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Impact of Climate Variations and Land Use Change: a Mann-Kendall Application

Leonardo F. P. Barbieri[1], Magaly de F. Correia[2], Maria R. da S. Aragão[3], Rafaella de A. A. Vilar[4] & Magna S. B. de Moura[5]

* Corresponding Author: poncianolf@yahoo.com.br
Todos autores contribuíram de forma igualitária

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ABSTRACT

The association between changes in land use combined with climate variations partially explains the degradation in the water resources of the Brazilian semiarid. The existence of local and regional tendencies in meteorological variables, which are important for agricultural and electric energy production sectors, and centers for prediction of meteorological extremes, was investigated, using parametric and non-parametric statistical tests. The application of the Mann-Kendall sequential test allowed detection of years when tendencies of increase or decrease in atmospheric humidity started by using meteorological data from the period 1975 to 2015. The results indicate that, despite the observed similarities in the climate regime, the Bebedouro (PE) and Mandacaru (BA) regions show distinct variability patterns, which may be attributed to effects caused by interventions in soil cover and use. Changes in the atmospheric pattern that favored the occurrence of extreme precipitation events were investigated by means of factorial analysis. The increase in atmospheric moisture due to agricultural expansion in Caatinga areas is one of the main factors involved in the increase of cloudiness.

Keywords: trend analysis, semiarid, extreme precipitation event

Introduction

Variations in the water resources in the Brazilian semiarid associated with climate changes or alterations in soil use require special attention due to the expressive water demand caused by the expansion of the irrigated agriculture in Caatinga areas, and electric energy production (RIBEIRO et al., 2016). Some studies indicate that the middle and submiddle of the São Francisco River Hydrographic Basin have experienced considerable changes in land cover and use (CORREIA et al., 2006, BARBIERI et al., 2013). The authors highlight the importance of the impacts caused by alterations in the surface energy balance, which results of the conversion from native vegetation (Caatinga) to agricultural crops. Bloschl et al. (2007) argue that the impact of land cover changes decrease with the extension of the hydrographic basin, since such changes are typically a local phenomenon. Studies on environmental impact in the Petrolina region (PE) give evidence that circulations thermally induced by surface processes in heterogeneous regions modify the pattern of wind, moisture, temperature and cloudiness on the mesoscale (CORREIA and SILVA DIAS, 2003; CORREIA et al., 2006; CAHU et al.; 2015).

The excess or absence of rainfall may cause irreversible damages resulting from phenomena as inundations or severe droughts. In the region of study, the number of registers of excessive precipitation increases in years in which the ITCZ (Intertropical Convergence Zone) reaches extreme latitudes in the Southern Hemisphere (XAVIER and XAVIER, 1983; SILVA ARAGÃO et al., 2000). According to Marengo et al. (2011), extreme precipitation events have become more frequent and intense, and last longer. They may occur outside the rainy period and even under the influence of El Niño, a phenomenon considered unfavorable to deep convection development

1 Student (CNPq) of Posgraduate Program in Meteorology, Federal University of Campina Grande, Campina Grande, Paraíba, Brazil.
2,3 PhD Professor of Department of the Atmospheric Sciences, Federal University of Campina Grande, Campina Grande, Paraíba, Brazil.
4 Student (CAPES) of Posgraduate Program in Meteorology, Federal University of Campina Grande, Campina Grande, Paraíba, Brazil.
5 Agrometeorology Researcher, EMBRAPA Semiarid, Petrolina, Pernambuco, Brazil.

(BARBOSA and CORREIA, 2005; FARIAS and CORREIA, 2008).

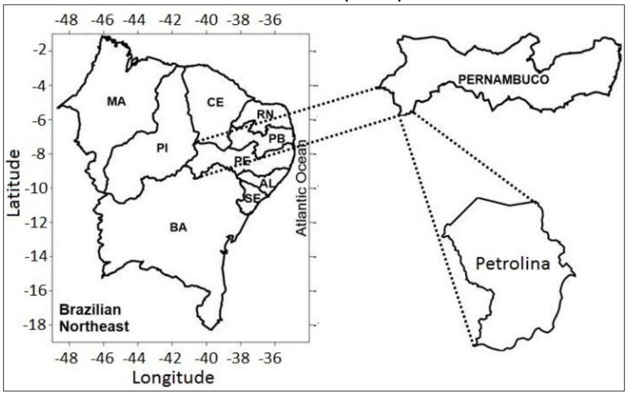
In this work parametric and non-parametric statistical methods were used aiming to detect tendencies and climate variations in time series of relative humidity. Connections between changes in regional climate due to anthropogenic causes, and the occurrence of extreme rainfall were also investigated through application of the technique of factorial analysis by principal components and the Mann-Kendall sequential method.

Material and Methods

Study Area

The region of study is located in the Brazilian semiarid and encompasses one of the most important poles producing of fruits in the country, namely the Juazeiro-Petrolina pole. The geographic location of the city of Petrolina (9.38°S; 40.48°W; 370m), is presented in Figure 1. With the construction of the Hydroelectric Power Plant of Sobradinho (1973 – 1977), the sectors named middle and sub middle of the Hydrographic Basin of the São Francisco River underwent large environmental modifications. The most significant alterations resulted from change in soil use in consequence of the agricultural expansion in areas of the Caatinga biome, and of urban growth (CORREIA, 2001; CORREIA et al., 2006).

Figure 1 - Geographic location of the city of Petrolina, in Northeast Brazil (NEB).



