Research, Society and Development, v. 9, n. 9, e637997737, 2020
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v9i9.7737

Análise de quantificação de recorrência de séries temporais mensais de chuva em Pernambuco, Brasil

Recurrence quantification analysis of monthly rainfall time series in Pernambuco, Brazil

Análisis de cuantificación de recurrencia de series temporales de lluvia mensual en Pernambuco, Brasil

Received: 19/08/2020 | Reviewed: 29/08/2020 | Accept: 31/08/2020 | Published: 01/09/2020

Leika Irabele Tenório de Santana
ORCID: https://orcid.org/0000-0002-5516-5887
Universidade Federal Rural de Pernambuco, Brasil
E-mail: leikatenorio10@gmail.com
Antonio Samuel Alves da Silva
ORCID: https://orcid.org/0000-0002-8759-0036
Universidade Federal Rural de Pernambuco, Brasil
E-mail: samuelmathematical@gmail.com
Rômulo Simões Cezar Menezes
ORCID: https://orcid.org/0000-0001-8740-366X
Universidade Federal de Pernambuco, Brasil
E-mail: rmenezes@ufpe.br
Tatijana Stosic
ORCID: https://orcid.org/0000-0002-5691-945X
Universidade Federal Rural de Pernambuco, Brasil
E-mail: tastosic@gmail.com

Resumo

A precipitação é a principal variável climática que é usada para modelar índices de risco para desastres naturais. Neste trabalho foi investigado a dinâmica não linear das séries temporais de chuvas mensais registradas de 1962 a 2012, em três estações no estado de Pernambuco, Brasil, localizadas em regiões com diferentes regimes de chuvas (Zona da Mata, Agreste e Sertão), fornecidos pelo Laboratório de Meteorologia do Instituto de Tecnologia de Pernambuco (LAMEP/ITEP). O objetivo deste trabalho é contribuir para uma melhor compreensão da distribuição espaço-temporal da precipitação no estado de Pernambuco. Para a concretização

da pesquisa, foi utilizado a metodologia da teoria da dinâmica não linear, Gráfico de recorrência (RP), que permite distinguir entre diferentes tipos de processos subjacentes. Os resultados mostraram que o regime de chuvas na região semiárida Sertão é caracterizado por um comportamento determinístico menos forte e menos complexo, comparado à Zona da Mata e Agreste, onde identificamos transições entre dinâmicas caóticas e não estacionárias. Para a zona de transição Agreste, a dinâmica das chuvas mostrou uma memória mais forte com um tempo médio de previsão mais longo, enquanto que a dinâmica da chuva na região com clima subúmido, Zona da Mata, é caracterizada por estados laminares (que mudam lentamente).
Palavras-chave: Precipitação; Gráfico de recorrência; Análise quantitativa de recorrência.

Abstract

Precipitation is the main climatic variable that is used for modeling risks indices for natural disasters. We investigated nonlinear dynamics of monthly rainfall temporal series recorded from 1962 to 2012, at three stations in Pernambuco state, Brazil, located in regions with different rainfall regime (Zona da Mata, Agreste and Sertão), provided by the Meteorological Laboratory of the Institute of Technology of Pernambuco (Laboratório de Meteorologia do Instituto de Tecnologia de Pernambuco – LAMEP/ITEP). The objective of this work is to contribute to a better understanding of the spatiotemporal distribution of rainfall in the state of Pernambuco. We use the methodology from nonlinear dynamics theory, Recurrence plot (RP) that allows to distinguish between different types of underlying processes. The results showed that rainfall regime in deep inland semiarid Sertão region is characterized by weaker and less complex deterministic behavior, comparing to Zona da Mata and Agreste, where we identified transitions between chaotic and nonstationary type of dynamics. For transitional Agreste region rainfall dynamics showed stronger memory with longer mean prediction time, while for sub humid Zona da Mata rainfall dynamics is characterized by laminar (slowly changing) states.
Keywords: Rainfall; Recurrence plot; Recurrence quantification analysis.

