930 and 1973 with a correlation coefficient of 0.8, in contrast what was found by Brooks (1934) for the same location, also suggesting that the phase behavior may change with time. More recently, Schlegel et al. (2001) found marked a difference in the correlation of lightning data obtained by lightning location systems with solar activity in Germany and Austria. Schlegel et al. (2001) concluded from previous studies that: (i) an influence of solar activity on thunderstorms could not be convincingly established so far, (ii) the correlation coefficient between solar activity and thunderstorm/lightning frequency varies with the location of the observing station on Earth, and (iii) it may change its sign over time scales of a few decades. Additionally, Girish and Eapen (2008) found from a study of thunder/lightning observations in Trivandrum an inverse relation of the same with sunspot activity for selected years between 1853 and 2005. They suggested that lightning-associated modulation of the E-region dynamo currents in the equatorial ionosphere acts as a moderator to regulate electric potential gradient changes in the global electric circuit due to solar activity changes. Also, Siingh et al. (2013) found an apparent inverse relation of the lightning data (obtained from TRMM satellite) with sunspot activity for the period from 1998 to 2010 in India.

The main goal of the present study is to investigate if a relationship exists between the thunderstorm activity in Brazil (Pinto and Pinto, 2003) and the solar activity, using monthly thunder day data (TD_M) for seven cities in Brazil, for which continuous and reliable information is available from 1951 to 2009: Rio de Janeiro, Sao Paulo, Porto Alegre, Campinas, Recife, Salvador and Goiania. In order to investigate if the monthly thunder days in the above cities are correlated with the monthly variation in the solar activity, we used wavelet analysis. In the past, annual thunder day data (TD_A) has been used to identify the 11-year periodicity in thunder day time series through time correlation with sunspot activity or using conventional Fourier analysis. In contrast, in this study the wavelet analysis is used to obtain a time series of the power in one year cycle (named TD1) from TD_M, the most prominent peak in the TD_M spectrum, associated with the well-known seasonal changes of thunderstorm activity (Nickolaenko et al., 1998; Pinto and Pinto, 2008; Williams, 1994, 2009). Then, wavelet analysis of TD1 has been used to identify the 11-year periodicity. Finally, a Wavelet Coherence Spectrum (WCS) analysis is applied to TD1 and sunspot number to find the correlation between the two series and the phase of this correlation in the 11-year cycle. For both GWS and WCS analysis, the results are given with their respective confidence levels.

2. Methods

TD_M data in the cities of Rio de Janeiro, Sao Paulo, Porto Alegre, Campinas, Recife, Salvador and Goiania (Fig. 1) from 1951 to 2009 were used in this study. Data were provided by the stations in the airports in these cities. Most time series began in 1951 and for this reason we adopted this year as the initial one for all cities. Data from Sao Paulo exhibited an approximate 4 year gap around 1968. TD_M data were compared with monthly data related to the solar activity, represented by the International Sunspot Number (ISN), compiled by the National Oceanic and Atmospheric Administration (NOAA) from the World Data Center for the Sunspot Index, Royal Observatory of Belgium. The ISN index stands for a visual sunspot count as a measure of solar activity.

2.1. Wavelet analyses

The time-series frequency domain analysis was done using a *Morlet* continuous wavelet transform (CWT). To investigate possible association between long-term periodicities of the thunderstorm days and solar activity, cross-wavelet and wavelet coherence methods were used. Wavelet, cross-wavelet, and wavelet coherence spectra were generated using Matlab (Matlab 7.11, MathWorks, Inc.) functions developed by several research groups (Torrence and Compo, 1998; Grinsted et al., 2004; Neto et al., 2010). The advantages of the continuous wavelet transform over traditional methods, such as Fourier-based methods, have been well established in the literature (Drago and Boxall, 2002; Karlsson et al., 1999; Meyers et al., 1993; Rioul and Vetterli, 1991; Takeuchi et al., 1994). The strength of the method lies in the fact that time information is conserved and signal variability can be resolved up to levels which would equivalently require a much longer data set with Fourier transform methods (Drago and Boxall, 2002).

To perform a wavelet transform several different generator functions can be used. In this paper, as in most studies that use wavelet transforms to quantify the frequency content of meteorological data (e.g. Elsayed, 2007; Grinsted et al., 2004; Partal, 2010; Torrence and Compo, 1998), the Morlet mother wavelet was used (Eq. (1); Torrence and Compo, 1998).

$$\Psi_0(t) = \pi^{-\frac{1}{4}} e^{i w_0 \eta} e^{\frac{-\eta^2}{2}} \quad (1)$$

where η is dimensionless time and w_0 is dimensionless frequency (in this study we used $w_0 = 6$, as it yields the function to have zero mean and be localized in both time and frequency space, as well as it provides a good balance between time and frequency (Grinsted et al., 2004). The wavelet transform applies the wavelet function as a band-pass filter to the time series (Eq. (2)).

$$W(s,\tau)^X = \int X(t) \Psi^*_{s,\tau}(t) dt \quad (2)$$

where X represents the time-series, s represents the wavelet scale or the dilation parameter (scale shifting, similar to the Fourier period), τ represents the location parameter (time shifting), the (*)

