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Signal of the ENSO phenomenon in rainfall in the western Paraná region

Sinal do fenômeno ENOS na precipitação pluvial da região Oeste do Paraná

Isabel Tamara Pedron [*], **Leila Limberger** [**]
* Centro de Ciências Agrárias, Universidade Estadual do Oeste do Paraná, Marechal Cândido Rondon, Brazil, itpedron@yahoo.com.br
**Departamento de Geografia, Universidade Estadual do Oeste do Paraná, Marechal Cândido Rondon, Brazil, leila.limberger@gmail.com

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Abstract

One of the modulators of variability in the precipitation pattern in the southern regionof Brazil is the El Niño/Southern Oscillation (ENSO) phenomenon, the focus of this study, which aimed to investigate the influence of ENSO in western Paraná, southern Brazil. The complexity of the manifestation on a local scale (precipitation) of a phenomenon on a global scale (ENSO) was evaluated. The study was developed using monthly rainfall series for Cascavel, Toledo, Palotina, Foz do Iguaçu, and Guaíra. The results indicated that there is no uniform behavior across the region for signal identification of the effects of ENSO events. Only Cascavel and Palotina showed a significant Spearman correlation between monthly accumulated precipitation and the ONI index (Oceanic Niño Index), not only in paired data (same month) but also lagged from one to four months. On the other hand, the wavelet analysis indicated the signal of the ENSO phenomenon in the rainfall data, highlighting the peak in periods from two to seven years in the power spectrum for Cascavel, Foz do Iguaçu, and Palotina. In the wavelet coherence analysis, all locations exhibited a correlation between the ONI index and the monthly rainfall, over the period of around four years. This study highlights the complexity of the manifestation of ENSO on a local scale, considering that the climate variability of the cities analyzed does not respond only to this variability modulator. It is necessary to consider other oceanic areas and local factors that generate variability, highlighting the challenge posed for the weather forecast.
Keywords:
Climate modes, Precipitation, ONI, Wavelets

Resumo

Um dos moduladores da variabilidade no padrão de precipitação na região Sul do Brasil é o fenômeno El Niño/Oscilação Sul (ENOS), foco deste estudo que tem como objetivo investigar a influência do ENOS no Oeste do Paraná, sul do Brasil. Avaliou-se a complexidade de manifestação em escala local (precipitação pluvial) de um fenômeno de escala global (ENOS). O estudo foi desenvolvido utilizando-se série mensal de chuva para Cascavel, Toledo, Palotina, Foz do Iguaçu e

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Guaíra. Os resultados indicam que não há um comportamento uniforme em toda a região para a identificação de sinal dos efeitos dos eventos ENOS. Somente Cascavel e Palotina apresentaram correlação de Spearman significativa entre acumulados mensais de precipitação e o índice ONI (Oceanic Niño Index), não só em dados pareados (mesmo mês) como também defasados de um a quatro meses. Por outro lado, a análise de ondeletas indica o sinal do fenômeno ENOS nos dados de chuva, ressaltando o pico nos períodos de dois a sete anos no espectro de energia para Cascavel, Foz do Iguaçu e Palotina. Na análise de coerência em ondeletas, todos os locais exibem correlação entre o índice ONI e as séries de acumulados mensais, no período em torno de quatro anos. Este trabalho destaca a complexidade da manifestação do ENOS em escala local, sendo que a variabilidade climática das cidades analisadas não responde somente a esse modulador de variabilidade. É necessária a consideração de outras áreas oceânicas e outros fatores, locais, que geram variabilidade, evidenciando o desafio posto para a previsão climática.
Palavras-chave:
Modos climáticos, Chuva, ONI, Ondeletas

I. Introduction

All natural elements go through cyclicities, and the interactions between the elements that make up the climate (atmosphere, biosphere, hydrosphere, lithosphere, cryosphere) generate both the global climate zones and diverse patterns of variability via complex interactions in the Surface-Atmosphere System. Climatology studies aim, to a great extent, to understand how this complex interaction occurs in different places on the planet, which is reflected in climate variability.

In the Surface-Atmosphere System, one of the main modulators of climate variability is the ocean (WELLS, 1998). Heat, water, momentum, radiatively important gases (such as CO_2) and many other substances cross the surface of the seas, making the ocean a central component of the climate system, particularly on large temporal scales (MARSHALL; PLUMB, 2008). The ocean has a much greater capacity than the atmosphere to store heat, as the ocean is a thousand times more dense than air and its "specific heat is approximately 4 times that of air; one should also consider the fact that the ocean covers approximately 70% of the surface of the planet" (MARSHAL; PLUMB, 2008, p. 261). The ocean and atmosphere form a coupled system, and an anomaly in one can have repercussions on the other. Sea Surface Temperature (SST) anomalies are atmospheric forcing that also generate climate variability (SILVA; SILVA, 2012), since "circulation anomalies start in the atmosphere, but the ocean tends to keep them persistent" (WELLS, 1998, p. 326).

Among the patterns of SST anomalies that couple to the atmosphere and generate anomalous circulation patterns (which, in turn, generate climate variability), the phenomenon of greatest global climatic importance is the El Niño/Southern Oscillation (ENSO).

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ENSO is a global-scale oscillatory climate phenomenon that occurs at the oceanic and atmospheric levels, characterized by a warming or cooling of surface waters in the Equatorial/Tropical Pacific Ocean, constituting the El Niño and La Niña phenomena, respectively (CAI et al*.,* 2020). It is one of the largest modulators of climate variability in South America and in other regions of the planet due to changes in circulation, including changes in the transfer of heat from the ocean to the atmosphere, the generation of Rossby waves such as the Pacific South America (PSA) pattern, and by changes in Walker cell circulation (BARROS et al*.,* 2008; TEDESCHI et al*.,* 2012; LIN; QIAN, 2019; CAI et al*.,* 2020).

For the region of Southern Brazil, El Niño causes an increase in precipitation while La Niña causes a decrease, especially in spring and early summer, when the phenomenon begins (GRIMM et al*.,* 1998; GRIMM; TEDESCHI, 2009). While it is not only the oceanic area that modulates the global climate, ENSO is by far the most important mode of low-frequency variability, and explains about 50% of the genesis of rainfall in Southern Brazil (GRIMM; AMBRIZZI, 2009).