Resumen

La precipitación es la principal variable climática que se utiliza para modelar los índices de riesgo de los desastres naturales. En este trabajo investigamos la dinámica no lineal de las series temporales mensuales de lluvias registradas de 1962 a 2012, en tres estaciones en el estado de Pernambuco, Brasil, ubicadas en regiones con diferentes regímenes de lluvia (Zona da Mata, Agreste y Sertão), proporcionada por el Laboratorio de Meteorología del Instituto de Tecnología de Pernambuco (Laboratório de Meteorologia do Instituto de Tecnologia de

Pernambuco - LAMEP/ITEP). El objetivo de este trabajo es contribuir a una mejor comprensión de la distribución espacio-temporal de las precipitaciones en el estado de Pernambuco. Para llevar a cabo la investigación, la metodología de la teoría de dinámica no lineal, Grafico de recurrencia (RP) que permite distinguir entre diferentes tipos de procesos subyacentes. Los resultados mostraron que el régimen de lluvia en la región semiárida de Sertão se caracteriza por un comportamiento determinista menos fuerte y menos complejo, en comparación con Zona da Mata y Agreste, donde identificamos transiciones entre el tipo de dinámica caótica y no estacionaria. Para la región de transición de Agreste, la dinámica de la lluvia mostró una memoria más fuerte con un tiempo de predicción medio más largo, mientras que la dinámica de la lluvia en la región con clima subhúmedo, Zona da Mata, se caracteriza por estados laminares (que cambian lentamente).

Palabras clave: Precipitaciones; Grafico de recurrencia; Análisis de cuantificación de recurrencia.

1. Introduction

Precipitation is the main climatic variable that is used for modeling risks indices for natural disasters that are consequences of luck or excess of rain, such as aridity index, flash floods and landslides vulnerability indices (Marengo & Bernasconi, 2015; Debortoli, Camarinha, Marengo & Rodrigues, 2017). Tropical countries experience severe floods and draughts, that affect human health, food and water supplies, and these problems are expected to increase in this century due to the climate change (Chadwick, Good, Martin & Rowell, 2016). In Brazil dry areas are mostly concentrated in the Northeast region (NEB) which represents 18.26% of Brazilian territory and includes the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia.

The intraanual rainfall variability in NEB, is influenced by Atlantic intertropical convergence zone (ITCZ) and South American monsoon system (SAMS), resulting in highly seasonal regime (with rainy season from February to April), while interannual variability (with excessive rainfall and severe drought) is related to El Niño – Southern Oscillation (ENSO) in the equatorial Indo–Pacific Ocean, and the meridional sea surface temperature gradient (MGRAD) over the tropical Atlantic (Robertson, Kirshner & Smyth, 2004). While spatial and temporal variability of rainfall in interior dry region of NEB was extensively studied (Hastenrath, 2012; Oliveira, e Silva & Lima, 2017), much less is known about rainfall patterns in eastern part of the region (Lyra, Oliveira-Júnior & Zeri, 2014; Medeiros, Lima, Olinda &

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Santos 2019).

Pernambuco is a coastal state which is located in the eastern part of NEB, between the parallels 7º15'45"S and 9º28'18"S and meridians 34º48'33"W and 41º19'54"W. It is surrounded by the states of Alagoas, Bahia, Piaui, Paraiba and Ceará and it is divided into three geographic regions: the coastal region Zona da Mata that stretches about 70 km inland to the mountain chain Borborema, a sub-humid transition zone Agreste, and the largest, semiarid region Sertão, which is located to the west of the Borborema. Zona da Mata is mostly covered by Atlantic rainforest and sugarcane fields, Sertão by Caatinga (semiarid biome which is dominated by tropical dry forest) while in the transition zone Agreste Atlantic forest mixes with Caatinga (Melo Santos, Cavalcanti, Silva & Tabarelli, 2007).

Climate in Pernambuco is diverse, from humid tropical in Zona de Mata (with strong east to west rainfall gradient from 1500 to 700 mm and the rainy season between May and July) to semiarid in Sertão (with the annual rainfall of less than 500 mm, concentrated from February to April) (Alvares et al., 2013). Due to climate variability Pernambuco experiences recurrent extreme conditions, droughts in Sertão and floods in the coastal region, which according to recent studies will continue increasing until the end of the century (Marengo & Bernasconi, 2015; Debortoli et al., 2017). The future projections of climate change strongly depend on accuracy of global and regional climate models which show uncertainties and biases in simulating main variables, mean precipitation and near-surface air temperature (Maslin & Austin, 2012). To decrease this uncertainty, it is necessary to study different aspects of the historical and current climate conditions, trough the comprehensive analysis of historical data using traditional and novel quantitative methods. Traditionally, rainfall data were studied using classical statistical methods (Longobardi & Villani, 2010; Buytaert, Celleri, Willems, De Bievre & Wyseure, 2006), however over the last decades, novel concepts and methods from complex system science have been increasingly used to assess the degree of nonlinearity and overall complexity of rainfall dynamics (Tan & Gan, 2017; Stosic, Telesca, de Souza Ferreira & Stosic, 2016; Jha & Sivakumar, 2017).