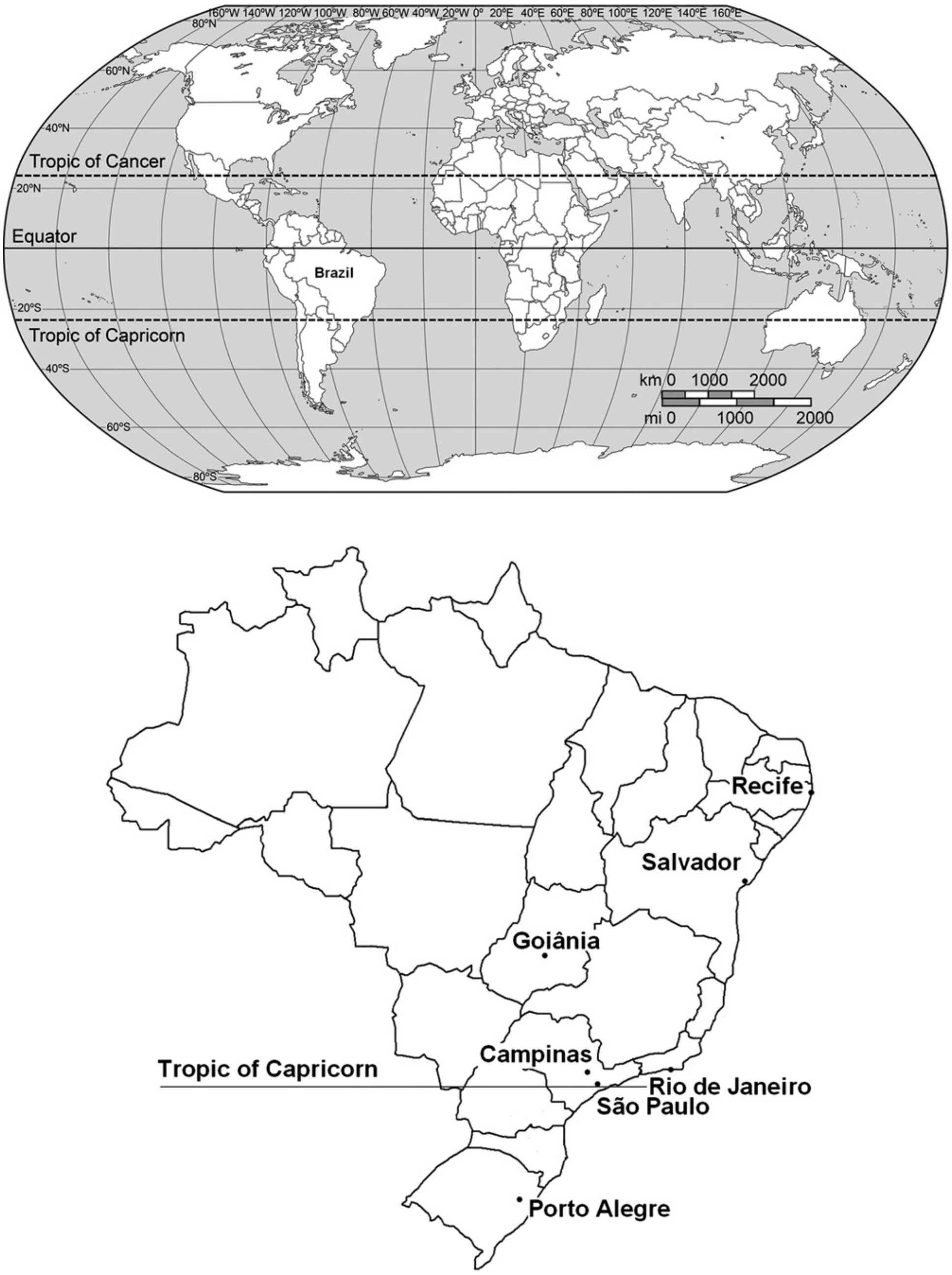

Fig. 1. World map and map of Brazil indicating the location of the seven cities were thunderstorm days were recorded from 1951 to 2009 used in this study.

indicates the complex conjugate, and the basic function $\Psi_{s,\tau}(t)$ is obtained by dilating and translating the mother wavelet Ψ_0 (t) (Addison, 2002).

From the wavelet transform of TD_M and TD_A for each city and the ISN, we obtained the time-averaged wavelet power spectrum (or Global Wavelet Spectrum—GWS) normalized by scale by calculating the average in time of the squared modulus wavelet transform normalized by the scale (Eq. (3)).

$$GWS^x = \sum_{\tau=i}^{\tau=n} \frac{|W^X(s,\tau)|^2}{s} / n \tag{3}$$

where n is the number of data points in the time series X.

Additionally, from the wavelet transform of TD_M for each city we also calculated the year-to-year fluctuations of the annual cycle within the data (TD1) based on Eq. (4). Note that TD1 is a new quantity that represents a time series of power.

$$TD1^x = \sum_{s=21}^{s=23} \frac{|W^X(s,\tau)|^2}{s} \tag{4}$$

Then, we obtained the wavelet transform of TD1, from which a GWS was estimated. As it will be shown in the results (Section 3), the use of TD1 instead of annual thunder day data enhances the capability to find the 11-year periodicity in the thunder day data.

2.1.1. Cross-wavelet and wavelet coherence

Cross-wavelet and wavelet coherence were estimated between TD1 data and the ISN. Analyses were performed between each city's TD1 (hereafter referred to by the name of the city followed by TD1, for example Rio de Janeiro TD1) and the ISN.

From the wavelet transform of two time series, the cross-wavelet transform can be calculated using Eq. (3) (Torrence and Compo, 1998).

$$W(s,\tau)^{XY} = W(s,\tau)^{X} W(s,\tau)^{Y*} \quad (5)$$

where $W(s,\tau)^{XY}$ is the cross-wavelet transform of signals $X(t)$ and $Y(t)$, $W(s,\tau)^{X}$ is the wavelet transform of signal $X(t)$, and $W(s,\tau)^{Y*}$ is the complex conjugate of the wavelet transform of signal $Y(t)$.