Currently, there is a discussion about the different types of ENSO and how they affect global climate variability. These different types are classified as Eastern, Central, or Mix, depending on the location of the greatest warming (ASHOK et al., 2007; McPHADEN, 2011; TEDESCHI et al*.,* 2015; 2016; CAI et al*.*, 2020). Goudard et al*.* (2022), using GPCC precipitation data, identified that the effects of East and Central El Niño for Southern Brazil vary in intensity and spatial pattern, and in East EN events, rainfall anomalies are more consistent with what was found in the literature; i.e. there are positive rainfall anomalies in Southern Brazil, while in Central EN events the positive anomalies are weaker or even non-existent, with negative precipitation anomalies in certain months.

In addition, Lin and Qian (2019) indicated a new way of verifying ENSO events, no longer in the pattern of El Niño (warm waters), La Niña (cold waters) and neutral events. These authors proposed an analysis of the life cycle from one event to another: the hot period, the hot to cold period, the cold period, the cold to hot period. They demonstrated that, for the entire globe, the patterns of precipitation anomalies are different in each of these proposed phases.

In short, it is clear that the ENSO phenomenon is very important for climate variability across the globe and that it is very complex, with new analytical proposals being presented as science on the subject develops (CAI et al*.*, 2020).

Thus, the aim of this article is to determine the influence of ENSO on different cities in Western Paraná, demonstrating the complexity of identifying its effects on a local scale. The article asks whether the effects of

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ENSO in different cities in Western Paraná have the same intensity and frequency. Or can the manifestation of the effects of global scale phenomena be influenced by local climate factors?

The article seeks to contribute to the discussion on the complexity of defining the effects on a local scale of the ENSO phenomenon, the main modulator of global climate variability.

Precipitation series from five meteorological stations in the region were used, focusing on the wavelet analysis method, thereby improving climate forecast models for better planning by farmers and managers e of water resources.

II. Materials and Methods

Data and regional characterization

The study was developed using precipitation data from the cities of Cascavel, Toledo, Palotina, Foz do Iguaçu and Guaíra (Figure 1). Rainfall series from Iapar (Agronomic Institute of Paraná, currently Institute of Rural Development of Paraná - IDR) were used for Cascavel and Palotina, and from Simepar (Meteorological System of Paraná) for Foz do Iguaçu, Guaíra and Toledo for the following time frame: from 1973 (Cascavel and Palotina) and from 1997 (Foz do Iguaçu, Guaíra and Toledo), all until 2017. In the study, series of monthly accumulated rainfall were used. In addition, monthly averages and their respective standard deviations were calculated.

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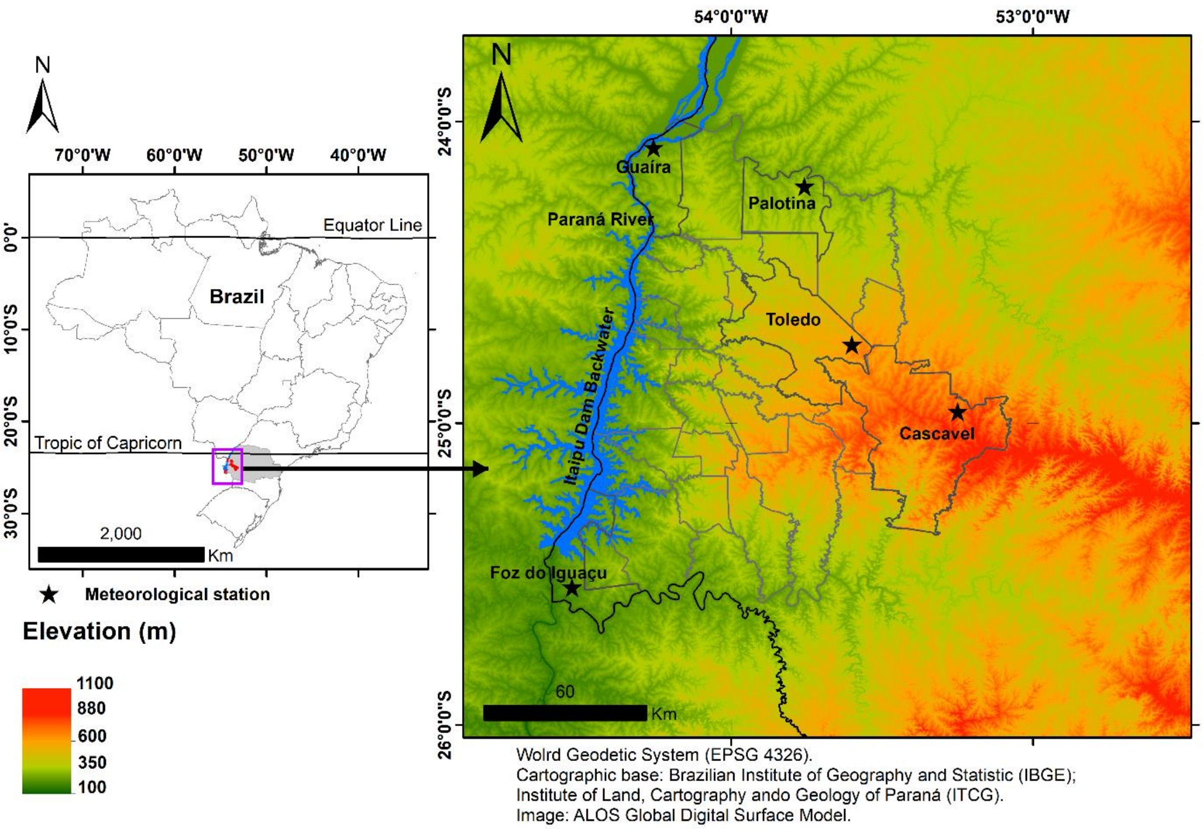

Figure 1. Location of selected meteorological stations in Western Paraná. (Elaborated by the authors).