The objective of this work is to contribute to a better understanding of the spatiotemporal distribution of rainfall in the state of Pernambuco, whose large part of territory (about 70%) is located in the so called “Drought Polygon” (Polígono das Secas), and is extremely affected by rainfall seasonal and interannual variability. We use Recurrence Plot (RP) and the Recurrence Quantitative Analysis (RQA) methods that were developed for nonlinear analysis of temporal series, by visualizing the recurrences and calculating different complexity measures (Marwan, Romano, Thiel & Kurths, 2007). These methods were widely

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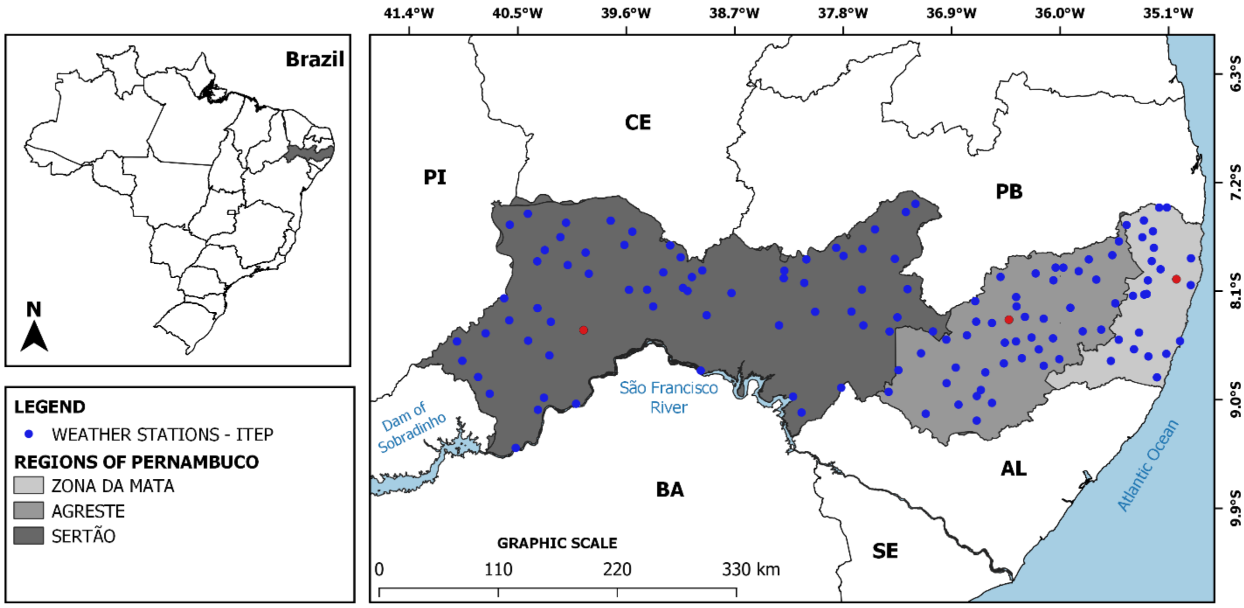
used in physiology (Afsar, Tirnakli & Marwan, 2018), geophysics (Donner et al., 2019), climatology (Panagoulia & Vlahogianni, 2014) and finances (Bastos & Caiado, 2011). We apply RP and RQA on monthly time series recorded during the period from 1962 to 2012, in three representative stations, in order to compare characteristics of rainfall regime in Zona da Mata, Agreste and Sertão.

2. Methodology

In this work we use the methodology Recurrence plot originated from network theory, which transforms the time series into network, by analyzing dynamics system trajectories in the phase space. It includes both qualitative and quantitative approaches (Pereira, Shitsuka, Parreira & Shitsuka, 2018) which permit to distinguish between different types of nonlinear dynamics.

The data used in this work are monthly series of precipitation recorded at three meteorological stations (Figure 1) in the state of Pernambuco, Brazil during the period from 1962 to 2012. The data are provided by the Meteorological Laboratory of the Institute of Technology of Pernambuco (Laboratório de Meteorologia do Instituto de Tecnologia de Pernambuco – LAMEP/ITEP) and the missing data were filled using the trend surface analysis interpolation method (Silva, Stosic, Menezes & Singh, 2019).