Data

In this work, data pertaining to different sources were used:

METAR/SPECI codes elaborated at the Petrolina International Airport and made available in the website of the Meteorology Network of the Brazilian Air Force Command (REDEMET);

Surface data collected at the surface meteorological station of Petrolina which belongs to the National Institute of Meteorology (INMET);

Upper air data from atmospheric soundings, made at 12 UTC in Petrolina and made available in the website of the Department of the Atmospheric Sciences of the University of Wyoming – USA (http://weather.uwyo.edu/);

Historical series of meteorological data collected in climatologic stations of EMBRAPA Semiarid.

Mann-Kendall Trend Test

The non-parametric Mann-Kendall test is used to determine the existence and significance of tendencies in data collected in meteorological stations. The technique also allows to detect the point in which starts a trend and abrupt changes in climate (KENDALL, 1975; RYAN et al., 1997). The test statistics is given by equation 1:

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

The function sign:

$$sign = \begin{cases} 1, if\ (x_i - x_j) > 0 \\ 0, if\ (x_i - x_j) = 0 \\ -1, if\ (x_i - x_j) < 0 \end{cases}$$

where: S is the correlation coefficient of Z_{MK} given below; x_i and x_j are the data estimated in the sequence of values; n is the number of elements of the time series.

The variance of S (Equation 2) is calculated when n is very large, making S to tend toward normality.

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

where: t_p is the number of data with equal values in a certain group p; q is the number of groups containing equal values in a series of data of a group p.

After calculating S and Var (S), Z_{MK} (Equation 3) is calculated to evaluate the presence of trend in a time series.

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, if\ S > 0 \\ 0, if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, if\ S < 0 \end{cases} \quad (3)$$

The sign of Z_{MK} indicates if the trend is positive ($Z_{MK} > 0$) or negative ($Z_{MK} < 0$).

Mann-Kendall Sequential Test

Proposed initially by Sneyers (1975), the test considers that in the hypothesis of stability (H_0) of a time series, the sequence of values occurs in an independent form and the probability distribution remains the same. For a time series of X_i of N terms (1 ≤ i ≤ N), the sum t_n of the numbers of terms m_i of the series, relative to value X_i, whose preceding terms (j < i) are inferior to the same ($X_j < X_i$), or:

$$t_n = \sum_{i=1}^{n} m_i \quad (4)$$

Under the null hypothesis (H_0) of absence of trend, t_n will show a normal distribution, with given mean and variance, respectively, by:

$$E(t_n) = \frac{N(N-1)}{4} \quad (5)$$

$$Var(t_n) = \frac{N(N-1)(2N-5)}{72} \quad (6)$$

In the sequence, the statistics $u(t_n)$ is calculated, given by the Equation:

$$u(t_n) = \frac{(t_n - E(t_n))}{\sqrt{Var(t_n)}} \quad (7)$$

The null hypothesis is rejected, or not, in accordance with the level of significance (a) adopted, based on a table of the reduced normal, in general of 5%. If there is a significant trend in the time series, above 1.96 or under -1.96, the null hypothesis is rejected. The point at which the change begins may be observed applying the same principle to the inverse series. In this way, it is calculated the number of terms m_i of the series X_j, such as that for $X_i > X_j$, with i < j, the values of $u^*(t_n)$ for the retrograde series will be given by the Equation:

$$u^*(t_n) = -u(t_{i\prime}) \quad (8)$$

The interception of the curves $u(t_n)$ and $u^*(t_n)$ indicates the year when a trend is beginning. For the trend to be significant, the point of interception must be between the critical values of the confidence interval or, in other words, between -1.96 and 1.96. The sign of the curve $u(t_n)$ indicates that the trend is increasing or decreasing.

Factorial Analysis by Principal Components (PCA)

In this work the factorial analysis by PC in P mode, as described in Richman (1986), was used to reduce the dimension of the variables and to help to understand the data structure. The P mode is very useful in analyses of data collected in specific experiments, or observations made at exclusive localities (CORREIA et al., 2013; QUEIROZ et al., 2014). With the objective of increase the explicative power of the factors in the analysis, the Varimax method was used in their rotation (WILKS, 2006). The data ensemble used in the application of PCA is comprised by the variables:

- Daily mean temperature, defined by Equation (9):

$$T = \frac{\sum_{i=1}^{n} T_i}{n} \quad (9)$$

where: T is the daily mean temperature (°C); T_i is the observed air temperature in each METAR/SPECI message (°C), and n is the number of messages.

- Mixing ratio, obtained based on Equation (10):

$$Rmix = 622 \times \frac{e}{P-e} \quad (10)$$

where: R_{mix} is the mixing ratio (g/kg); $e = RH \times e_s(T_m)$ is the vapour pressure (mb); RH is the relative humidity (%); P is the atmospheric pressure (mb) and $e_s(T_m) = 6.11 \times \exp\left[\frac{17.67 \times T_m}{(T_m + 243.5)}\right]$ is the saturation vapour pressure (mb).

- Daily mean wind intensity at 10 meters, determined by Equation (11):

$$V_{10m} = \frac{\sum_{i=1}^{n} V_i}{24} \quad (11)$$

where: V_{10m} is the daily mean wind intensity and V_i is the observed air speed (m/s).

- Height of the cloud base, obtained as a function of the dew point temperature, following instructions of the Air Space Control (ICEA) of the Air Force Command and determined based on Equation (12):

$$h\_base = (T - T_d) \times 125 \quad (12)$$

where: h_base is the height of the cloud base; T is the air temperature (°C) and T_d is the dew point temperature (°C).

