



Spatial and temporal variability of rainfall in the Tocantins-Araguaia hydrographic region

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ABSTRACT. Current paper examines the space-time dynamics of yearly rainfall of the Tocantins-Araguaia Hydrographic Region (TAHR), foregrounded on rainfall volume from isohyet maps and interpolated by Kriging geo-statistical method. Rainfall space dynamics was undertaken by the analysis of descriptive statistics, Index of Meteorological Irregularity (IMI) and Variation Coefficient. Temporal dynamics was analyzed through the distribution of total annual volume precipitation for each TAHR sub-basin by the Standardized Anomaly Index, trend and magnitude test provided by Mann-Kendall and Sen Tests. Results correlated with meteorological anomalies of the Atlantic (Dipole) and Pacific (ENOS) Oceans show a highly heterogeneous rainfall behavior with temporal variability. Or rather, a decrease of rainfall extensiveness during years of intense meteorological anomaly with a rainfall increase south of the High Tocantins and Araguaia sub-basins and a decrease of rainfall in the Lower Tocantins sub-basin, with El Niño features. Although the Mann-Kendall test does not show statistically a significant trend for rainfall in the TAHR region, Sen's estimator reveals a decrease in rainfall in the High Tocantins ($-1.24 \text{ km}^3 \text{ year}^{-1}$) and Araguaia ($-1.13 \text{ km}^3 \text{ year}^{-1}$) sub-basins and a rainfall increase in the Lower Tocantins sub-basin ($0.53 \text{ km}^3 \text{ year}^{-1}$) and in the TAHR region ($-1.5 \text{ km}^3 \text{ year}^{-1}$).

Keywords: spatial and temporal dynamics, precipitation, Tocantins-Araguaia hydrographical region, Mann-Kendall, Sen's.

Variabilidade espaço-temporal da precipitação na região hidrográfica Tocantins- Araguaia

RESUMO. Este artigo examina a dinâmica espaço-temporal da precipitação anual da Região Hidrográfica Tocantins-Araguaia (RHTA) com base nos volumes precipitados obtidos por meio de mapa de isoietas, interpolados pelo método geoestatístico de krigagem. A dinâmica espacial da precipitação foi realizada pela análise da estatística descritiva, Índice de Irregularidade Meteorológica (IIM) e Coeficiente de Variação. A dinâmica temporal foi analisada pela distribuição dos totais anuais de precipitação volumétrica para cada sub-bacia da RHTA, pelo Índice de Anomalia Padronizada, teste de tendência e magnitude representados respectivamente pelos Testes de Mann Kendall e Sen's. Os resultados correlacionados com as anomalias meteorológicas do Oceano Atlântico e Pacífico indicam o comportamento da precipitação bastante heterogêneo marcados pela diminuição da amplitude pluviométrica, em anos de anomalia meteorológica intensa ocasionando um incremento de precipitação ao sul das sub-bacias TOA e ARA e diminuição da precipitação na sub-bacia TOB. Não se pode comprovar pelo teste de Mann Kendall que há uma tendência estatisticamente significativa no volume precipitado na RHTA, mas o estimador Sen's dá indícios de queda na precipitação na sub-bacia TOA ($-1,24 \text{ Km}^3 \text{ ano}^{-1}$) e Araguaia (ARA) ($-1,13 \text{ Km}^3 \text{ ano}^{-1}$) e aumento da precipitação na sub-bacia do Tocantins Baixo (TOB) ($0,53 \text{ Km}^3 \text{ ano}^{-1}$) e RHTA ($-1,5 \text{ Km}^3 \text{ ano}^{-1}$).

Palavras-chave: dinâmica espaço-temporal, precipitação, região hidrográfica Tocantins-Araguaia, Mann-Kendall; Sen's.

Introduction

Since rainfall is a hydrographical cycle factor, it is closely linked to all climate factors that contribute towards its formation of ascension and collision of air masses in the atmosphere. They directly influence surface discharge, infiltration, leaching, underground recharge and evaporation.

As a dynamic process, with constant changes in form and intensity, rainfall is measured at pluviometric stations. Detailed rainfall measurements vary on the

spatial and temporal scales and the comprehension of the variable in yearly occurrences has social and economical implications. When such variability is known, extreme events comprising drought and floods, requirements for irrigation, hydroelectricity and other projects involving water resources may be foreseen (BERTONI; TUCCI, 2007; COE et al., 2009).

The hydrological cycle and especially rainfall may be affected by natural and human alterations, especially

the meteorological anomalies in the Pacific (ENSO) and Atlantic (Atlantic dipole) oceans. The El Niño-Southern Oscillation (ENSO) is an anomaly of Sea Surface Temperature that occurs in different regions of the Pacific and causes the region's water heating/cooling. There is a negative (El Niño phenomenon) and a positive (La Niña) phase. On the other hand, the Atlantic Dipole is a phenomenon caused by an anomaly of sea surface temperature of the northern Atlantic, or rather, when the waters of the Pacific are hotter than usual and the waters of the South Atlantic are cooler and those of the North Atlantic hotter (positive dipole). Negative dipole occurs when the waters of the Pacific are cooler than usual and the waters of the South Atlantic hotter and those of the North Atlantic cooler.

