Hydrological variability in the Capibaribe river basin (Brazil) in the 20th and 21st centuries

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This work aimed to apply analysis methods of the temporal variability of precipitation and streamflow in Capibaribe River Basin (CRB), Pernambuco-Brazil, using Mann-Kendall and Pettit tests. The study was developed using measured precipitation series from 20th century and IPCC AR4 scenario simulations for analysis of the 21st Century. The results allowed to verify the influence of the different elements: variables, region of the basin, method used and model run. The results did not show trend change for the 20th Century data. The application of the method on the IPCC scenarios indicates trend change around the middle of the century.

1. INTRODUCTION

In the last decades there is a concern about analyzing climate variabilities that are occurring on the planet, especially as regards to a possible increase of some events, as heavy rainfalls or prolonged drought periods.

The identification and knowledge of seasonal and annual trends in precipitation and streamflow volumes can contributes to the understanding of global climate change and variation, and is essential to the development of water resources planning and management for basins (Joseph, Falcon & Sharif, 2013).

The temporal and spatial variability of rainfall, combined with the high crop water requirements, typical in the semi-arid and arid parts of the world, should be studied with great attention by scientists and policy makers in order to avoid future problems with food production and economic development (Mekonnen & Hoekstra, 2014).

In Brazil, in addition to effects of possible climate change, other factors contribute to the increase of water resources vulnerability, including: demographic pressure, disordered urban growth, poverty and rural migration and low investment in infrastructure and services (Salviano, Groppo & Pellegrino, 2016).

The identification of alterations in climate and hydrological regimes is an important step in order to evaluate the possible impacts that may be caused by climate changes. This fact is particularly important in arid and semiarid regions, such as the upper Capibaribe River Basin, located in Pernambuco State-Northeast Brazil. In these regions, the vulnerability and consequences of changes are higher.

In this perspective, this work aims to characterize the temporal variability of precipitation and streamflow in the Capibaribe River Basin (CRB) for the 20th and 21st Centuries. The database consisted of precipitation and streamflow time series for 20th Century and Intergovernmental Panel on Climate Change (IPCC) scenarios for 21st Century.

2. METHODOLOGY

2.1. Study Area

With a drainage area of approximately 7454 km², the CRB is located in the Pernambuco State – Northeast Brazil. The Capibaribe River runs in the direction west-east to the Atlantic ocean. The west portion is characterized by shallow soils, Caatinga vegetation (thornscrub, cactus, and bunch grasses), and a semiarid climate with 550 mm yr^{-1} of rainfall and mean air temperatures between 20 and 22◦C. Periodically, this region suffers with the consequences of drought events. Whereas the east part of the basin is characterized by deeper soils, Atlantic Forest vegetation, and a humid/sub-humid climate, with 2400 mm yr^{-1} of rainfall and mean air temperature between 25 and 26◦C (Ribeiro Neto et al., 2014). The CRB was divided into two regions taking into account the climate and physical characteristics (Figure 1): Region 1 is a semiarid land and Region 2 is wetter.