- Index of instability K calculated using Equation (13):

$$K = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}) \quad (13)$$

where: T_{850} is the air temperature, in °C, at the 850 mb level; T_{500} is the air temperature, in °C, at the 500 mb level; T_{d850} is the dew point temperature, in °C, at the 850 mb level; T_{700} is the air temperature, in °C, at the 700 mb level, and T_{d700} is the dew point temperature, in °C, at the 700 mb level.

- Daily number of sunshine hours (Insolation).

Results and Discussion

Trend Analysis Using the Non-Parametric Mann-Kendall (MK) Test

A synthesis of the results obtained with the MK test applied to the time series of relative humidity for Bebedouro PE and Mandacaru BA (annual, rainy period and dry period) is presented in Table 1. Values of the statistical parameters described in the table indicate the existence of negative tendencies (atmospheric moisture decrease) without statistical significance for the Bebedouro PE station. In the Mandacaru case, the behavior is the opposite. The results of the MK test show the existence of a positive trend (atmospheric moisture increase) significant at the 95% confidence level. Cabral Junior (2015) found similar results.

Table 1 - Application of the Mann-Kendall trend test for Bebedouro (Beb) and Mandacaru (Man). The sign (-) indicates negative trend (reduction), non-significant; and the sign (+ +): positive trend (increase), statistically significant.

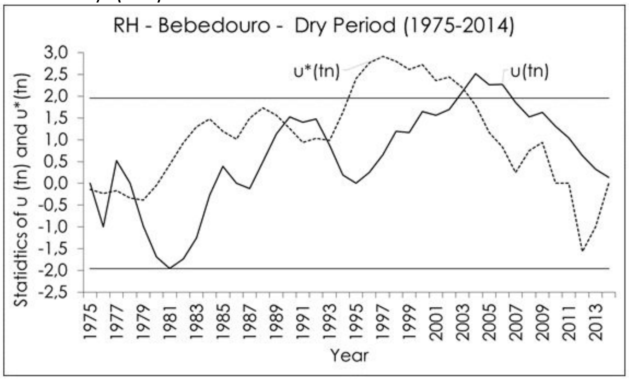
Variable	Mann-Kendall			Statistics
	S	Z calculated	p-value	Significance
RH Annual - Beb	-70	-0,8040	0,4214	-
RH Rainy- Beb	-98	-1,1305	0,2583	-
RH Dry- Beb	-57	-0,6527	0,5139	-
RH Annual - Man	384	4,4636	8,06E-06	++
RH Rainy - Man	329	3,8247	1,31E-04	+ +
RH Dry - Man	443	5,1515	2,58E-07	+ +

In function of the apparent contradiction in the trend, results obtained with series of observed data in stations so close to each other it was decided to use also the modified version of MK, namely Mann-Kendall Sequential test (MKS) aiming to detect abrupt changes in the behavior of the variable during the analyzed period. Our understanding is that although the MK test shows a significant increase in RH for Mandacaru BA, in the period of 1975-2014, indicating a possible climate change, the result does not minimize the importance of local factors as processes that alter the atmospheric moisture content. The analyses of the application of MKS were concentrated on the results obtained with the time series of RH of the dry period (May to October), and the month of October, motivated by the extreme rain event registered on October 2009. The results are presented in Figure 2. The horizontal lines indicate the confidence intervals of ± 5%, respectively. The trend is significant when the values of $u(t_n)$ are larger than the confidence intervals.

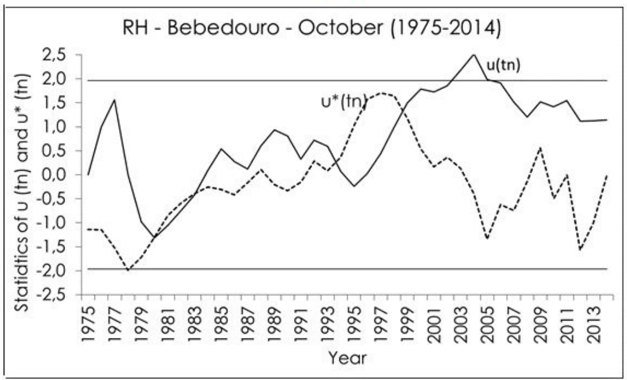
The behavior of the tendencies detected by the MKS test in the series of October and of the dry period is very similar. However, it is possible to verify some differences characterized by abrupt changes that allow detection of the beginning of the periods with positive or negative tendencies in the series of October. There is increase in RH beginning in the years of 1980 and 1999 and decrease of RH beginning in 1994 for the Bebedouro station. At the Mandacaru station, there is an abrupt reduction beginning in 1991 and an abrupt increase in 2009 becoming significant in 2010.

The graphs of relative humidity for the dry period (Figures 2a and 2b) show clearly an increase in the RH variable in Bebedouro between 1980 and 2004. However, the SMK test does not confirm the trend, as it can be verified in Figure 2a, since there were two crossings of curves $u(t_n)$ and $u^*(t_n)$ between the confidence intervals.