The importance of rainfall and knowledge of its variability are highly relevant for agricultural regions and potential hydro-energetic and navigation areas, such as the TAHR, besides other activities for the management and planning of water resources. TAHR is a highly strategic region for Brazil since its main social and economical activities directly depend on hydric resources.

Certain studies found in the literature deal with rainfall analysis for different regions, such as Spain (MUÑOZ-DÍAZ; RODRIGO, 2006; MIRÁS-AVALOS et al., 2009); Greece (STATHIS; MYRONIDIS, 2009); Oman (KWARTENG et al., 2009); Australia (LI et al., 2010) and others. Few studies have been undertaken on rainfall within the TAHR region (FERNANDES et al., 2012; VALVERDE; MARENGO, 2014).

Current investigation has been motivated by rainfall data for the understanding of long-term spatial and temporal dynamics in the TAHR basin where annual rainfall data are investigated.

Material and methods

Current study was undertaken within TAHR, between latitudes $0^{\circ} 30'$ and $18^{\circ} 05' S$ and between longitude meridians $45^{\circ} 45'$ and $56^{\circ} 20' W$ (Figure 1). The region has a South-North elongated design and follows the dominant direction of the main water courses, namely, the rivers Tocantins and Araguaia, which merge in the region's southern section. This section is called river Tocantins till its mouth in the bay of the Marajó Island.

The climate is tropical with annual mean temperature $26^{\circ}C$ and two well-defined climatic periods: the rainy season from October to April, with more than 90% of rainfall, and certain dry mid-summer days between January and February;

the dry season from May to September, with low air moisture (MMA, 2006).

Rainfall regime is characterized by the occurrence of rain increase related to decrease in latitude (south-north direction). Distribution and total rainfall occurs almost exclusively due to systems of atmospheric circulation which lessens the relevance of topography.

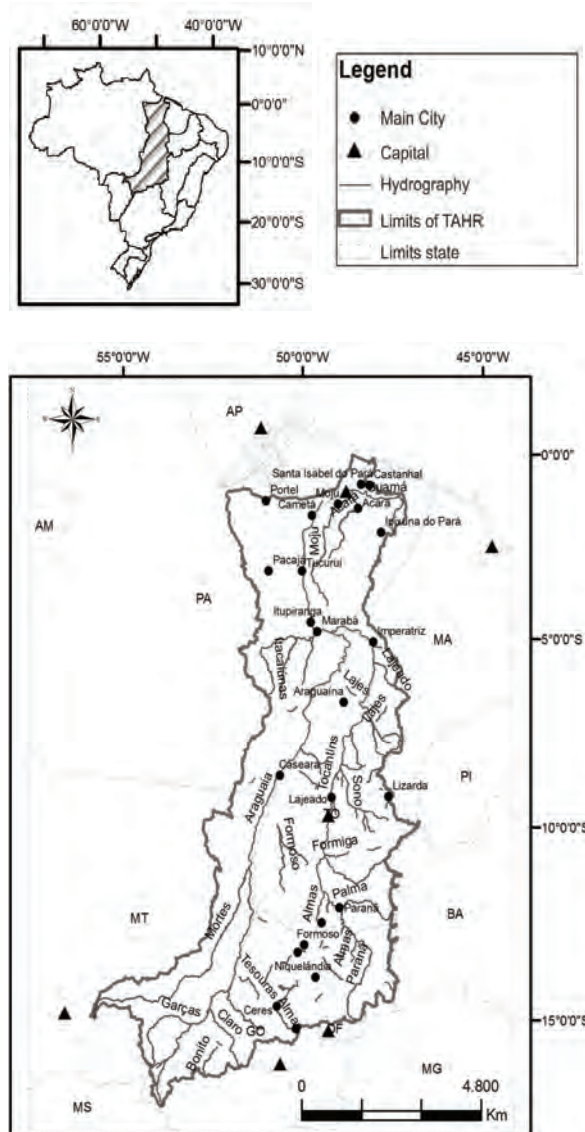


Figure 1. Localization and limits of TAHR.

For planning purposes, the HR is divided into sub-basins (MMA, 2006), as shown in Figure 2.

Data on rainfall were obtained through the 'Hydrological Information System HydroWeb/ANA (Water National Office)'.

Brazil'. The rainfall stations network has 133 stations within the TAHR and 17 have a 30-year-old period (1977-2006) data availability (Figure 3).

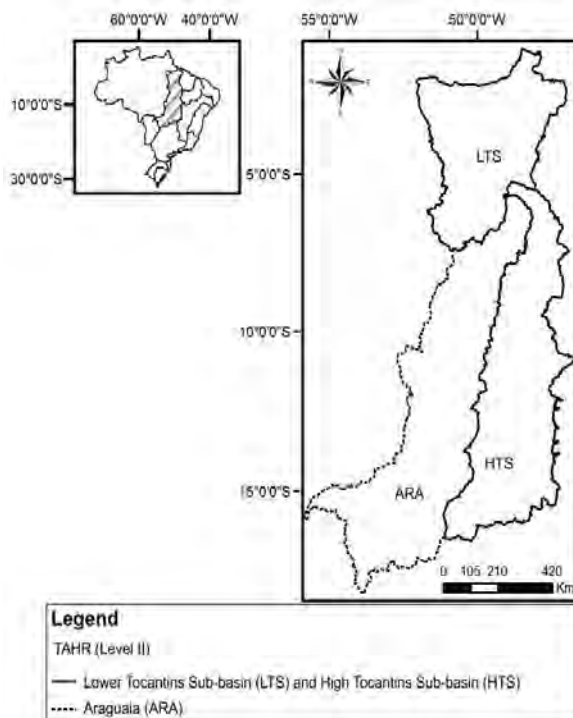


Figure 2. Limits of TAHR Level II.