The region has a humid subtropical climate and is influenced by tropical and polar air masses: the Atlantic tropical air mass, the continental tropical air mass and the polar air mass (MENDONÇA; DANNI-OLIVEIRA, 2007). The incursions of hot and humid air that move from the north and center of Brazil occur practically throughout the year and are a source of moisture for rainfall in the region (MANGILI, 2021). This flow transports moisture from the Amazon basin to Southeastern and Southern Brazil via low-level jets (LLJs) (LIEBMANN et al*.,* 2004). Many severe rain and wind events result from the meeting of cold air masses (polar) with these warm and humid air masses that come from the tropical north, associated with frontal rains. From October to May, mesoscale convective complexes (MCCs) are frequent and contribute a part of the total rainfall (DURKEE; MOTE, 2010). Convective rains, associated with precipitation extremes and floods, predominate from November to March. Another active system is a low pressure center that originates in Paraguay, Southern Bolivia and Northwest Argentina, the so-called Chaco Depression (GRIMM, 2009). The South Atlantic high pressure system also influences surface winds, stronger in winter when it penetrates deeper into the continent.

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Index of the ENSO phenomenon

Studies that address modes of climate variability can be conducted by correlating climate data on continents with sea surface temperature (SST) data, as in Limberger (2015). Ocean indices calculated by meteorological research institutes can also be used, as performed by Lindemann and Justino (2015). In this study, observed precipitation data and data from oceanic indices that assess the ENSO phenomenon were used. As there are several indices associated with this phenomenon, in this research the Oceanic Niño Index (ONI) was used.

The ONI is calculated from the sea surface temperature (SST) and serves to identify El Niño (warm) and La Niña (cold) events in the tropical Pacific. Data were obtained from NOAA (2022).

The index is derived from the average anomaly from 3 months of SSTs observed in the Niño 3.4 region (area comprising 5°N-5°S, 120°-170°W). Events are defined as 5 consecutive 3-month overlapping periods at or above the +0.5° anomaly for warm events (El Niño), and at or below the -0.5° anomaly for cold events (La Niña). The classification of the indices considers the definition of weak events (with average SST anomalies from 0.5 to 0.9), moderate (1.0 to 1.4), strong (1.5 to 1.9), and very strong events (≥ 2.0), and the criterion used for categorization of weak, moderate, strong or very strong events is defined when the mean SST anomalies equal or exceed the threshold of at least 3 consecutive overlapping periods of 3 months observed (ONI, 2022).

The methodology at this point considered in block weak, moderate and strong intensities of the events, that were classified as presented in https://ggweather.com/enso/oni.htm.

Spearman Correlation

In the quantitative investigation, Spearman's correlation was also used. The correlation is calculated by considering the monthly accumulated series of each location and the ONI index; first with paired data (Lag 0), then the current value of accumulated rainfall with the ONI index of the previous month (Lag 1) and so on.
Spearman's coefficient is a non-parametric correlation measure that is based on the ordering of two variables without any restriction regarding the distribution of values (SIEGEL, 1975). This coefficient is equivalent to Pearson's correlation coefficient adapted to data transformed into ranks, with the attribution of ranks being made separately for each of the variables (WILKS, 2011). If the sample is large, the statistical significance of the measure can be evaluated by means of a test that uses Student's *t* probability distribution as a reference distribution (DANIEL, 1978; SIEGEL, 1975). The non-correlation hypothesis was tested against the alternative hypothesis that there is a non-zero correlation. Those with $p<0.05$ were considered significant coefficients.

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Analysis of trends

The existence of trends in time series can lead to false interpretations in the calculation of correlations (BOMBARDI; CARVALHO, 2017). To identify trends, the non-parametric Mann–Kendall (MK) test was used (MANN, 1945; KENDALL, 1975; HIRSCH et al., 1982).

The test does not depend on the parameters of the probability distribution of the data. It is widely used in several areas of research and is suitable for analyzing trends in time series, "because it is simple, robust, adapts to missing data and the data does not need to conform to any statistical distribution" (ELY; DUBREUIL, 2017, p. 560).

Wavelet Analysis

To determine the frequencies both in the intensity of the EN events and in the rainfall intensities, the wavelet transform (WT) method was applied.

Wavelets are functions that satisfy certain mathematical requirements and are used to represent data or even other functions. WT is a technique that has adjustable windows, in time or space, that expand or compress, capturing low and high frequency signals (DAUBECHIES, 1990; TORRENCE; COMPO, 1998). This characteristic makes the model very useful in the study of climatological time series such as sea surface temperature (GERÓLAMO; KAYANO, 2010), rainfall extremes (PEDRON et al., 2016; SILVA, 2017), river flow (LABAT, 2008; HOLDEFER; SEVERO, 2015) and Standardized Precipitation Index (SPI) (BLAIN; KAYANO, 2011; SANTOS et al., 2019), among other examples. The use of techniques based on wavelets for the identification of climatic modes is widely used, especially for the ENSO phenomenon (GU; PHILANDER, 1995; TORRENCE; WEBSTER, 1999).

Mathematically, a WT deconstructs a signal in terms of some elementary functions $\psi_{a,b}(t)$ (daughter wavelets) derived from a mother wavelet $\psi(t)$ by dilation and translation (LAU; WENG, 1995):

$$\psi_{a,b} = \frac{1}{a^{1/2}}\psi\left(\frac{t-b}{a}\right) \quad (1)$$

where b denotes the position (translation) and a(>0) denotes the scale (dilation) of the wavelet.

The technique is based on the convolution of a series f(t) with a set of functions $\psi_{a,b}(t)$ obtained by translation and contraction/dilation of the reference wave function $\psi(t)$. Thus, the continuous wavelet transform, used in this study, is defined as

$$W(a,b) = \frac{1}{a^{1/2}}\int_{-\infty}^{+\infty}\psi\left(\frac{t-b}{a}\right)\, f(t)dt. \quad (2)$$

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The wavelet power spectrum, defined as the square of the absolute value of the transform, $|W(a,b)|^2$, gives a measure of the variance of the series in each scale and at each time point. The normalization factor $a^{1/2}$ keeps the total energy of the scaled wavelet constant.

In this study, the Morlet function was used for the transform (GRINSTED et al., 2004). The function belongs to the family of non-orthogonal complex wavelets, as plane waves with a Gaussian envelope and presents a great representation of non-stationary signals obtained in nature.

In the scalograms, color maps present the WT results, as well as the cone of influence (COI). The COI represents the errors that occur at the beginning and end of the wave power spectrum when considering a time series of finite length. Edge effects are reduced when the number of time series elements equals a power of 2. Therefore, it is necessary to fill the time series with zeros to bring the time series length to the next higher power of 2 before calculating the wavelet transformation (TORRENCE; COMPO, 1998). Within the COI in the scalogram, the information is reliable.