We quantified how coherent the cross-wavelet transform is in the time frequency space determining the normalized cross-wavelet coherence power spectrum (WCS), which identifies localized correlation coefficients in the wavelet time frequency space (Eq. (4); Grinsted et al., 2004).

$$R_n^2(s,\tau)^{XY} = \frac{|S(s^{-1}W^{XY}(s,\tau)|^2}{S(s^{-1}|W^{X}(s,\tau)|^2) \times S(s^{-1}|W^{Y}(s,\tau)|^2)} \quad (6)$$

where S is a smoothing operator that has a similar footprint as the *Morlet* wavelet (Torrence and Webster, 1998). The WCS shows the correlation between the common frequencies of two signals with values ranging from 0 to 1. Additionally, the coherence spectrum shows the relative phasing of the two time series in question, as arrows. Phase arrows pointing right mean in-phase time series, while pointing left means anti-phase, pointing down means time series 1 leading time series 2 by 90°, and pointing up means time series 2 leading time series 1 by 90°.

2.2. Statistics

The statistical significance level of the GWS and WCS were estimated using Monte Carlo methods (Torrence and Compo, 1998; Grinsted et al., 2004). In order to determine the significant periodicities in the GWS of the TD and ISN data, we generated and quantified the wavelet spectra of an arbitrary ensemble of 1000 surrogate data sets with the same first order autoregressive (AR1) coefficients as the input datasets (values larger than 1000 were tested without no significant changes). Additionally, to determine the significant periodicities in the GWS of TD1, we generate 1000 surrogate AR1 data sets, determine the annual periodicity within each surrogate data set and then calculate the wavelet transform of each annual periodicity surrogate data. To determine the significant regions in the wavelet coherence spectra, we generated 1000 surrogate AR1 data sets and 1000 annual periodicity data sets (obtained from another 1000 surrogate AR1 data sets), and then estimated the cross-wavelet and wavelet coherence of 1000 pairs of surrogate data. Two significance levels were estimated: α=0.05 and α=0.01. Only results obtained outside the cone of influence (COI) were considered. The COI is the region of the wavelet spectrum in which edge effects become important and is defined as the e-folding time for the autocorrelation of wavelet power at each scale (Torrence and Compo, 1998).

3. Results

Wavelet analysis of ISN indicated one distinct significant ($p<0.01$) periodicity of 11 years (Fig. 2). The same analysis for TD_M indicated only one distinct significant ($p<0.01$) periodicity in 1-year, for all cities (Fig. 3), without significant periodicity around 11 years. Fig. 4 snows the wavelet analysis for TD_A for the same cities in Fig. 3. In this case, which corresponds many previous studies (except that, most of them used conventional Fourier analysis) some periodicities in 2, 3 and 12 years are significant ($p<0.01$). The presence of peaks with periodicities other than one-year and 11-years indicates that other physical phenomena should influence annual thunder day data. The use of TD_M time series, however, allows to obtain TD1 and the wavelet analysis of TD1 indicated only one significant ($p<0.01$) periodicity in 11 years (Fig. 5). In particular, the periodicity in 11 years was highly significant ($p<0.01$) for three cities: Rio de Janeiro, Recife and Sao Paulo.

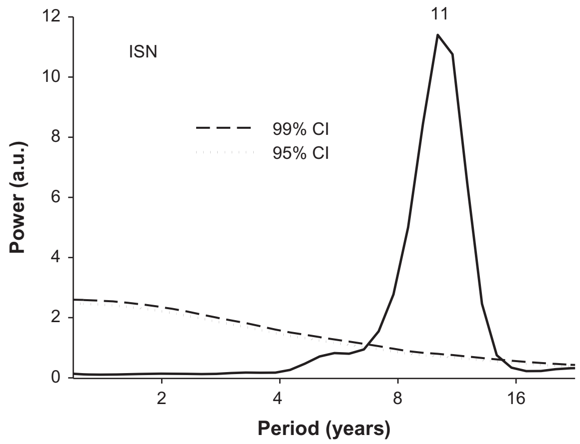

Fig. 2. Global wavelet spectrum (GWS) in arbitrary units of International Sunspot Number (ISN). Lines for confidence interval (CI) of 99% and 95% are indicated.

Fig. 6 shows a comparison between the amplitude of the 11-year signal and the annual variation in the monthly thunder day data. It can be seen from Fig. 6 that the one-year amplitude is modulated by the 11-year cycle, supporting the introduction of the new quantity TD1.

The results presented in Figs. 4 and 5 are compared in detail in Tables 1 and 2. Table 1 shows values of latitude, periodicity in years near 11-year cycle with significance level and time correlation (R^2 and phase) between TD1 and ISN for the 11-year cycle for the whole period outside the COI for all cities studied and Table 2 the same for TD_A and ISN. The comparison of Tables 1 and 2 shows that more significant peaks as well as higher correlation coefficients can be seen in Table 1. So, the use of TD1 instead of TD_A shows more clearly the periodicity in the 11-year cycle and higher time correlation. In both tables the correlation is always in anti-phase for all cities where the 11-year periodicity was identified.

Fig. 7 shows the TD1 time series for these three cities along with the time series of ISN. The time correlation between ISN and TD1 for the three cities is significant (see Table 1 afterwards), although not so evident in this figure.

The parameters shown in Table 1 for the time correlation between TD1 and ISN for the 11-year cycle for the whole period for Rio de Janeiro, Recife and Sao Paulo are consistent with the results of wavelet coherence analysis between the TD1 and ISN for these cities (Fig. 8). Fig. 8 indicates that, at a 5% significant level, the 11-year periodicity in TD1 from each city was significantly correlated with the 11-year periodicity in ISN for the period of analyses outside the COI (1966 to 1990) with a predominant anti-phase behavior (indicated by the predominant arrows orientation to left side in the figures).