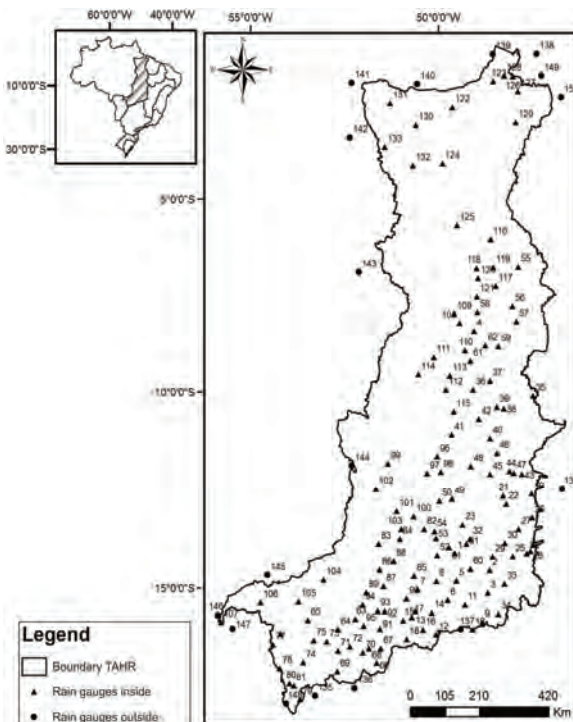


Figure 3. Localization of internal and external pluviometric stations.

The technique used to fill gaps in this study was the Regional Ponderation with Linear Regression (RPLR). Method for gaps completion was based on the existence of correlation (coefficient of Pearson's

correlation) between two sets of data obtained from close localizations and which quantify the spatial self-correlation force (RAMESH et al., 2005).

After the filling of gaps, double mass analysis is frequently used to check homogeneity and consistency of the data set of the pluviometric stations (SEARCY; HARDISON, 1960).

Rainfall spatial dynamics was evaluated by:

the Meteorological Irregularity Index (MII), calculated by the relationship between the intensity of maximum and minimum annual rainfall during a significant period. The higher the coefficient, the more irregular is the rainfall;

the Coefficient of Spatial Variation (CSV) of annual rainfall for the whole TAHR and its sub-basins.

Rainfall temporal dynamics was evaluated by:

plotting distribution graphs of total yearly graphic sub-region;

Standardized Anomaly Index (SAI) contrasting the anomalies of the Atlantic (di-pole) and Pacific (ENOS) oceans.

Annual rainfall volume was normalized to counter the ENOS effect. In fact, standardization avoids that rainfall volume groups with high means and standard deviations outweigh the others. Equation 2 was employed to calculate SAI.

$$z_i(t) = \frac{p_i(t) - \bar{p}_i}{\sigma_i} \quad (2)$$

where:

$z_i(t)$ is the volume of rainfall anomaly in the hydrographic sub-region i and year t ;

$p_i(t)$ is the volume of rainfall in the hydrographic sub-region i and year t ;

\bar{p}_i and σ_i are respectively the averages and standard deviation for 1977-2006;

The Coefficient of Temporal Variation (CTV) for each hydrographic sub-region of rainfall volume; the higher the CTV, the higher is the rainfall variability;

Inter-yearly rainfall variation for each sub-basin.

The idea behind the standardized anomaly is to try to remove the influences of location and spread from a data sample. The Physical units of the original data cancel, so standardized anomalies are always dimensionless quantities. Subtracting the mean produces a series anomalies, $p_i(t) - \bar{p}_i$, located somewhere near zero.

The Mann-Kendall method, suggested by the World Meteorological Organization (WMO) and

highly used by researchers, is a non-parametric test to evaluate trends in the temporal series (MANN, 1945). The test compares each rate of the temporal series with the other remaining rates in sequential order. The test is based on statistics S (Equations. 3, 4, 5 and 6) (SHADMANI et al., 2012):

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sign}(x_i - x_j) \quad (3)$$

where:

x_j are sequential rates; n is the size of the temporal series and variation $(x_i - x_j) < 0$ is -1 for $(x_i - x_j) = 0$ is 0 and $(x_i - x_j) > 0$ is 1.

Mean $E[S]$ and variance $Var(S)$ of statistics S are given as:

$$E(S) = 0$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5)}{18} \quad (4)$$

where:

n is the number of rates; q is the number of replicated groups;

t_p is the number of data scores in p^{th} rates of the groups. If the hypothesis is nil and the rate replication in the temporal series is lacking, variance $Var(S)$ is:

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \quad (5)$$

The second term of the expression represents the number of repeated terms. Normalized statistical test (Z_{MK}) is given as:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \quad (6)$$

Trend statistical presence is evaluated by employing the Z_{MK} rate. Statistics is used to test the nil hypothesis that there is no trend. Further, 95% at significance level were associated to test each growth or no growth of the trend. Z_{MK} rate indicated trend

growth when it was positive and its rate was higher than significance level. In the case of trend decreasing level, Z_{MK} rate was negative and lower than significance level. No trend existed if Z_{MK} rate lay between levels of significance.