Wavelet analysis was applied using the algorithm developed by C. Torrence and G. Compo (http://atoc.colorado.edu/research/wavelets/).

Wavelet Coherence Analysis

Wavelet Coherence Analysis was applied to verify the relationship between the ONI index and the series of monthly precipitation data. Coherence is a bivariate framework used to study the interaction between different time series that may be non-linear in their evolution over a continuous time and frequency space. The model provides a measure of the correlation between the signals. It is very similar to the traditional correlation coefficients and can even be understood as a coefficient located in the frequency-time space. To define the coherence coefficient, the cross correlation between two signals x and y is considered (TORRENCE; COMPO, 1998)

$$W_{xy}(a,b) = W_x(a,b)\overline{W}_y(a,b) \tag{3}$$

and $W_x(a,b)$ and $W_y(a,b)$ represent the continuous transform of each of the signals. The bar represents the complex conjugate of the transform. The coherence squared is given by GRINSTED et al. (2004)

$$R_t^2 = \frac{|S(a^{-1}W_t^{xy}(a))|^2}{S\left(a^{-1}|W_t^x(a)|^2\right).S\left(a^{-1}|W_t^y(a)|^2\right)} \tag{4}$$

where S is a time- and scale-smoothing operator.

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As stated above, it is useful to understand coherence as a correlation coefficient located in the time-frequency space. The estimate of magnitude-squared coherence is a function of frequency with values between 0 and 1, and the closer the value to 1, the greater the correlation between the signals. Coherence coefficients can be displayed in a scalogram for the two input signals. This coherence technique to correlate different variables in the same period shows the frequency bands within which two time series are covarying (GRINSTED et al*.,* 2004). In the scalogram, arrows that represent phase vectors between the series can also be indicated. The coherence phase is defined as $tan^{-1}\left[\mathcal{I}\left\{\mathrm{W}_{\mathrm{t}}^{\mathrm{xy}}(\mathrm{a})\right\}/\mathcal{R}\left\{\mathrm{W}_{\mathrm{t}}^{\mathrm{xy}}(\mathrm{a})\right\}\right]$ with $\mathcal{R}$ and $\mathcal{I}$ corresponding to the real and imaginary parts of the transform, respectively (TORRENCE; COMPO, 1998). To verify the phase difference between two analyzed time series, the phase diagram presented in Barbosa and Blitzkow (2008) was used.

III. Results and Discussion

Rainfall distribution and correlation with the ONI index

The annual averages of monthly accumulated precipitation and the respective standard deviations for all meteorological stations are presented in Figure 2. For all the analyzed cities, the months of July and August were the driest, while October was the wettest month. Thus, the characteristic pattern of rainfall is marked by a transition between the monsoon climate (driest season in winter), which occurs in the north of the southern region, and the subtropical climate, with well-distributed rainfall throughout the year and a rainy winter, which occurs in the south of Southern Brazil (MANGILI, 2021; NASCIMENTO Jr. et al., 2020).

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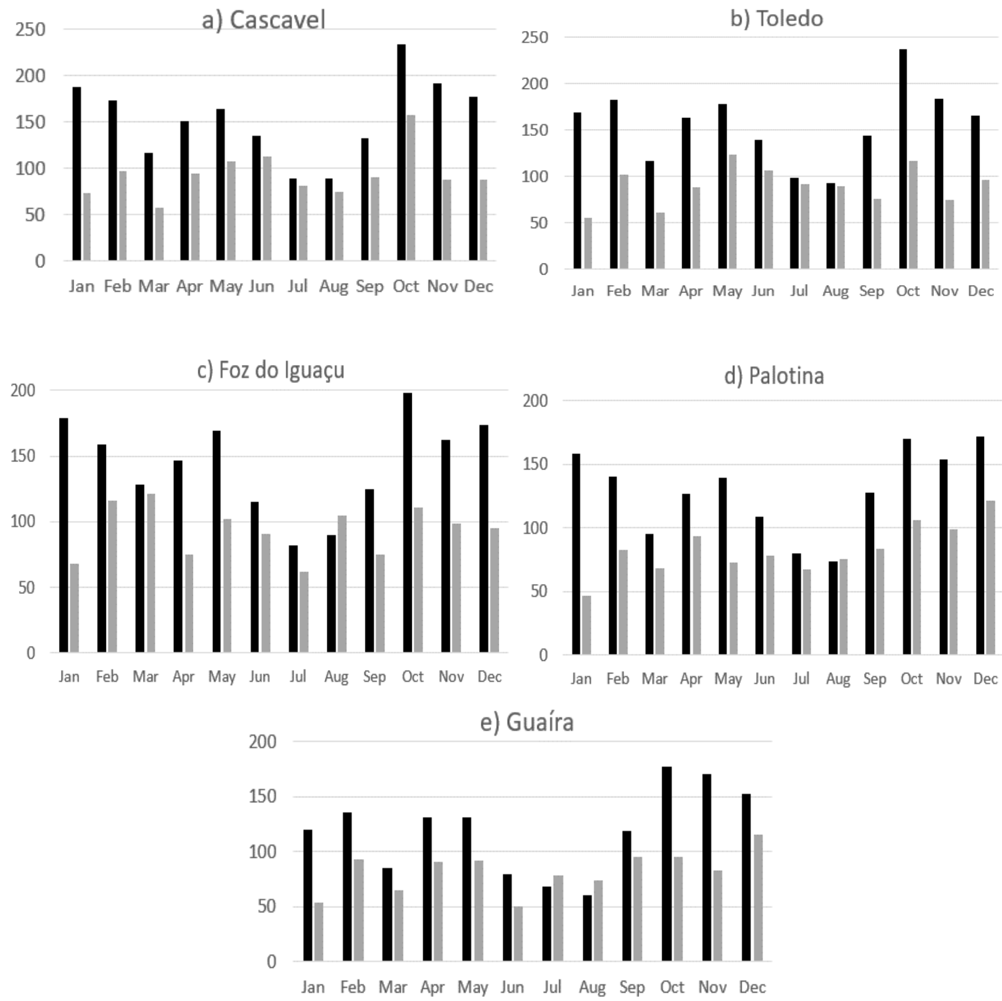

Figure 2 – Means, in mm, of monthly rainfall (black bars) and respective standard deviations (grey bars) for: a) Cascavel; b) Toledo; c) Foz do Iguaçu; d) Palotina, and e) Guaíra. (Elaborated by the authors).