4. Discussion and summary

The above results demonstrate that the long term (more than one year) variability of the thunderstorm activity in Brazil can be primarily explained by one distinct periodicity of 11 years (Fig. 5). The 11-year periodicity was significant at a 1% significance level for three cities: Rio de Janeiro, Recife and Sao Paulo. Time correlation and wavelet coherence analysis indicated that this periodicity, for these three cities, was correlated with the 11-year solar cycle (Fig. 7) for the whole period of analysis with a

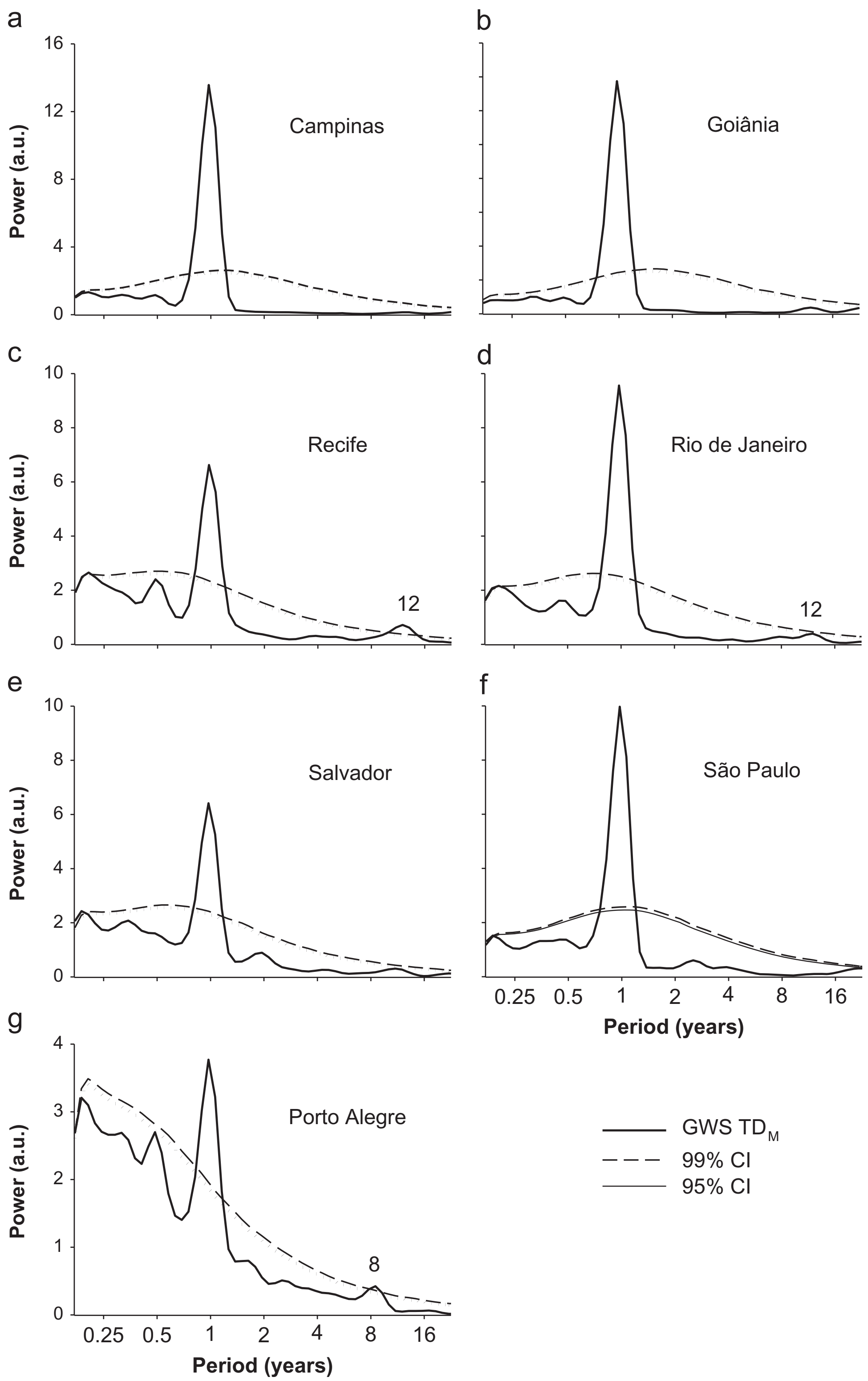

Fig. 3. Global wavelet spectrum (GWS) in arbitrary units of monthly thunder day data (TD_M) of: (a) Campinas, (b) Goiania, (c) Recife, (d) Rio de Janeiro, (e) Salvador, (f) São Paulo and (g) Porto Alegre. Lines for confidence interval (CI) of 99% and 95% are indicated.

predominant anti-phase behavior. For three other cities (Goiania, Salvador and Campinas) the 11-year was also identified, although with lower level of significance, and in these cases also the anti-phase behavior was evident. Only in one city (Porto Alegre) the 11-year periodicity was not identified conclusively. This anti-phase behavior agrees with most previous reports for several other regions on Earth (Kleymenova, 1967; Lamb, 1972).