Mann-Kendall test only shows the trend of a single series but does not provide any estimate on the trends' magnitude. It merely uses a simple procedure developed by Sen in which the trends' inclination may be obtained by calculating $N' = n(n-1)/2$ estimated inclinations, $S_e = x_j - x_i / j - i$,

where x_j and x_i are data rates in time j and i , respectively, in which $j > i$; N' is the number of data pares in which $j > i$. The median of N' rates of S_e is the estimates rate of Sen's inclination (SEN, 1968).

Mann-Kendall test was applied, following equations 3 to 6, coupled to Sen's estimator to analyze its magnitude, so that growth or decrease trend of the temporal series of volume rainfall in the hydrographical sub-regions and for each station within the domain of TAHR could be investigated.

Significance level (α) at 1, 5 and 10% was employed in Mann-Kendall's test for comparison. The results of the two tests for each pluviometric station will be interpolated by standard Kriging and graphically represented by iso-line maps.

Results and discussion

According to Figure 4a, the lowest pluviometric averages (rates below 1,400 mm) may be found in the south-eastern region of the High Tocantins sub-basin, namely in the municipalities of Flores de Goiás, São Domingos and Formosa. Contrastingly, the highest pluviometric averages (over 2,700 mm) may be found to the North of the Lower Tocantins sub-basin, or rather, in the municipalities of Santa Izabel and Castanhal. Rainfall volume increases to the north of the TAHR.

Analysis of maximum rainfall (Figure 4b) demonstrates in which municipalities occur high intensity pluviometric events. Current study shows that the highest pluviometric events (over 2,500 mm) are concentrated in the Lower Tocantins sub-basin, especially on the coast of the state of Pará where rainfall volume is close to 3,600 mm.

Analysis of the lowest rainfall volume (Figure 4c) indicates that the greatest lowest rainfall volumes (over 2,000 mm) lie to the north of the Lower Tocantins sub-basin and the lowest

indexes (lower than 900 mm) occur to the southeast of the high Tocantins sub-basin. Figure 4d shows that rainfall represents a temporal variability between 14 and 22%, with the lowest at the southwestern region of the Araguaia sub-basin and the highest at the eastern region of the high Tocantins sub-basin.

Figure 5 shows that, as a rule, a decrease in the amplitude of annual rainfall occurs during the years of meteorological anomalies, as may be observed during 1979, 1980, 1981, 1983, 1987, 1992 and 1997.

A less than 15% in spatial variability coefficient demonstrates this fact. Irregular meteorological index corroborates the above with rates below 2.5 for 2005, characterized by the anomaly of warm waters in the North Atlantic. The above may also be demonstrated by high spatial variability and meteorological irregularity for 1984, 1986 and 1993. This means that the spatial rainfall behavior of the region under analysis is highly heterogeneous and irregular, with oscillations associated to the dynamics of climatic anomalies.