Figure 1. Geographical location of the state of Pernambuco, Brazil, and the spatial distribution of the ITEP weather stations. Red circles show the locations of three representative stations in *Zona de Mata* (São Lourenço da Mata), *Agreste* (Belo Jardim) and *Sertão* (Santa Maria da Boa Vista) regions.



Source: Authors (2020).

2.1. Recurrence plot

Recurrence plot (RP) was introduced by Eckmann, Kamphorst e Ruelle (1987) in order to visualize the recurrences in the dynamics of systems. RP is represented by a NxN matrix

$$R_{ij} = \Theta\left(\varepsilon - \| \vec{x_i} - \vec{x_j} \|\right)\ i,j = 1,\dots,N, \quad (1)$$

where ε is a cut-off distance, $\vec{x_i}$ and $\vec{x_j}$, are phase space vectors, $\|.\|$ is a norm (e. g. the Euclidean norm) and $\Theta(x)$ the Heaviside function. For one-dimensional time series $u_i, i = 1,\dots,N,$ $\vec{x_i}$ and $\vec{x_j}$ are constructed by using an embedding dimension m and a time delay τ: $\vec{x_i}$ =$(u_i, u_{i+\tau},\dots,u_{i+(m-1)\tau})$. The dynamics of the systems is described by a series of these vectors, representing a trajectory in an abstract mathematical space (Marwan et al., 2007). Parameters m and τ can be obtained using the methods of false nearest neighbors and mutual information respectively (Kantz & Schreiber, 2004). RP is obtained as a matrix plot with the colors black ($R_{ij} = 1$) and white ($R_{ij} = 0$).

The patterns in RPs are classified as large scale patterns (typology) and small-scale structures (texture) and are related to a specific behavior of the dynamic system. (Marwan et al., 2007). Large scale patterns show homogeneous, periodic, drift and disrupted behavior. Homogeneous RPs are typical of stationary systems, periodic and quasi-periodic systems have RPs with diagonal lines and checkerboard structures, drift (RP pales away from the main main black diagonal line – line of identity LOI) is caused by a process that contains trend, while disrupted RP's (consist white areas or bands) are caused by nonstationarity, abrupt changes in the dynamics, and extreme events.

Small-scale structures (texture) appear as single dots, diagonal lines and vertical and horizontal lines. Single, isolated points occur if states are rare and persist only for a very short time, diagonal lines parallel with the LOI occur when the evolution of states is similar at different times, and vertical (horizontal) lines occur when the system is in a state that does not change or changes very slowly (laminar states) (Marwan et al., 2007).

2.2. Recurrence Quantification Analysis

Recurrence Quantification Analysis (RQA) provides a set of measures of complexity which quantify the small scale structures in RPs (Webber Jr & Zbilut, 2005): REC (Recurrence Rate) - fraction of recurrence points in the recurrence plot, estimates the probability that a certain state recurs; DET (Determinism) - fraction of recurrence points forming diagonal lines, indication of determinism (predictability) in the system; L (Average diagonal line length) - measures the time phase space trajectories visit the same phase space regions, indication of mean prediction time; LMAX (Length of the longest diagonal line other than LOI) – the inverse of this measure DIV-divergence is related to the exponential divergence of the phase–space trajectory; ENTR (Shannon entropy of the distribution of lengths of diagonal lines) - measures the complexity of the deterministic structure of the system; LAM (Laminarity) - fraction of recurrence points forming vertical lines, related to the occurrence of laminar (slowly changing) states in the system; TT (average length of vertical lines) - estimates the average time that the system remains at a specific state ("trapping time").