The reason for an anti-phase correlation between thunder day and the ISN is not clear. Nevertheless, there are more than one possible physical mechanism to explain the relationship between

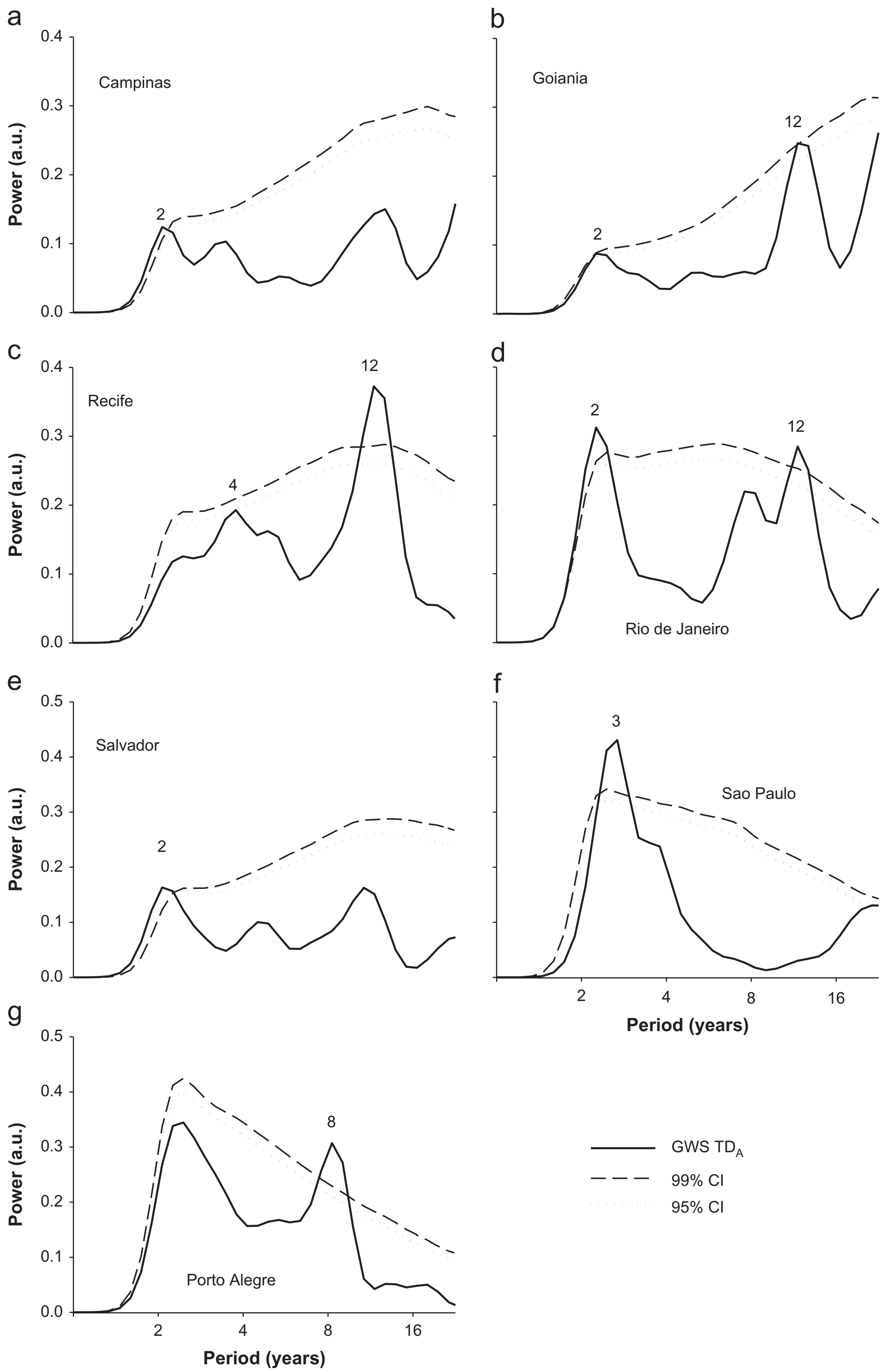

Fig. 4. Global wavelet spectrum (GWS) in arbitrary units of annual thunder day data (TD_A) of: (a) Campinas, (b) Goiania, (c) Recife, (d) Rio de Janeiro, (e) Salvador, (f) São Paulo and (g) Porto Alegre. Lines for confidence interval (CI) of 99% and 95% are indicated.

solar and thunderstorm activity. They are basically related to changes in the cosmic ray fluxes reaching the Earth's atmosphere modulated by the solar activity and its impact on the cloud microphysics, air conductivity and ionospheric potential (Herman and Goldberg, 1978; Markson and Muir, 1980; Markson, 1978, 1981; Tinsley, 2000; Benestad, 2002; Harrison and Usoskin, 2010). All these mechanisms tend to act at global scale and to be latitude dependent due to the Earth's magnetic field configuration.