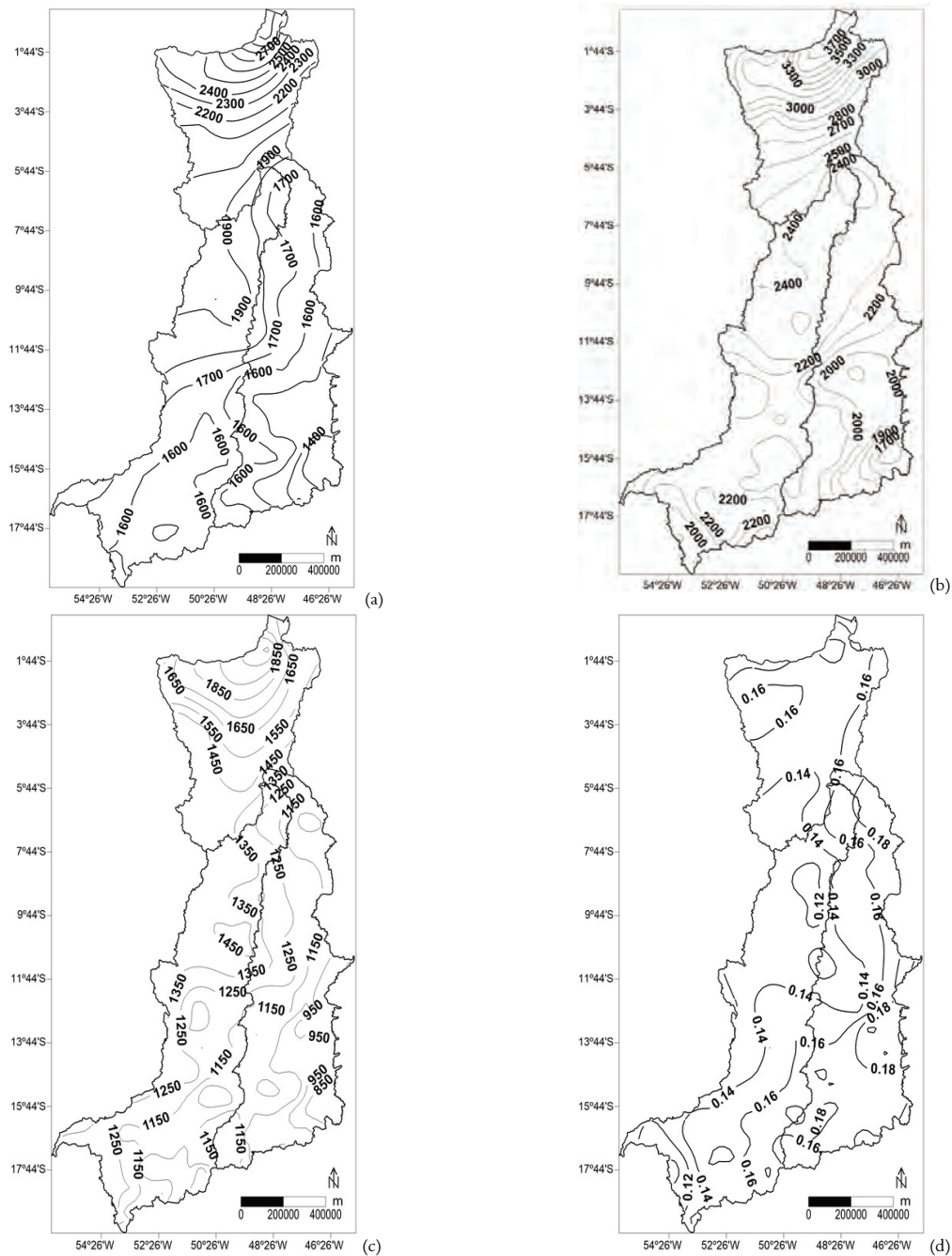


Figure 4. Statistical description of rainfall (a) average, (b) maximum, (c) minimum, (d) variation coefficient.

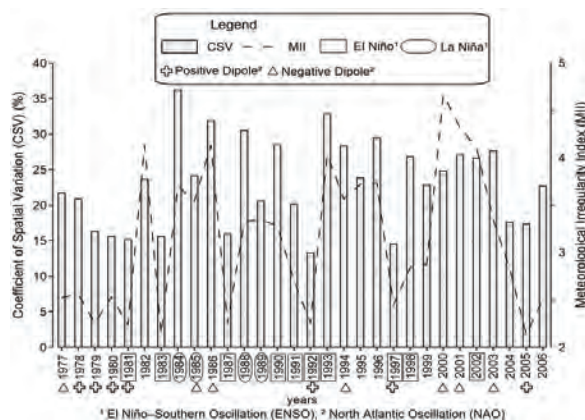


Figure 5. Meteorological Irregularity Index (MII) and Coefficient of Spatial Variation (CSV).

Figure 6 shows that, following meteorological anomalies, the temporal variation of rainfall in the Lower Tocantins sub-basin amounts to 9%, with an average rainfall volume on almost 510 km³. Although intense El Niño occurrences were reported for 1987 and 1991, more intense events occurred in 1981 and 1983 which were associated to the negative dipole of the Atlantic according to the negative rates of climatic anomaly. High inter-annual variability occurred for 1984, 1985, 1988 and 1989, with significant rainfall, principally during 1985, associated with negative dipole which contributed towards an increase in rainfall during the period.

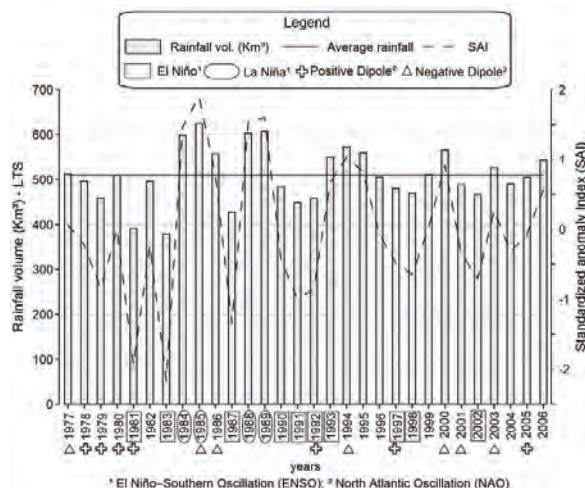


Figure 6. Rainfall volume in the Lower Tocantins sub-basin and the influence of the anomaly in the Pacific (ENOS) and Atlantic (dipole) oceans for 1977-2006.

Figure 7 shows that in the High Tocantins sub-basin the meteorological phenomena were not so intense and, up to a certain point, opposite those of the Low Tocantins sub-basin, with a 14% temporal variation and mean rainfall volume on slightly

higher than 473 km³. These characteristics may be confirmed for 1992 in which El Niño and the Atlantic positive dipole events triggered a positive rainfall anomaly. The same anomaly occurred in 1983. A different behavior for the La Niña year also occurred with negative anomaly for 1984. However, a significant increase in rainfall occurred in 1985 and 1989, similar to the behavior of the Lower Tocantins sub-basin. On the other hand, the El Niño events of 1981, 1990 and 1993 did not have the same intensity of the Lower Tocantins sub-basin.

Results of rainfall volume on the 656 km³ Araguaia sub-basin (ARA) show that the meteorological anomaly works differently throughout the sub-basin. In fact, the El Niño events caused the opposite in rainfall intensity towards the south of the Low Tocantins basin.