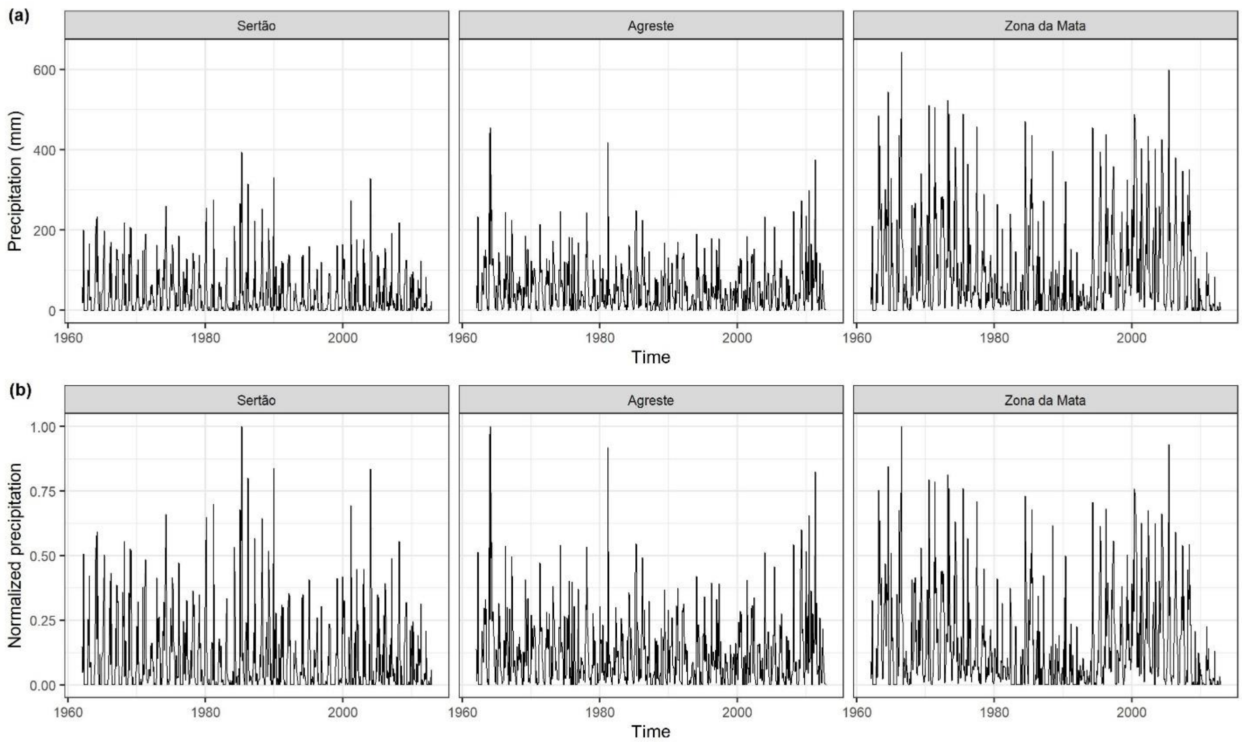
3. Results and Discussion

To perform RP/RQA analysis, as recommended in the literature (Bastos & Caiado, 2011), original precipitation series are normalized between 0 and 1, according to equation 2

$$\tilde{P} = \frac{P - \min(P)}{\max(P) - \min(P)} \quad (2)$$

where the values of min (P) and max (P) are the minimum and maximum values of the series in the analyzed period, respectively. The original and normalized series are displayed on Figure 2.

Figure 2. Original (a) and normalized (b) monthly rainfall time series, recorded in three representative stations.

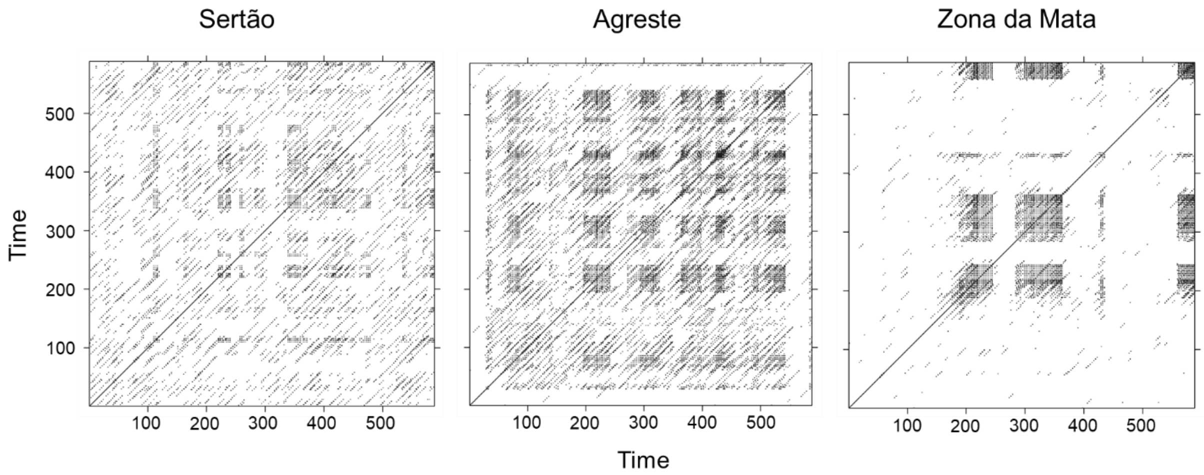


Source: Authors (2020).