Figure 3 shows the average seasonal precipitation accumulations from October to January, which are the months most affected by ENSO (GRIMM, 2009) and the critical months for summer agricultural crops in the region (FERREIRA, 2017), associated with each El Niño, La Niña or Neutral event. Cascavel had the highest volume of precipitation in La Niña years; Toledo had the highest in neutral years; and the other locations had the highest in El Niño years. Neutral years may have more or less precipitation, depending on the association with other areas of SST anomalies that define their variability (LIMBERGER; ELY, 2019). Even so, the same relationship pattern with the ENSO index did not appear for all cities. Local factors, specifically relief, can affect response to events. In addition, one must consider that the precipitation variable has a large random component (TEEGAVARUPU, 2012).

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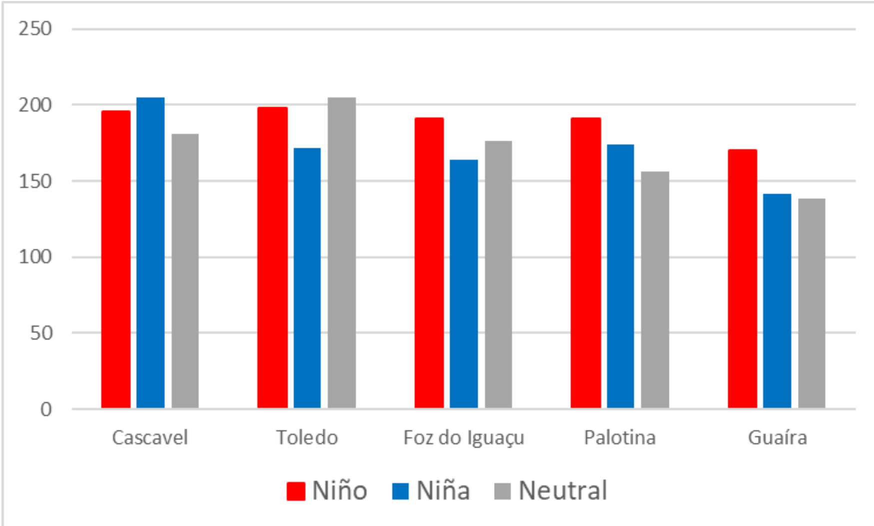

Figure 3 - Averages of seasonal accumulated rainfall (Oct/Nov/Dec/Jan) (mm). (Elaborated by the authors).

The same pattern appeared in the period from January to April (Figure 4), critical months for the installation of the second agricultural harvest, or "safrinha", in the region. Neutral years had less rain than El Niño years, but were not less dry than La Niña years. In Southern Brazil, according to Alberto et al. (2006), the neutral years were more irregular, in terms of precipitation distribution, during the development cycle of summer crops (soybean and corn).

With the exception of Cascavel, all sites had an expected response to the ENSO signal for the southern region, with more rain in El Niño years and less rain during La Niña years. This result agrees with Grimm et al. (1997) which indicated that the ENSO signal is stronger in the spring/summer in Southern Brazil and that the impact of El Niño on rainfall in Paraná is greater in the spring of the year in which the phenomenon begins.

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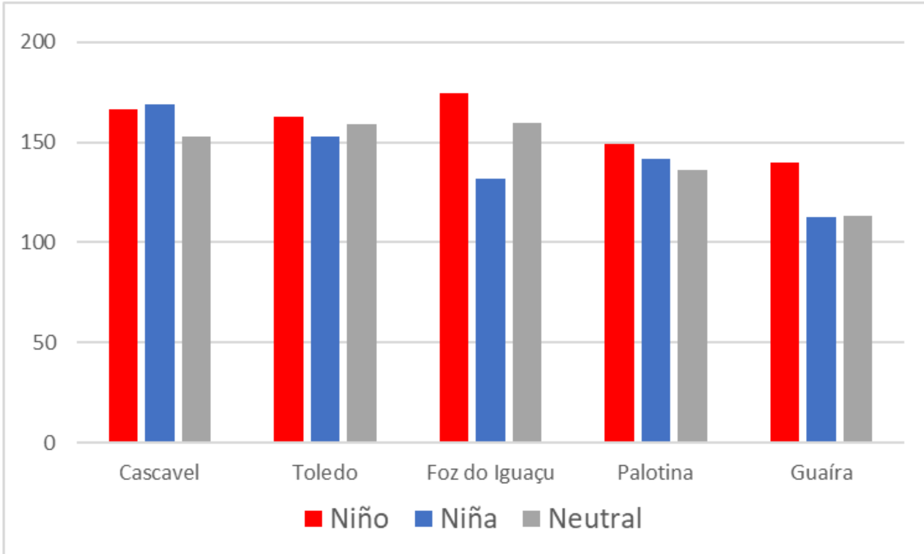

Figure 4 - Averages of seasonal accumulated rainfall (Jan/Feb/Mar/April) (mm). (Elaborated by the authors).

Table 1 presents the values of the Spearman's correlation coefficient between the accumulated monthly rainfall and the ONI index, for the analyzed cities. The shorter series (Toledo, Foz de Iguaçu, and Guaíra) did not present a significant correlation (with the exception of Foz do Iguaçu for Lag 0). The low values in Table 1 are justified since high values were not expected in the correlation between such complex natural variables and from remote points or areas on the globe, as pointed out by Cavalcanti and Ambrizzi (2009).

Table 1 - Spearman's correlation coefficient between monthly precipitation accumulations and the ONI index; first with paired data (lag 0), then the current value of accumulated rainfall with the ONI index of the previous month (Lag 1) and so on, with a lag of two months (Lag 2), three months (Lag 3) and four months (Lag 4).

	Cascavel	Toledo	Palotina	Foz Iguaçu	Guaíra
Lag0	**0.11**	0.08	**0.11**	**0.14**	0.11
Lag1	**0.10**	0.06	**0.10**	0.11	0.09
Lag2	**0.10**	0.05	**0.09**	0.09	0.09
Lag3	**0.09**	0.06	**0.10**	0.09	0.10
Lag4	0.08	0.06	**0.11**	0.08	0.10

[1]In bold, significant values with $p<0.05$. (Elaborated by the authors).