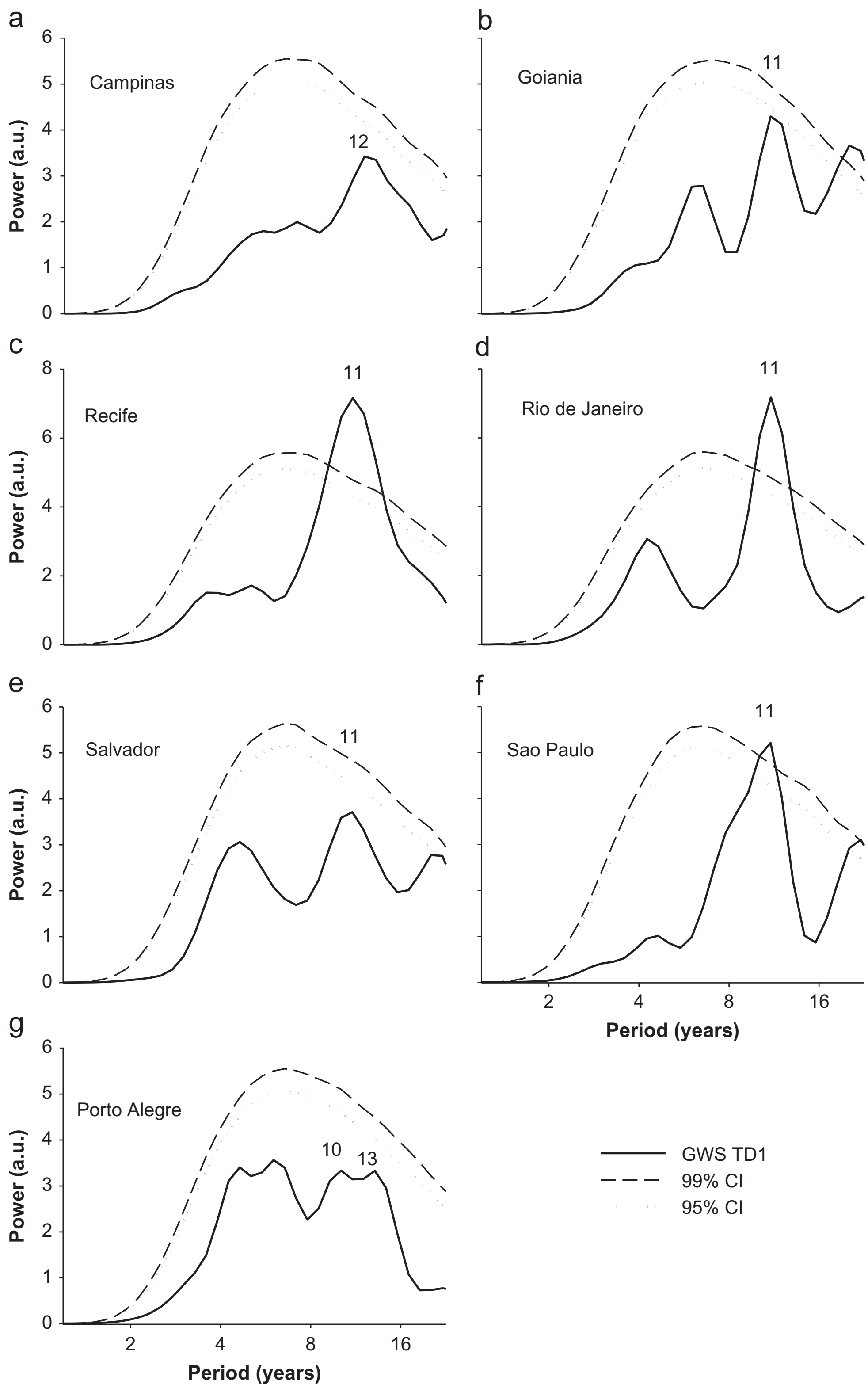

Fig. 5. Global wavelet spectrum (GWS) in arbitrary units of the power of the 1-year cycle within monthly thunder day data (TD1) of: (a) Campinas, (b) Goiania, (c) Recife, (d) Rio de Janeiro, (e) Salvador, (f) São Paulo and (g) Porto Alegre. Lines for confidence interval (CI) of 99% and 95% are indicated.

Our results indicate that only 3 out of the 7 cities investigated exhibit a significant correlation between solar and thunderstorm activities with an anti-phase correlation, although three other cities shows the same tendency with a lower level of statistical confidence. Only in one city (Porto Alegre) no clear evidence of an 11-year cycle was found. No clear explanation for this lack of evidence was found, although it is worth noting that Porto Alegre is the only city studied that is outside the tropics. It is possible that changes in the significance of the 11-year cycle in the thunderstorm activity in different cities can be a result of changes in the global circulation caused by variations in the solar radiation, which affects thunderstorm occurrence at different places. Evidence on this mechanism has been found by Balachandran et al. (1999), Arnold and Robinson (1998, 2000) and Schlegel et al. (2001), who suggested that the solar radiance may affect the developments of planetary waves and, in consequence, the atmospheric circulation. The effect of planetary waves on localized convection has been discussed by many authors (e.g. Hall, 1989; Hendon and Wheeler, 2008). In contrast with the other mechanisms mentioned previously, such mechanism could explain the observed spatial (not only latitude dependent) variability of the correlation (intensity and phase) between thunderstorm and solar activity in different studies (e.g. Brooks, 1934). Clearly more studies would be necessary to clarify this point.

In summary, for the first time the correlation between solar and thunderstorm activity in Brazil was investigated for several cities. We presented a new and more robust statistical analysis based on the wavelet analysis applied to the fluctuations in the variability of the power in one-year cycle of monthly thunder day data instead of applied to annual thunder day data. The results were also accomplished with statistical significance tests with 5 and 1% significance levels, not always reported in previous studies.

Our results suggest a significant correlation between solar and thunderstorm activity, from 1951 to 2009, for three out seven cities in Brazil with an anti-phase behavior. Three other cities showed the same behavior with lower level of statistical significance. Table 3 shows a summary of the results obtained by different authors at different locations and periods. Although there are some controversial results in the literature, most of the published results at middle latitudes suggest an anti-phase