The construction of RP's requires the specification of values for the time delay τ, the embedding dimension m, and the threshold distance ε. These values are obtained using mutual information ($\tau = 3$) and false nearest neighbors method ($m = 9$). The value of threshold ε was determined to produce the value of REC between 2% and 5% (Webber Jr & Zbilut, 2005) which gives $\varepsilon = 0{,}17$. The RP/RQA analysis is performed using software R Core Team (2020). The graphs of RP for three representative stations obtained using these parameters are shown on Figure 3.

It is seen from Figure 3 that variation of monthly precipitation is not random, since RP's do not display only isolated points. For *Sertão* monthly precipitation series exhibits a nonlinear deterministic (chaotic - like) behavior indicated by short lines parallel to the LOI. For *Agreste* rainfall dynamics changes around 1978 (~200 months) towards strong variability and non-stationary behavior, indicated by checkerboards patterns. For *Zona da Mata* three transitions are observed, from chaotic to nonstationary around 1978 (~200 months), from nonstationalry to chaotic around 1992 (~ 360 months), indicated by white band, and again towards strong variability and nonstationarity in the end of analyzed period, around 2010 (~ 570 months).

Figure 3. Recurrence plot for monthly rainfall time series for three representative stations.



Source: Authors (2020).

The results of RQA for individual series are shown on Table 1 where we can observe several specific properties of rainfall dynamics in different regions of Pernambuco. The values of all indices except of recurrence rate are lowest for Sertão indicating weaker and less complex deterministic behavior, and lower degree of predictability and intermittency. It reflects the climate conditions in this region where annual seasonality is often disturbed by longer periods of drought. Agreste shows highest REC, L, LMAX and ENTR values indicating that rainfall series are characterized by a more complex process with stronger memory and longer periods of predictability. DET, LAM and TT indices have highest values for Zona da Mata indicating rainfall regime with higher degree of determinism and presence of laminar states, in which system persists for long time.

Table 1. Recurrence quantification analysis for monthly rainfall time series for three representative stations.

	Sertão	*Agreste*	*Zona da Mata*
Recurrence Rate	0,029	0,059	0,022
Determinism	0,147	0,205	0,252
Average diagonal line length	2,054	2,119	2,069
Length of the longest diagonal line	9	23	11
Shannon entropy	0,073	0,167	0,110
Laminarity	0,201	0,373	0,405
Average length of vertical lines	2,076	2,253	2,445

Source: Authors (2020).

4. Final Considerations

We analyzed monthly rainfall temporal series for the state of Pernambuco, Brazil, using the method based on nonlinear dynamics theory and recurrence analysis of dynamical systems. By comparing RP plots and the values of corresponding RQA parameters, we found distinct dynamical characteristics in rainfall regime for *Zona da Mata*, *Agreste* and *Sertão* regions.

For *Sertão* monthly precipitation series showed nonlinear deterministic (chaotic - like) behavior while for *Agreste* and *Zona da Mata* several transitions from chaotic to nonstationary regime were identified.

Rainfall dynamics in *Sertão* is characterized by weaker and less complex deterministic behavior and lower degree of predictability, while in *Agreste* the process is more complex, with stronger memory and longer mean prediction time. *Zona da Mata* showed process with stronger laminarity (presence of slowly changing states in which system persists for long time).

Future studies should include data from larger number of meteorological stations which permits the speacial analysis of rainfall properties revealed by patterns of RP's and the values of RQA indices. Also time dependent RP/RQA analysis could be performed in order to identify possible climatic changes.

Acknowledgments

The authors acknowledge support of Brazilian agencies CNPq, CAPES and FACEPE through the following research grants: CNPq 307445/2018-6, 304497/2019-3, 441305/2017-2;

INCT -MCTI / CNPq / CAPES / FAPs 465764/2014-2; Facepe APQ-0296-5.01/17, APQ-0532-5.01/14.

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Percentage of contribution of each author in the manuscript

Leika Irabele Tenório de Santana – 25%

Antonio Samuel Alves da Silva – 25%

Rômulo Simões Cezar Menezes – 25%

Tatijana Stosic – 25%