There is no physical explanation in the local or regional scale circulation for this difference in correlation significance. All correlation values are low, yet significant for Cascavel and Palotina. Local scale phenomena (relief, slope, vegetation, urban area) or even the length of the time series of the data might explain this difference. It is therefore important to consider other techniques to associate the ONI index and rainfall.

Cascavel and Palotina, with longer series, presented a significant correlation not only in the current

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month but also in a situation when the correlation was made with the El Niño signal lagged by up to four months. This means that the impacts of anomalies in the Pacific Ocean that define El Niño/La Niña events can manifest themselves with a delay of a few months in the region. This important information may be useful when there is a need to adapt to the event, once the process has started. The lagged configuration of the El Niño impact is known in the literature; for example, in Maringá – PR, Galvani et al. (1998) found that the most significant correlation coefficient between the Southern Oscillation Index (SOI) and the rainfall deviation occurs with a lag of three to four months. Correlations are also more intense with a lag of one or two months for precipitation in Southern South America (SCHNEIDER; GIES, 2004). This occurs because one of the ways of transferring the oceanic anomaly to the atmosphere and its teleconnection with the continents is via Rossby waves (AMBRIZZI, 2003), by the Pacific South America (PSA) standard, which take approximately 3 months to disturb the atmosphere in Southern South America and modify the dynamics of cold front passages.

The monthly accumulated precipitation series did not show significant trendswhen analyzed by the Mann-Kendall test.

Wavelet Analysis

Figure 5 shows the WPS (Wavelet Power Spectrum) in letter *a* and the GWS (Global Wavelet Power Spectrum) or variance in letter *b*, for the ONI index and precipitation in all analyzed locations, considering their series of monthly accumulation. It should be noted that for the ONI (Figure 5A), periods appeared between 2 and 7 years, referring to the index that characterizes the ENSO phenomenon. These frequencies have already been indicated in the literature, as by Torrence and Webster (1999). In item b of all the figures of the study sites, the first significant peak of power corresponds to the seasonality of the data. Cascavel (Figure 5B) shows a peak between two and eight years, with higher powers in the mid-1980s. It should be noted that in 1982/1983 a very strong ENSO event occurred. Toledo (Figure 5C) and Guaíra (Figure 5F) did not show relevant powers in this analysis. Foz do Iguaçu (Figure 5D) and Palotina (Figure 5E) showed significant peaks around the four-year period. Palotina also showed relevant power in the early 1980s.

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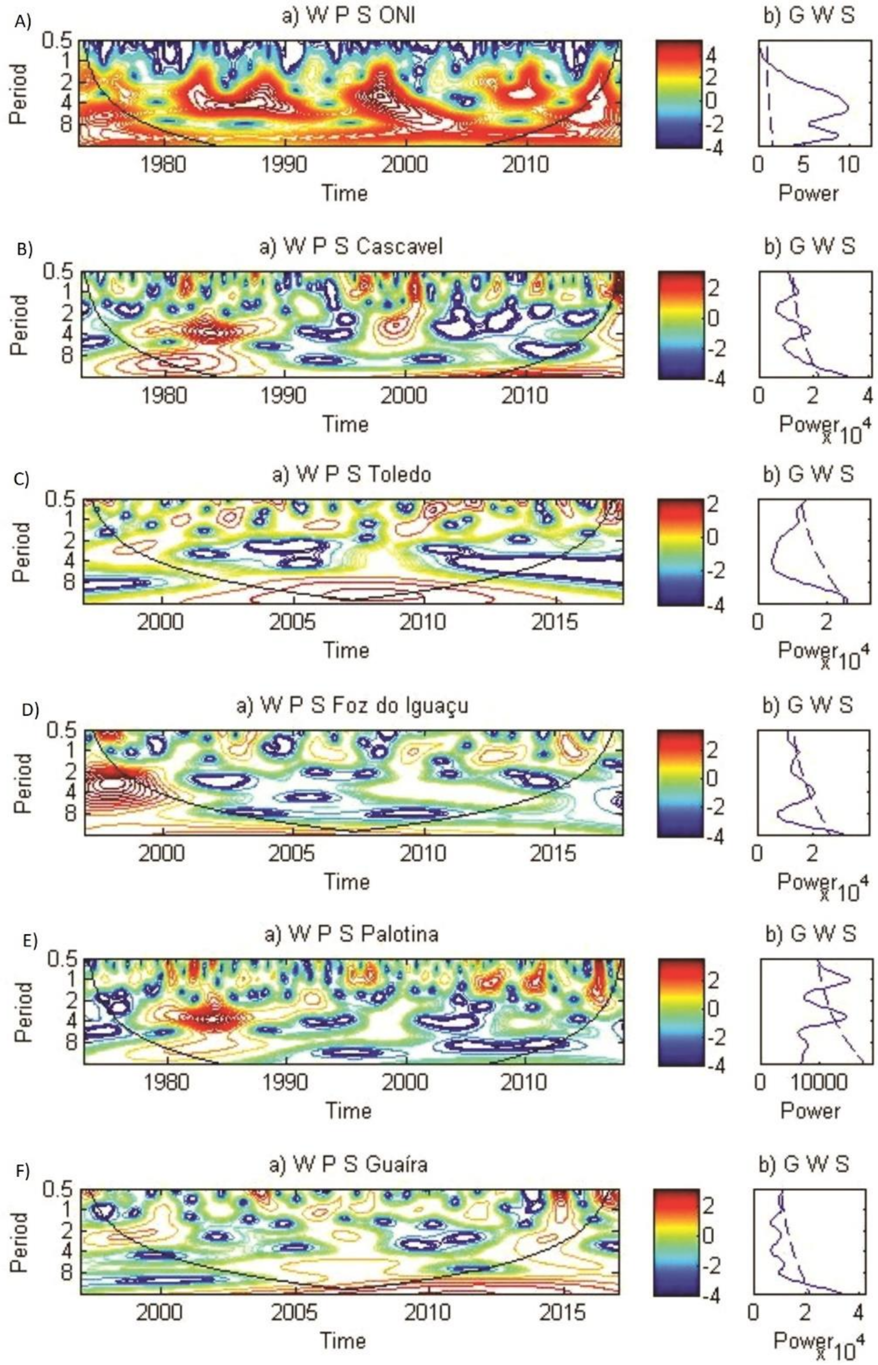

Figure 5 - Wavelet Power Spectrum (WPS) and Global Wavelet Power Spectrum (GWS) for the ONI series and monthly data from the sites under study. In A) ONI, B) Cascavel, C) Toledo, D) Foz do Iguaçu, E) Palotina and F) Guaíra. WPS is shown under letter a and GWS under letter b in the figures. The solid black line in letter a is the cone of influence and the dashed line in letter b is the 5% significance level for the GWS. Period and time are measured in years. Power: °C^2 for the ONI and mm^2 for the other series. (Elaborated by the authors).