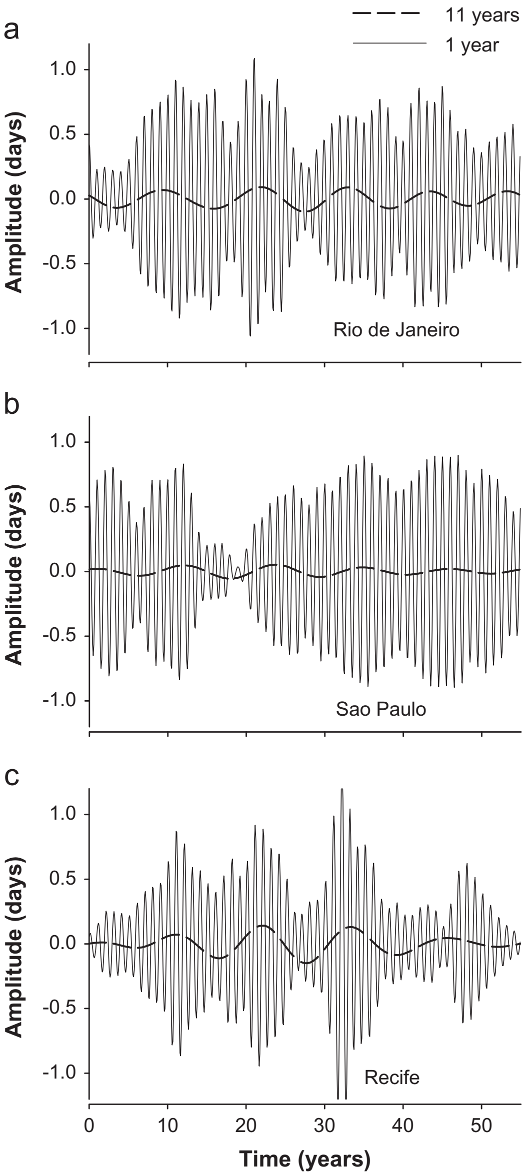

Fig. 6. Comparison between the amplitude of the 11-year signal and of the annual variation in the monthly thunder day data for (a) Rio de Janeiro, (b) São Paulo and (c) Recife.

Table 2
Values of latitude, periodicity in years near 11-year cycle with significance level and time correlation (R^2 and phase) between TD_A and ISN for the 11-year cycle for the whole period for all cities studied (see text for details).

City	Latitude (degrees S)	Periodicity in years near 11-year cycle (significance level)	Correlation between TD_A and ISN for the 11-year cycle for the whole period outside the COI	
			R^2	Predominant phase (years)[a]
Rio de Janeiro	22.6	12 (> 99%)	0.70	5.3
São Paulo	23.5	–	–	–
Recife	8.1	12 (> 99%)	0.72	5.0
Porto Alegre	30.1	–	–	–
Goiania	16.4	12 (99%)	0.50	5.5
Salvador	12.6	–	–	–
Campinas	22.8	–	–	–

[a] Values near 5.5 years represent anti-phase variation and near 0 represent in-phase variation.

Table 1
Values of latitude, periodicity in years near 11-year cycle with significance level and time correlation (R^2 and phase) between TD1 and ISN for the 11-year cycle for the whole period outside the COI for all cities studied (see text for details).

City	Latitude (degrees S)	Periodicity in years near 11-year cycle (significance level)	Correlation between TD1 and ISN for the 11-year cycle for the whole period outside the COI	
			R^2	Predominant phase (years)[a]
Rio de Janeiro	22.6	11(> 99%)	0.83	5.0
São Paulo	23.5	11 (> 99%)	0.83	4.1
Recife	8.1	11 (> 99%)	0.77	5.4
Porto Alegre	30.1	–	–	–
Goiania	16.4	11 (> 95%)	0.59	5.1
Salvador	12.6	11 (> 95%)	0.68	4.6
Campinas	22.8	12 (> 95%)	0.22	5.2

[a] Values near 5.5 years represent anti-phase variation and near 0 represent in-phase variation.

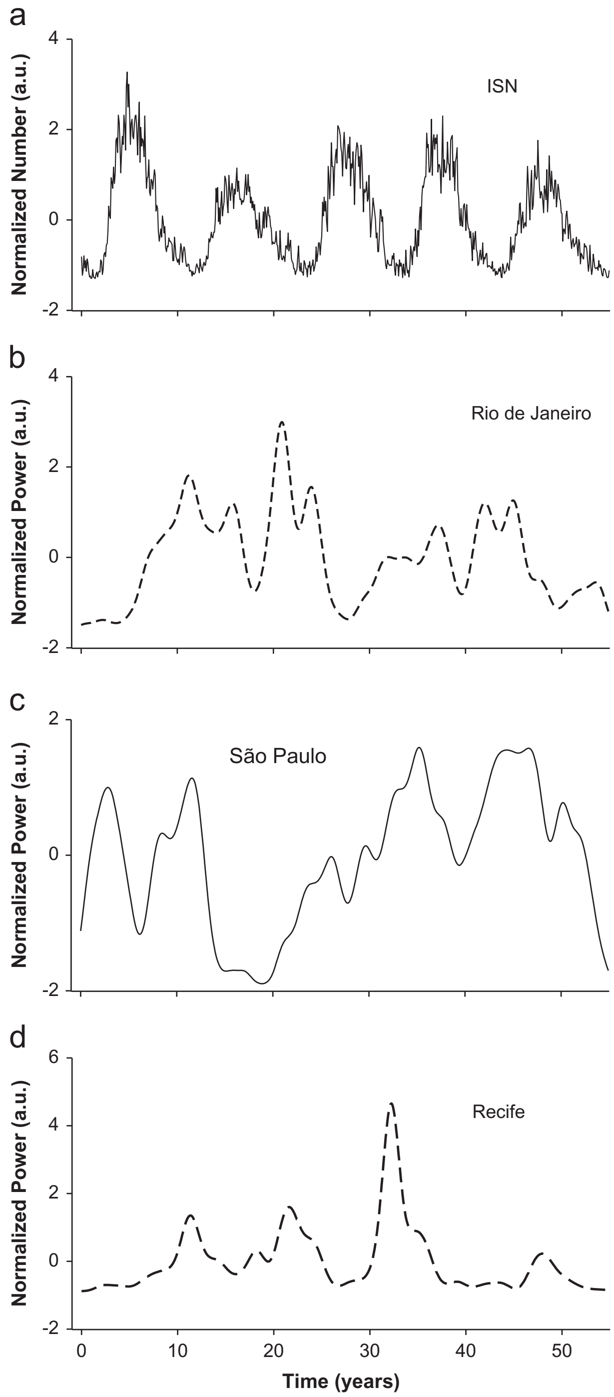

Fig. 7. Time series of: (a) ISN, (b) TD1 in Rio de Janeiro, (c) TD1 in São Paulo and (d) TD1 in Recife. Values are normalized by subtracting the average and dividing by the standard deviation.