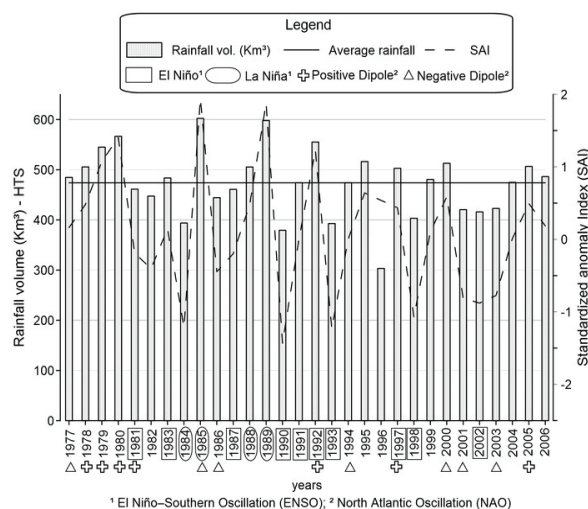


Figure 7. Rainfall volume in the High Tocantins basin and the anomaly influence of the Pacific (ENSO) and Atlantic (dipole) during 1977-2006.

However, events occur mildly when compared to the High Tocantins basin. This is very similar to what occurs during the El Niño years, as the 1984 negative anomaly demonstrates. Its activities are more associated with magnitude and with the negative dipole throughout the whole sub-basin for 1985. Activities may be proved by the temporal coefficient variation close to 12%, as Figure 8 shows.

Figure 9 shows that rainfall behavior in the TAHR is very close to what occurs in the Low Tocantins basin and represents the average of what occurs in the sub-basins, or rather, average rainfall volume on slightly higher than 1,639 km³ and a 10% coefficient of temporal variation. The above rates are an indication that TAHR is the source of great rainfall volume that triggers several economical activities.

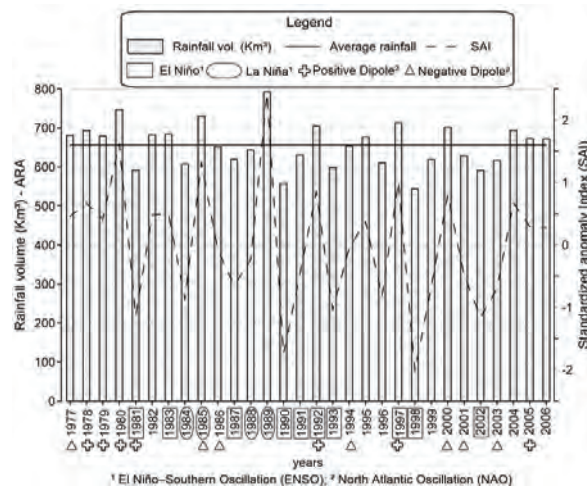


Figure 8. Rainfall volume on the Araguaia sub-basin and the influence of the anomaly of the Pacific (ENSO) and Atlantic (dipole) Oceans in 1977-2006.

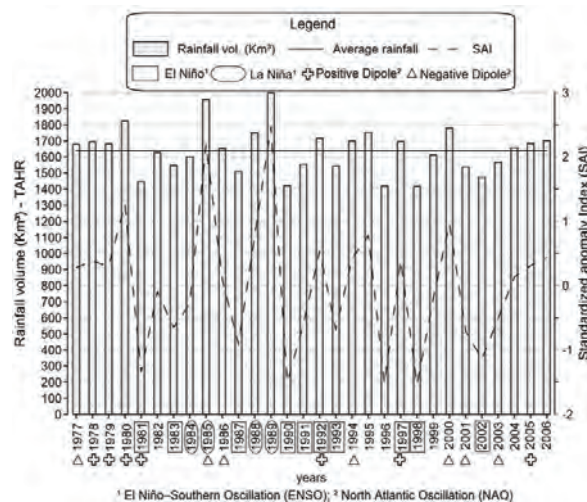


Figure 9. Rainfall volume in the TAHR and the influence of the anomaly of the Pacific (ENSO) and Atlantic (dipole) oceans in 1977-2006.

Results show that annual rainfall variations in the TAHR are related to the meteorological anomalies of the Pacific (ENOS) and Atlantic (Dipole) Oceans and their occurrence and magnitude to the area. Figures 5 – 9, therefore, show that meteorological anomalies work differentially within the TAHR. In other words, in El Niño years a rainfall decrease occurs in the Low Tocantins basin and a rainfall increase occurs to the south of the High Tocantins and Araguaia basins, as may be seen from data for 1981, 1983, 1987 and 1992.

Similar results were also found in a study on the rainfall anomalies of the Atlantic and Pacific oceans in the Amazon region for 1975-2003 (VILLAR et al., 2009). In fact, the authors concluded that the behavior of meteorological phenomena was different for the

northeastern and southeastern section of the region (exactly within the Araguaia sub-basin) are widely dependent on the Andean country. There was a rainfall increase during the El Niño/Positive dipole period in the southeastern region and a decrease in the northeastern one formed by the joint action of La Niña/Negative Dipole.