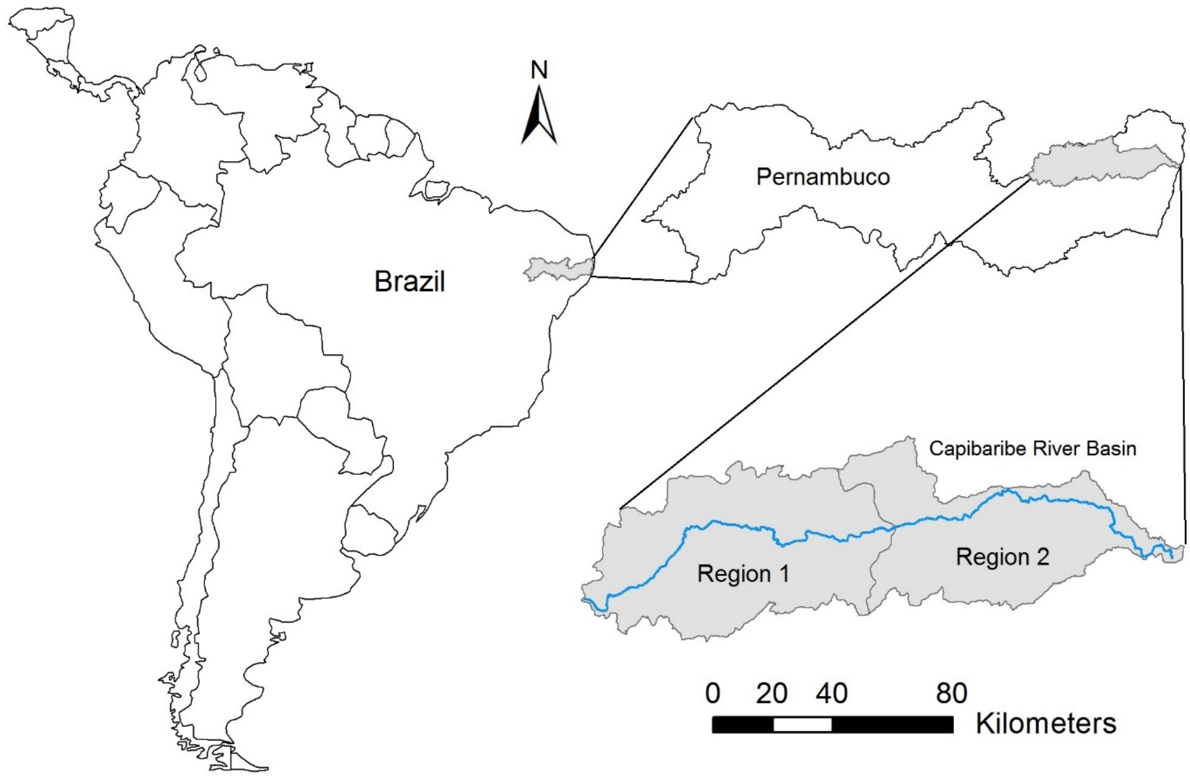

Figure 1 – Regions of Capibaribe River Basin (Brazil).

2.2. Statistical methods

The Mann-Kendall sequential test is the most appropriate method to analyze trend changes in time series, making possible to detect and locate, on estimative way, the starting point of a particular trend. It is considered that, in the hypothesis of a series stability, the succession of values occurs independently, and the probability distribution must always stay the same (Meschiatti et al., 2012).

Considering a series Y_i of N terms to be analyzed, being $1 \leq i \leq N$, the test consists of carrying out the sum t_n of the number of m_i of the series, relative to the value Y_i whose previous terms (j<i) are lower than Y_i ($Y_j < Y_i$). For series with large number of terms (N), under the null hypothesis of no trend (H_0), t_n will present a normal distribution with average and variance given by:

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

$$\text{var}(t_n) = \frac{N(N-1)(2N+5)}{72} \quad (2)$$

Testing the statistical significance of t_n to the null hypothesis, using a bilateral test, the null hypothesis can be rejected for large values of the statistic $U(t_n)$, given by the equation:

$$U(t_n) = \frac{(t_n - E(t_n))}{\sqrt{\text{var}(t_n)}} \quad (3)$$

The probability value is calculated by a standard normal distribution table, using a significance level of 0.05, generating bilateral interval values of -1.96 to 1.96. In the same line of reasoning, in the inverse direction of the series, starting from the value i = N to i = 1, the inverse statistic $U^*(t_n)$ is generated. The intersection of the two statistical curves, $U(t_n)$ and $U^*(t_n)$, corresponds to the location of the approximate point of trend change. However, this is a significant factor only if this point occurs within the range of bilateral significance -1.96 to 1.96.

The Petit test performs a verification of two samples $Y_1, Y_2, ..., Y_t$ and $Y_{t+1}, Y_{t+2}, ..., Y_T$ coming from identical populations. The statistic $U_{t,T}$ counts the number of times that a member of the first sample is larger than a member of the second sample (Meschiatti et al., 2012).