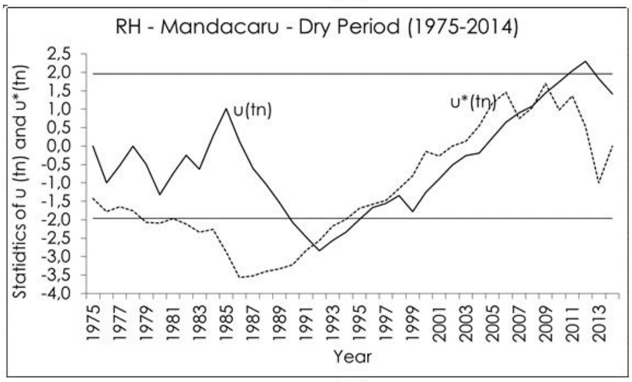
Figure 2 - Mann-Kendall sequential test for Relative Humidity (RH) in Bebedouro and Mandacaru.



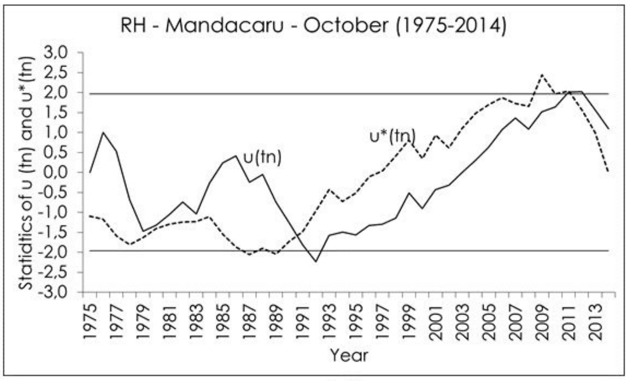
(a)



(b)



(c)



(d)

At Mandacaru it is observed a trend in increase of RH in the first years of the series, with a maximum

peak around the year of 1986, decreasing afterwards until the year of 1992, when it returns to show an increase in the atmospheric moisture content. Despite the two stations being relatively close, they are located in opposing margins of the São Francisco River. The moisture transport associated with the river breeze has a direct influence in RH. Circulations induced by spatial discontinuities in soil cover due to underlying environmental gradients associated with agricultural areas, pastures and native vegetation represent mechanisms of vapor and energy transports also.
In synthesis, changes in the pattern of the local wind resulting from coupling between thermally generated circulations and the mean flow has a direct influence in the formation and spatial distribution of clouds, as well as the intensification of rain events. This result indicates that anthropogenic activities represent one of the important factors for increase or reduction in the atmospheric vapor content.

The Extreme Rainfall Episode of October 2009

In October 2009, end of the dry period in the region of study, it rained 106.1 mm, registered in the meteorological station of Petrolina PE of the National Institute of Meteorology (INMET) and made available by the Water National Agency (ANA), with 72 mm registered in one day only (26) (Figure 3b). The historical mean for the month in question is 11.9 mm (Figure 3a). Pluviometric data registered in the region of Juazeiro – BA (9.41°S; 40.5°W; 368m), show values of up to 78 mm. The rains caused urban damages, with inundations in various points of the city, as well as agricultural losses due to destruction in orchards.

According to the meteorologist and professor of the Federal University of the São Francisco Valley (UNIVASF), Dr. Mário Miranda, the event that occurred in Petrolina – PE was the most intense in the last 98 years, in the month of October (personal communication). The time evolution of the monthly precipitation total for the month of October in the period from 1961 to 2015 is presented in Figure 4. The climatological mean (11.9 mm) and the value of the percentile 90, P90 (36.3 mm) are represented by red and black lines, respectively. The P90 is considered as the threshold to identify extreme precipitation events in the data series. The maximum value of monthly precipitation, of 127.4 mm, is observed in October 1973. This year, in two days only, it rained the equivalent to 108.5 mm. Possibly the La Niña phenomenon acting in the period, represented an additional factor for the increase in convective activity and the occurrence of intense precipitation. In October 2009, the atmosphere was under the influence of El Niño, a phenomenon normally associated with rains below the climatologic mean in the Region.

Figure 3 - Monthly mean precipitation in Petrolina – PE, with the month of October in red (a), and daily precipitation distribution for October in the year of 2009 (b). (Source: INMET/ANA).

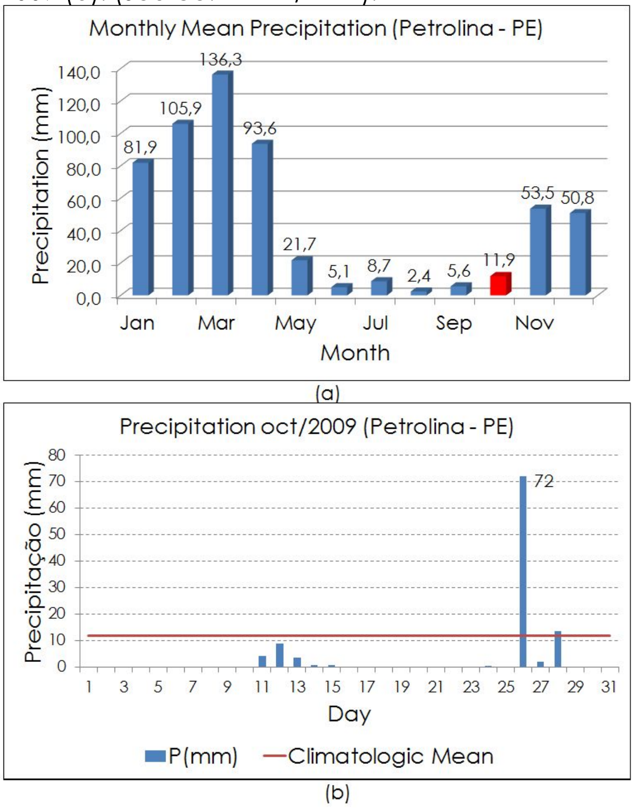
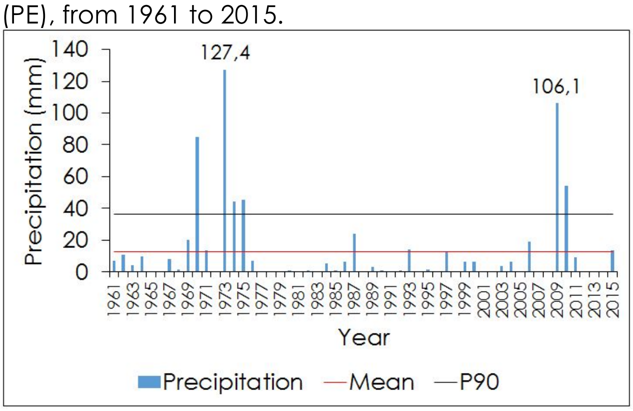