The WPS and GWS results for the analyzed cities corroborated the linear correlation results presented in the previous item; that is, even being in the same geographical mesoregion, the results of the association between rainfall and the ENSO index do not follow the same pattern for all cities, demonstrating the complexity of rainfall variability.

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To expand on this analysis, Figure 6 shows the global wavelet power spectrum (GWS) corresponding to Figure 5, letter *b,* for: A) ONI, B) Cascavel, D) Foz do Iguaçu and E) Palotina, which showed significant peaks in addition to seasonality. This corresponds to the first peak in the monthly accumulated precipitation series. The global ones are normalized (divided by the respective maximum values) so that each one has a maximum value equal to 1. The second peak in the Figure 6, in the periods between two and seven years, corresponds to the well-known El Niño pattern and manifests itself in the precipitation series represented. The presence of these frequencies marks the signature of the phenomenon and can be related to the local rainfall pattern.

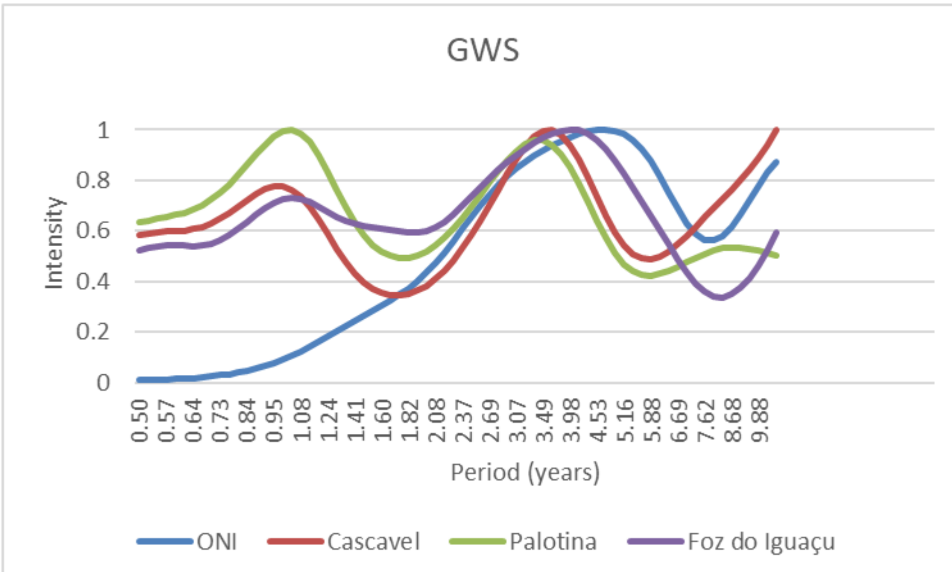

Figure 6 - Global wavelet power spectrum (GWS) of the ONI series and the monthly accumulated rainfall in Cascavel, Palotina and Foz do Iguaçu. Units: °C² for ONI and mm² for other series. (Elaborated by the authors).

Identification of the ENSO phenomenon is common in the literature using wavelet analysis: Labat et al*.* (2005) indicated a 3 to 6 year oscillation typical of the ENSO variability observed in the monthly flow of large Atlantic rivers (Amazon, Paraná, Orinoco and Congo); Hudgins and Huang (1996) found its correlation with the monsoon in Asia; Jevrejeva et al. (2003) found its influence on Baltic Sea ice conditions; and Rigozo et al*.* (2003) identified its variability in tree-ring data in Southern Brazil, among other examples.

Coherence in Wavelets

Figure 7 shows the coherence scalograms between the ONI index and the monthly accumulated precipitation for each location. The horizontal axis represents the temporal domain and the vertical axis represents the scales used to calculate coherence. Coherence is a kind of correlation (in the frequency domain). Red (1) means that the two signals are highly correlated and blue (0) means that there is no correlation. Arrows are used (which indicate the phase vector between the series) only for correlation above 0.7. The dashed line

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delimits the significance region. The regions with low coherence coincide with the low power spectrum of the wavelets. One can check the frequency bands within which the two time series are covarying.

Cascavel, in Figure 7a, showed significant coherence in a period of four years with the series in phase, between 1990 and 2005 approximately. For a period of around three years, ONI appears advanced in relation to the monthly accumulated precipitation series, which corroborates the results of Table 1. Toledo, in Figure 7b, presented coherence in phase in periods of two to four years between 1998 and 2010. At the beginning of the series, in a three-year period, the signal of the ONI index was advanced in relation to the monthly accumulated precipitation. It lagged around 2010 and returned to in phase from 2015. In Foz do Iguaçu, Figure 7c, around the year 2000 and for a period of two to four years, the ONI was advanced; however, from 2002 to 2012 it remained lagged for a period of eight years. Palotina, Figure 7d, had ONI in phase with the series of precipitation accumulation data for a period around four years, between 1995 and 2016. With a slightly longer period, ONI was ahead of schedule, which was also detected in Table 1. Guaíra, Figure 7e, showed significant coherence in phase only from 2014 and with a period of two to four years.