In their investigation Clarke et al. (2010) corroborate findings on the irregular rainfall behavior. They compared the results of rainfall variability estimated by two gridded data sets and a national rain gauge network in the Amazon region during the 1979-1991. El Niño period. Both results show a rainfall decrease in the north (Low Tocantins basin) and in the east of the Amazon region (Araguaia and Low Tocantins basin) and a mild rainfall increase to the south of the region (Araguaia basin) during the El Niño period.

Kane (2007) also provided similar results. He studied the simultaneous occurrence of TSM anomaly in the Pacific and Atlantic oceans and concluded that the El Niño and Positive Dipole activity brought negative rainfall anomalies which extended themselves towards the central and eastern part of the Amazon (Araguaia basin) and thus contributed towards the anomalous distribution of rainfall.

According to Figure 10a, the statistically significant trends (1% significance level, with 99% correctness) comprised rainfall increase to the north of the Araguaia sub-basin and another rainfall decrease station in the same sub-basin at a higher latitude. In fact, Figure 10b shows that an increase in significance level increases the number of stations with statistically significant trends. Six rainfall decrease stations lay principally in the Araguaia sub-basin and three rainfall increase stations were located to the north of the same sub-basin. According to Figure 10c, the previous figure analogously provides (at 10% significance level) an increase of the zone of influence. Seventeen stations have decreasing statistically significant trends in the Low and High Tocantins sub-basins, whereas three stations have negative trends to the north of the Araguaia sub-basin.

The Mann-Kendall's test failed to show either an increase or a decrease in the Low Tocantins sub-basin although, due to an increase in the significant level, albeit with less probability of correctness, it could be inferred that a relative increase occurred.

Regardless of the fact that the pluviometric stations did not provide significant trends for high significant levels, Sen's estimator, as in Figure 11a, showed that there was, as a rule, a relative rainfall decrease throughout the period under analysis in the central and southern regions of the High Tocantins

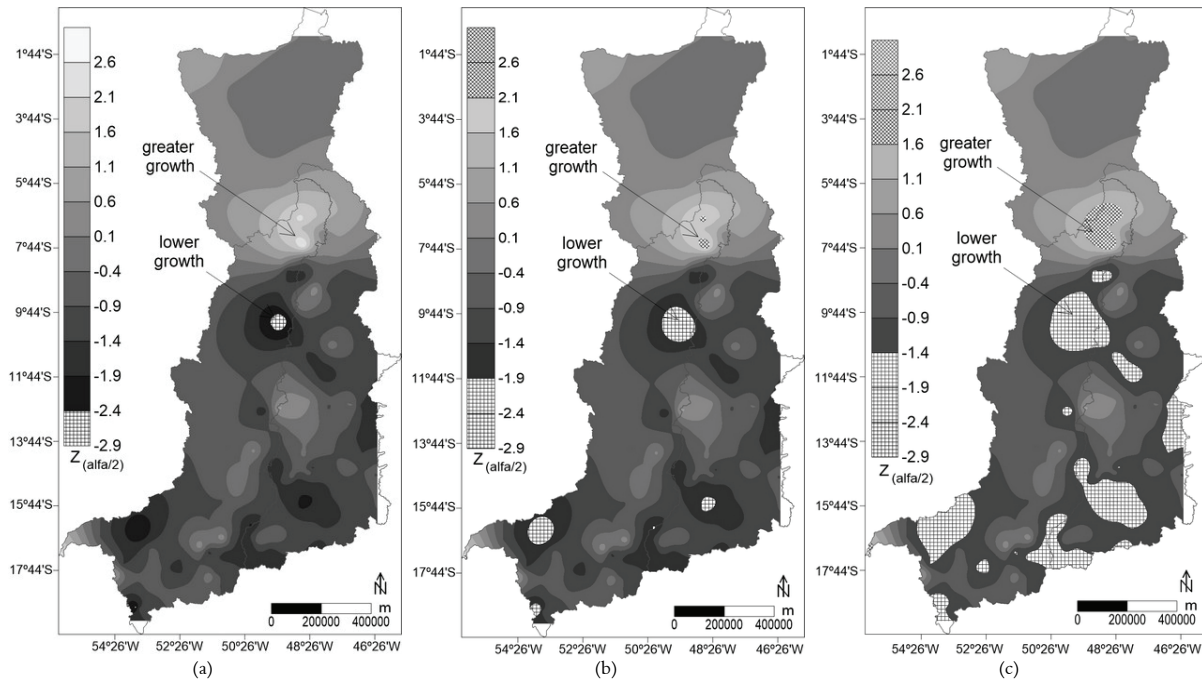


Figure 10. Mann-Kendall's test for each pluviometric station at 1% (a), 5% (b), 10% (c) levels of significance.