Figure 4 - Time series of the accumulated precipitation for the month of October in Petrolina (PE), from 1961 to 2015.



Statistical Analysis

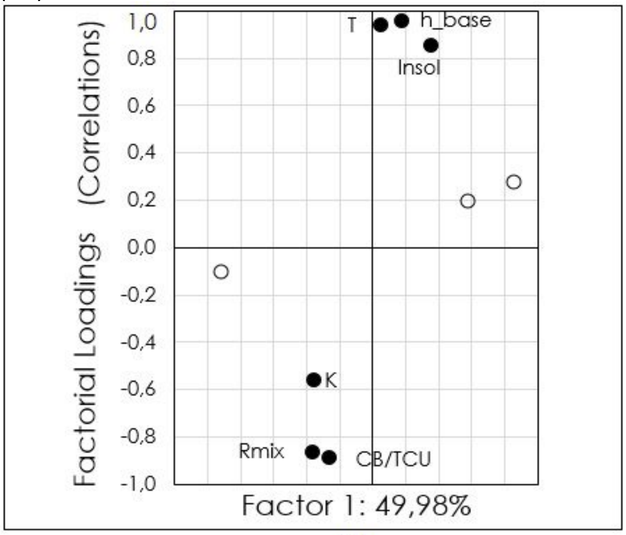
The application of the tests of KAISER and BARTLETT allowed evaluation of the adequacy of the data to realize the factorial analysis. The result of KMO, of 0.74, indicates that the selected sample is appropriate for application of the technique, while the value of BARTLETT < 0.05 validates the analysis (HAIR et al., 1995; CORRAR et al., 2007). Table 2 presents the results of the eigenvalues and the explained and accumulated explained variances of each retained factor. It is observed that two factors were retained, with power explanation of, approximately, 77% of the original data variance.

Table 2 - Proper Values (eigenvalues) and percentages of the Explained Variance (EV) and Accumulated Variance (AV), obtained for October 2009.

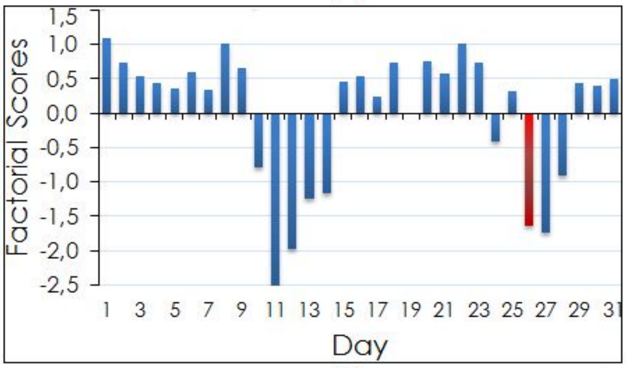
PC	Eigenvalues			Rotated Loads		
	Total	% EV	% AV.	Total	% EV	% AV
1	5,45	60,56	60,56	4,49	49,98	49,98
2	1,43	15,94	76,51	2,38	26,53	76,51
3	0,90	10,02	86,54			
4	0,55	6,21	92,75			
5	0,29	3,19	95,94			
6	0,16	1,78	97,72			
7	0,11	1,19	98,91			
8	0,08	0,87	99,79			
9	0,02	0,21	100,00			

With the purpose of making easier the identification of similar structures and to evidence the degree of relationship between variables and factors. The results were shown by means of diagrams. A diagram illustrating the groups of variables with higher factor loadings in the first factor, and the time evolution of the scores are presented in Figure 5.

Figure 5 - Diagramatic representation of the factor loadings (a) and the time evolution of the scores (b) of the first factor for October 2009, obtained from data collected at the Petrolina International Airport (PE).



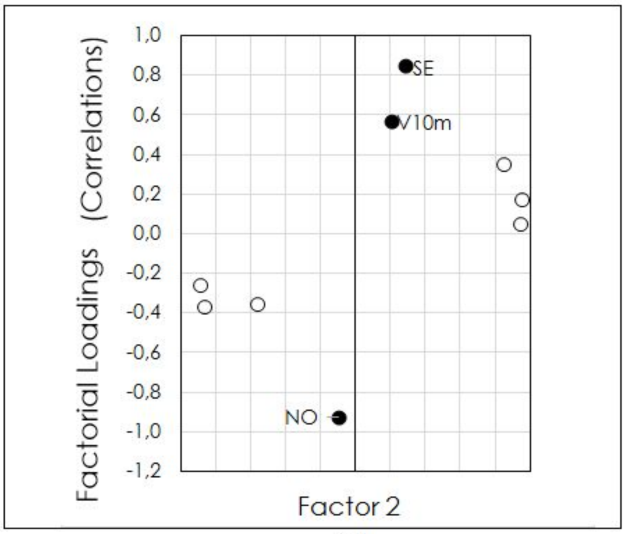
(a)