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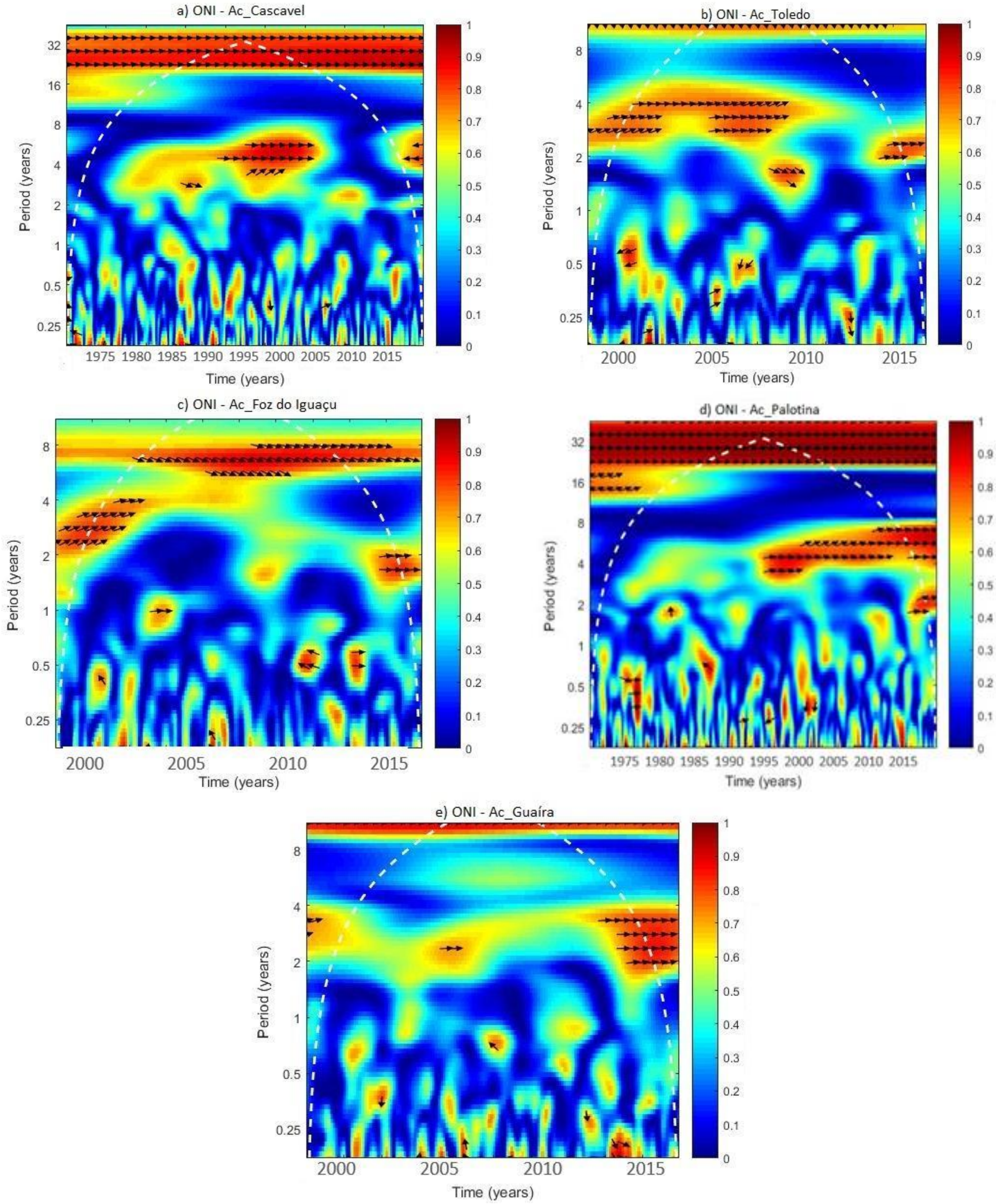

Figure 7 - Wavelet coherence scalograms between the ONI signal and the monthly accumulated precipitation of the studied locations. Arrows are used (indicate the phase vector between the series) only for correlation above 0.7. (Elaborated by the authors).

In general, it can be concluded from the results shown in Figure 7 that at some point all locations showed coherence between the ONI index and the monthly accumulated precipitation series. Coherence mostly occurred around the 4-year period. The variability in precipitation that occurred in the regions under study was influenced by the ENSO phenomenon, which generated conditions of interannual and interdecadal variability in

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precipitation.

IV. Conclusions

The objective of this work was to identify the signal of ENSO events in the precipitation of five cities in the western region of Paraná: Cascavel, Toledo, Palotina, Foz do Iguaçu and Guaíra.

The mean of seasonal precipitation accumulations (Oct/Nov/Dec/Jan) showed that the highest precipitation volumes for Palotina, Foz do Iguaçu and Guaíra occurred in El Niño years. For Cascavel it occurred in La Niña years and Toledo in neutral years. The pattern was repeated for (Jan/Feb/Mar/April), and in this period Toledo also had higher volumes in El Niño years. Neutral years were less rainy than El Niño years, however, they were not less dry than La Niña years, in all locations. Therefore, it is suggested, in future research, to use the ENSO classification methodology suggested by Lin and Qian (2019), considering years of hot anomalies, hot to cold, cold, and cold to hot.

Cascavel and Palotina showed a significant (Spearman's) correlation between monthly accumulated precipitation and the ONI index, not only in paired data (same month), but also when lagged from one to four months. This means that the impacts of temperature and pressure anomalies in the Pacific Ocean that define the ENSO event can manifest themselves with a delay of a few months in the western region of Paraná and not homogeneously in all cities. Toledo and Guaíra did not show significant correlations and Foz do Iguaçu only in paired data.

The sign of the ENSO phenomenon appears clearly in the wavelet analysis. Power peaks manifest themselves in periods of two to seven years in the precipitation data from Cascavel, Foz do Iguaçu and Palotina. In addition, at some point all locations exhibited coherence between the ONI index and the monthly accumulated precipitation series. The correlation occurred around the four-year period. This study shows the complexity of the local manifestation of a phenomenon of global variability, such as ENSO. The importance of using various techniques to identify the influence of ENSO on rainfall at a local scale is highlighted. Spearman's correlation coefficient may not capture the signal between series due to its low magnitude. On the other hand, the wavelet transform and coherence are useful to analyze non-stationary signals, which is the case of most weather series.

The results of this research indicate the challenge of climate prediction for the western region of Paraná, since the ENSO signal is not univocal in the studied locations. Therefore, it is necessary to consider several areas

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of oceanic anomalies and other local factors that generate variability in order to understand the climate modulation in the area.

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