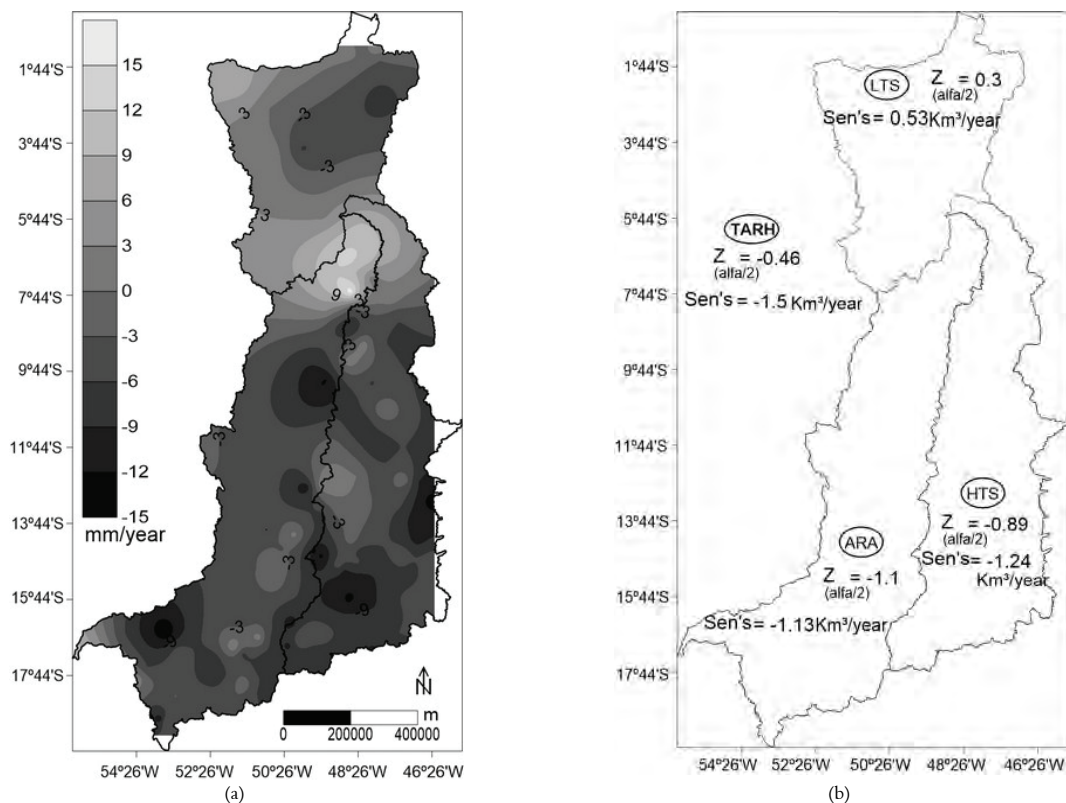


Figure 11. Sen's estimator of the trend's magnitude (a) and of the trend and magnitude of rainfall volume (km^3) (b).

and Araguaia sub-basins with a decrease of approximately 15 mm year^{-1} in the south-western region of the Araguaia sub-basin and in the eastern region of the High Tocantins sub-basin. An inverse

occurrence was recorded in the western section of the Low Tocantins basin and in the north of the High Tocantins and Araguaia sub-basins, with a $3\text{--}6 \text{ mm year}^{-1}$ increase.

When rainfall volume per sub-basin was provided (Figure 11b), the sub-basins did not show any significant trend by the Mann-Kendall's test that would prove a decrease or an increase of rainfall volume per region, regardless of the significance levels used. Sen's estimator showed that, throughout the period under analysis, the Low Tocantins sub-basin had a $0.53 \text{ km}^3 \text{ year}^{-1}$ rainfall increase in the sub-basin, regardless of the test's significance. On the other hand, a $1.24 \text{ km}^3 \text{ year}^{-1}$ and $1.13 \text{ km}^3 \text{ year}^{-1}$ decrease occurred respectively in the other two High Tocantins and Araguaia sub-basins.

As a rule, there was no significant trend in rainfall volume decrease for the TAHR, although Sen's estimator pointed towards a $1.5 \text{ km}^3 \text{ year}^{-1}$ rainfall decrease during the investigated period. However, throughout 30 years this variation was equivalent to a 2.78% rainfall decrease within the TAHR.

In studies on the Brazilian Amazon and Tocantins basin for the 1948-2005 period, a negative rainfall trend within the Amazon basin was identified (VALVERDE; MARENGO, 2014). An inter-decade variation was discovered with relatively drier and more humid periods with different behaviors to the north and to the south, very much alike the behavior between the Low and High Tocantins sub-basins.

Results by (SATYAMURTY et al., 2010) on rainfall trends in the TAHR did not report any significant trends in the Amazon Basin as a whole and stated that the region's rainfall had not undergone any significant changes, with the exception of certain particular stations, as reported in current study. Marengo (2009) reached a similar result and concluded that there was no long term systematic trend for dry or humid conditions in the eastern Amazon since 1920 (Low Tocantins and Araguaia sub-basins).

Conclusion

During the occurrence of intense meteorological anomaly a decrease of pluviometric amplitude may be verified, characterized by rainfall increase south of the High Tocantins and Araguaia sub-basins and a decrease to the north of the Low Tocantins basin during the El Niño and/or Atlantic Positive Dipole events, as verified for 1981, 1983, 1987 and 1992. The Mann-Kendall's test does not attest to any rainfall volume trend within the TAHR, although Sen's estimator demonstrates a rainfall decrease in the sub-basin of the High Tocantins ($-1.24 \text{ km}^3 \text{ year}^{-1}$) and Araguaia ($-1.13 \text{ km}^3 \text{ year}^{-1}$) and a rainfall increase in the Low Tocantins sub-basin ($0.53 \text{ km}^3 \text{ year}^{-1}$).

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