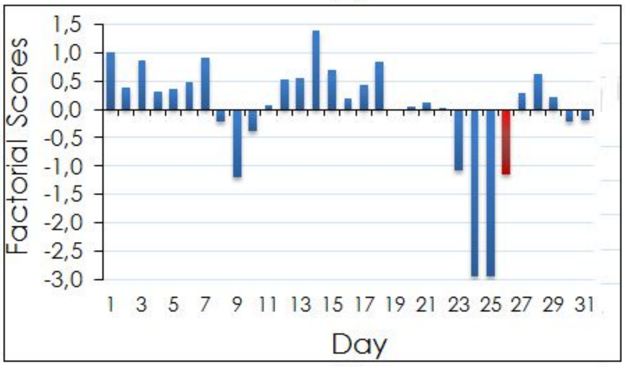
(b)

It is possible to identify a pattern of behavior of the atmosphere in October 2009 associated with the first factor (F1) defined by the presence of two groups of variables. The variables, T, h_base, and Insol (positive correlation) form group 1 and the second group (negative correlation), is formed by variables K, Rmix and CB/TCU. This result indicates characteristics of a very humid ambient (high water vapor content), a necessary condition for deep cloud formation and intense rainfall occurrence. High score values show the relevance of the variables in the evolution of the severe weather conditions.

Figure 6 - Diagrammatic representation of the factor loadings (a) and the time evolution of the scores (b) of the second factor for October 2009, obtained from data collected at the Petrolina International Airport (PE).



(a)



(b)

The time series of the scores of the first factor (F1) shows positive values, between 0.5 and 1 in most of the period, positively related with temperature and insolation, characteristics typical of the dry period. However, scores negative values higher than -1.5 on the day of the extreme event are related with variables Rmix, K and CB/TCU. In synthesis, the thermodynamic factor was determinant in the formation and development of intense convective systems (precipitation efficiency). There is an evident relationship between the frequency of clouds with large vertical extension of the CB and

TCU types, high moisture content and lower (close to the surface) lifting condensation level (height of the convective cloud base). Lowering of the temperature is an expected effect in days with precipitation, besides the decrease in the number of sunshine hours.

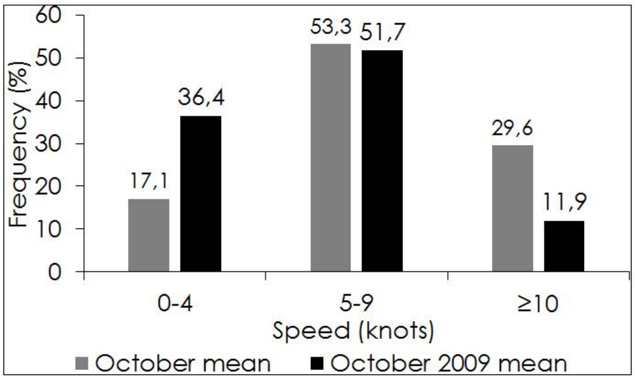
When the lifting condensation level (LCL) is close to the surface, there is higher probability of cloud formation and evolution. The process of evaporation contributes for the lowering in temperature also, a result that explains, in part, the inverse relationship between CB/TCU and T. The diagram illustrating the groups of variables with higher factor loadings in the second factor and the time evolution of the scores is presented in Figure 6. The second component retains close to 27% of the total data variance.

The second factor (F2) is positively correlated with stronger winds measured at 10 m height (V10m) and predominant direction of southeast (SE), and negatively correlated with winds of northwest (NW). Negative scores higher than -2.5, are related with northwesterly winds in the extreme event day, showing the relevance of the wind in the evolution of the weather conditions. The change in wind direction may be considered a strong indicative of variations in atmospheric conditions. The F2 has higher loads (higher contributions) on days that precede the intense rainfall (Figure 6b).

Wind Behavior and Development of Precipitating Systems

The importance of wind as contribution of dynamical factors in the development of intense convective systems (CS) in the month of October may be verified as a function of the wind speed frequency distribution illustrated in Figure 7.

Figure 7 - Wind speed frequency distribution by class.



It is observed in the month of October that the wind intensity varies mostly between moderate and strong. This is a characteristic clearly observed in the mean values (historical series) and also in the values for October 2009. However, the characteristic that determined the change in weather conditions was the considerable increase in the frequency of winds with intensity between 0 and 4 knots (weak winds) in October 2009.

Figure 8 - Wind speeds and predominant directions for the month of: (a) October in the period from 2003 to 2014, and (b) October of year 2009.