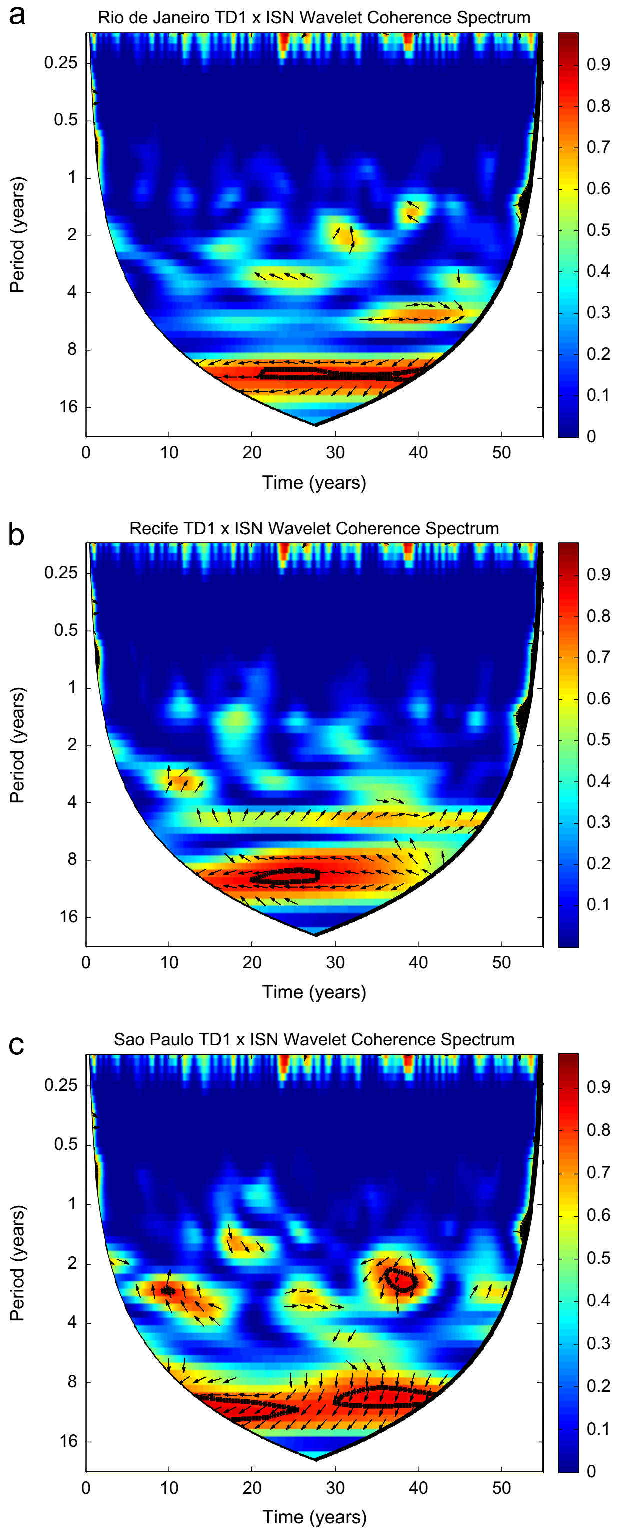

Fig. 8. Wavelet transform coherence spectrum (WCS) of the International Sunspot Number (ISN) with TD1 in: (a) Recife, (b) Rio de Janeiro and (c) São Paulo. It shows the correlation between the frequency content (y-axis) of the two time-series through time (x-axis) with R^2 values, ranging from 0 to 1, color coded from blue to red. Thick contours indicate 1% and 5% significance levels. Arrows show phase behavior (arrows oriented to the right (left) side means in-phase (anti-phase)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

behavior, in agreement with the results found in this article. At very high latitudes, however, the available evidences suggest an in-phase behavior and at low-latitudes anti-phase behavior. The possibility that the solar and thunderstorm activities shows an in-phase relationship at high latitudes and an anti-phase relationship at low latitudes is in agreement with the suggestion given by Markson (personal communication, 2012) that magnetic shielding effects at low latitude stations may promote anti-phase behavior at low latitude, but that in-phase behavior may be more prevalent at high latitudes if the energetic radiation from the Sun during solar max are more prevalent then and these particles are less effectively shielded.

Finally, we suggest that more studies should be done using the methodology described here in order to verify if the relationship between the thunderstorm and solar activity also occur in other regions on Earth.

Table 3
Summary of the observations of the phase correlation between thunderstorm and solar activities.

Author	Location	Period	Behavior
Fritz (1878)	Europe and North-America	1755–1875	In-phase and anti-phase
Septer (1926)	Siberia	1888–1924	In-phase
Brooks (1934)	Europe, North-America, Asia, Japan, Australia, New Zealand and Tropical Pacific Islands	1867–1928	In-phase and anti-phase
Myrbach (1935)	Austria	1810–1934	Anti-phase
Kleymenova (1967)	North-America, Africa, China and Germany	Review past data	In-phase and anti-phase
Aniol (1952)	Germany	1881 and 1950	Change with time with periods in-phase and periods anti-phase
Stringfellow (1974)	Britain	1930–1973	In-phase (in same region where Brooks found anti-phase in a previous period)
Girish and Eapen (2008)	India	1853–2005	Anti-phase
Siingh et al. (2013)	India	1998–2010	Anti-phase

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