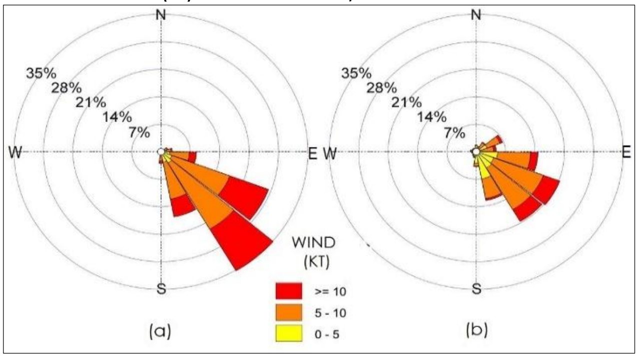
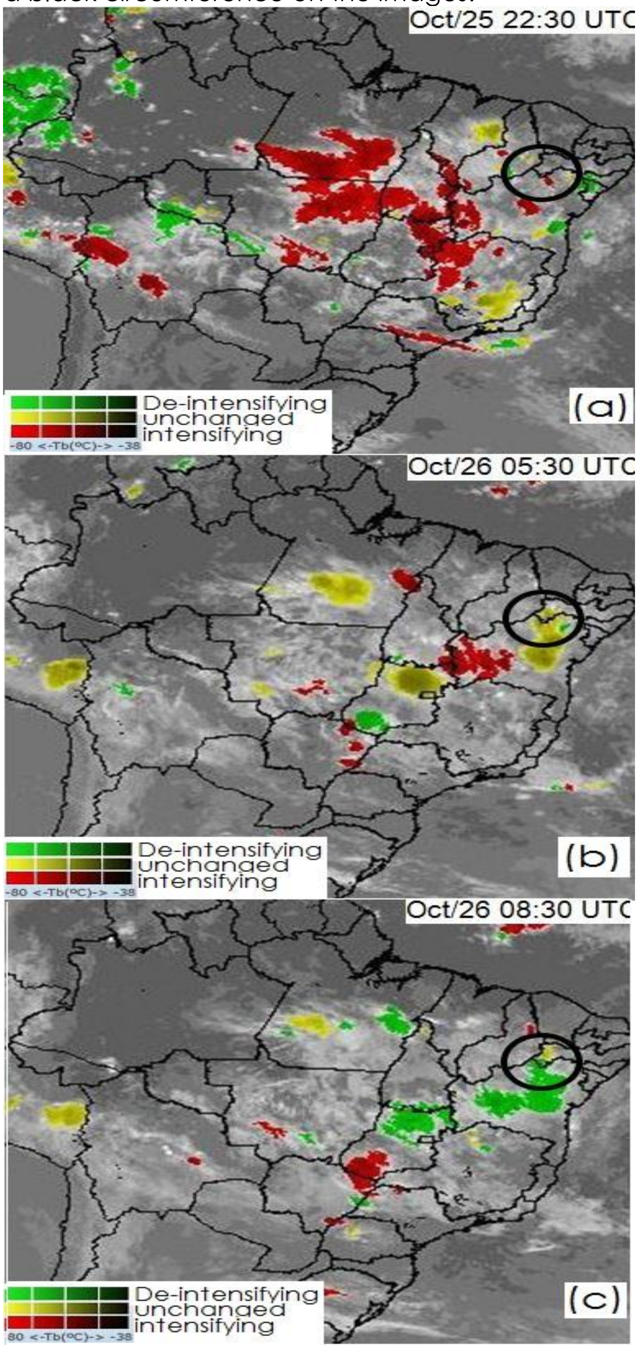


Figure 9 - Time sequence of FORTRACC images showing the intensification (a), maturation (b) and dissipation (c) stages of the convective system in the region of Petrolina (PE). The area is delimited by a black circumference on the images.



Speeds and predominant wind directions in the period from 2003 to 2014 are presented in Figure 9. It is clearly seen that the month of October is characterized by predominance of southeasterly (SE) winds with intensity varying typically from moderate (5 – 10 kt) to strong (> 10 kt).

The mean flow in this period is commonly named southeasterly trade winds and has direct association with the South Atlantic Subtropical High. By the other hand, it is verified higher variability in the direction of the winds with intensity lower than 5 knots, in October 2009 (Figure 8b). This behavior validates the results obtained by means of PCA (F2).

The precipitation registered on day 26 occurred with higher intensity in the first morning hours. The intensification of the CS is evident in the sequence of FORTRACC images presented in Figure 9. At 22:30 UTC on day 25 (Figure 9a) there is significant evolution in the areas indicated by red nuclei (intensification stage), including the area of study inside the black circumference. There, at 05:30 UTC on day 26 (Figure 9b) the image indicates that the convective system is in mature stage. At 08:30 UTC (Figure 9c) the CS is in decaying stage.

Conclusions

The results of the MK test indicate the existence of negative tendencies (atmospheric humidity reduction) without statistical significance for the Bebedouro PE station. However, for the Mandacaru BA station they show the existence of significant positive trend (atmospheric humidity increase) at the 95% confidence level;

These results indicate that in the last 40 years, the atmospheric humidity increased significantly in the Mandacaru region. However, the same behavior was not detected in Bebedouro. It is concluded that the increase or reduction in the values of this variable were not caused by natural factors;

The modified version of Mann-Kendall, MKS, allowed detection of abrupt changes (increase or reduction) in RH in specific years in both stations. This give evidence that anthropogenic activities, particularly those associated with changes in soil use, represent important factors for increase or reduction in atmospheric humidity in the region;

The results obtained by means of PCA indicate that the distribution of variables in relation with the first factor (F1) for October 2009 show a pattern which is typical of the dry period. The group of variables with high factor loadings in F1 indicates the dominance of mechanisms associated with convective transports. The presence of the Rmix variable with negative factor loading shows the importance of the atmospheric vapor content in the day of the extreme event. Anthropogenic activities represent one of the important factors in the increase or reduction in atmospheric humidity;

Negative scores higher than 2.5, related with northwesterly winds in the day of the extreme event, shows the importance of the wind direction in the evolution of the weather conditions.

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References

BARBIERI, L. F. P.; CORREIA, M. F.; BRAGA, C. C.; GONÇALVES, W. A.; MOURA, M. S. B. Desempenho de método de estimativa da temperatura média diária: um estudo em áreas com forte pressão antrópica. *Revista Brasileira de Geografia Física*, Recife, v. 6 n. 4, 2013.

BARBOSA & CORREIA. Sistemas convectivos intensos no semiárido brasileiro: o controle da grande escala. *Revista Brasileira de Meteorologia*, São Paulo, v. 20, n. 3, 2005.

BLOSCHL, G.; ARDOIN-BARDIN, S.; BONELL, M.; DORNINGER, M.; GOODRICH, D.; GUTKNECHT, D.; MATAMOROS, D.; MERZ, B.; SHAND, P.; SZOLGAY, J. At what scales do climate variability and land cover change impaction flooding and low flows? *Hydrological Process*, Medford, v. 21, 2007.

CABRAL JÚNIOR, J. B. *Estimativas, variabilidade e análise de tendência da evapotranspiração de referência em perímetros irrigados, no semiárido do Nordeste brasileiro*. 2015. 109 f. Dissertação (Mestrado em Ciências Climáticas) – Universidade Federal do Rio Grande do Norte, Natal, 2015.

CAHU, T. B.; MACHADO, J.; JÚLIO da SILVA, C. O.; WANDERLEY, R. A. Modelo digital de terreno na microrregião de Petrolina com base em índices de desenvolvimento local. *Revista Geama*, Recife, v. 3, n. 2, 2015.

CORRAR, Luis J. et al. *Análise Multivariada: Para os Cursos de Administração, Ciências Contábeis e Economia*. São Paulo: Editora Atlas, 2007. 344 p.

CORREIA, M. F.; COSTA, M. N. M.; SILVA, A. B.; SILVA ARAGÃO, M. R.; QUEIROZ, J. N. Processos de desestabilização atmosférica e convecção profunda no semiárido brasileiro. *Revista Ciência e Natura*, Santa Maria, Edição Especial, 2013.

CORREIA, M. F.; SILVA DIAS, M. A. F.; SILVA ARAGÃO, M. R. Soil occupation and atmospheric variations over Sobradinho lake area. Part two: a regional modeling study. *Meteorology and Atmospheric Physics*, v. 94, 2006.

CORREIA, M. F.; SILVA DIAS, M. A. F. Variação do nível do reservatório de Sobradinho e seu impacto sobre o clima da região. *Revista Brasileira de Recursos Hídricos*, Porto Alegre, v. 8, n.1, 2003.

CORREIA, M. F. *Impacto das ações antrópicas no clima do submédio São Francisco: um estudo numérico e observacional*. 2001. 181 f. Tese (Doutorado em Meteorologia) – Universidade de São Paulo, São Paulo, 2001.

FARIAS, W. R. G. F.; CORREIA, M. F. Descargas atmosféricas e interrupções de energia elétrica na área da CHESF: relação com variáveis atmosféricas em anos de El Niño e La Niña. *Revista Brasileira de Meteorologia*, São Paulo, v. 23, n. 3, 2008.

HAIR JR., Joseph F. et al. *Análise Multivariada de Dados*. 6. ed. Porto Alegre: Editora Bookman, 1995. 688 p.

KENDALL, M. G. *Rank correlation methods*, Charles Griffin, London, 1975.

MARENGO, J. A.; ALVES, L. M.; BESERRA, E. A.; LACERDA, F. F. *Variabilidade e Mudanças Climáticas no Semiárido Brasileiro. Recursos Hídricos em Regiões Áridas e Semiáridas*. Campina Grande: Instituto Nacional do Semiárido, p. 383-422, 2011.

QUEIROZ, J. N.; SOUSA, L. F.; RIBEIRO, R. E. P.; SILVA ARAGÃO, M. R.; CORREIA, M. F., Fatores físicos na atmosfera do semiárido brasileiro em janeiro de 2004. *Revista Brasileira de Geografia Física*, Recife, v. 7, n. 5, Número Especial – VIWMCRHPE, 2014.

RIBEIRO, E. P.; MOREIRA, E. B. M. M.; SOARES, D. B.; CORREIA, A. B.; LIMA, M. S. Climate change and desertification in the semiarid region of northeastern Brazil. *Revista Geama*, Recife, v. 5, n. 1, 2016.

RICHMAN, M. B. Rotation of principal components. *International Journal of Climatology*, Reading, v. 6, 1986.

RYAN M. G, BINKLEY D, FOWNES J. H. 1997. *Age-related decline in forest productivity: pattern and process*. Adv Ecol Res. 27: 213–261.

SILVA ARAGÃO, M. R; CORREIA, M. F.; ARAÚJO, H. A. Characteristic of C-band meteorological radar echoes at Petrolina, Northeast Brazil. *International Journal of Climatology*, Reading, v. 20, 2000.

SNEYERS, R. *Sur l'analyse statistique dés series d'observations*. Genève: Organization Météorologique Mondial (OMM Note Technique, 143), 1975. 192p.

XAVIER, T. de M. B. S.; XAVIER, A. F. S. Analysis espacial de regimens pluviales en la region Nordeste do Brazil. In: INTERNATIONAL CONFERENCE ON SOUTHERN HEMINPHERE METEOROLOGY, 1, 1983, São José dos Campos. Proceedings... Boston: American Meteorological Society, 1983.

WILKS, D. S. *Statistical Methods in the Atmospheric Sciences*. 2. ed. Amsterdam: Elsevier Academic Press Publications, 2006. 627 p.