In this way, it is obtained the statistic $K(t)$ of the test by the maximum absolute value of $U_{t,T}$. It is precisely the statistic $K(t)$ that locates the point where there was a sudden change in the average of a time series. In this case, the range of significance can be evaluated by the equation bellow:

$$p \cong 2 \cdot e^{\left(\frac{-6 \cdot K(t)^2}{T^3 - T^2}\right)} \quad (4)$$

This test indicates that the abrupt change point is the one in which the value of t occurs for the maximum value of K(t). Through the inversion of the previous equation it is possible to infer the critical values (minimum or maximum) of K(t) by means of the equation:

$$K_{crit.} = \pm\sqrt{\frac{-\ln\left(\frac{p}{2}\right)\cdot\left(T^3 + T^2\right)}{6}} \qquad 5$$

where p is the significance level (0.05 in the present application) and T is the number of elements of the sample (number of years).

To be able to affirm (or not) the existence of trend changes in the data it is necessary to apply both tests, Mann Kendall and Pettit. The trend change occurs when in both cases there is a crossing in the line of significance. In the Mann-Kendall test, the observed crossing is only on the $U(t_n)$ curve. To determinate when the change occurs, it is necessary to observe, on Mann-Kendall Test, where occurs an intersection of the two curves $U(t_n)$ e $U^*(t_n)$, between the significance level.

2.3. Time series

The precipitation data of the 20th Century was obtained from the hydrometeorological networks of the Brazilian National Water Agency (ANA) and Water and Climate of Pernambuco State Agency (APAC). The 82 raingauges have monthly time step and the series covers the period from January 1933 to December 2009.

For the 21st Century, the precipitation time series is determined with simulation of the IPCC scenarios derived from Chou et al. (2012), who used the output data of the GCM HadCM3 (UK Met Office Hadley Centre) as the boundary condition in simulations of the regional climate model Eta-CPTEC. Eta is a model developed in the National Centers for Environmental Prediction (NCEP) in the United States (Black, 1994) and Eta-CPTEC is a version modified by the Center for Weather Forecasting and Climate Research (CPTEC) of the National Institute for Space Research (INPE) in Brazil. The horizontal spatial resolution of the Eta-CPTEC version used is 40 km.

The precipitation from Eta-CPTEC model was calculated for the IPCC AR4 A1B scenario for the period of 2010-2099 and using perturbations of the parameter set as presented in Chou et al. (2012). The perturbations, also called members, are classified as control (CTRL), medium (MIDI), low (LOW) and high (HIGH). This is a try to quantify the modeling uncertainty in the simulation or projections of climate that depends on the way processes are represented in the model, i.e., in their physics parameters. The HadCM3-Eta-CPTEC runs presented bias for rainfall. The bias correction was made using cumulative distribution functions (CDFs) according to Bárdossy and Pegram (2011). The IPCC climate scenarios point to the reduction in precipitation and the increase in air temperature in Northeast Brazil.

Rainfall and air temperature may be used to determine the discharge in the Capibaribe River in the future using a hydrological model. MODHAC (the acronym from Portuguese "Self Calibrated Hydrological Model") is a rainfall-runoff lumped model, whose input variables are mean rainfall, potential evapotranspiration and streamflow

(Lanna, 1997). Three reservoirs represent the main processes responsible for rainfall-runoff transformation: interception, evapotranspiration and runoff generation, i.e., determination of the volume of water that will either be infiltrated into the soil or flow on the surface. The model has 14 parameters that can be calibrated automatically using four options of objective functions. MODHAC has performed hydrological simulations well in several basins located in the semiarid lands in the Northeast Brazil (Lanna, 1997). The calibration and validation of MODHAC for the CRB is described in Ribeiro Neto at al. (2014).

3. RESULTS AND DISCUSSION

The methods used in the analysis are applied with annual average time series. The first step in the analysis is to verify if the series is independent, i.e., no observation in the sample may influence the occurrence or not of any other observation in next time step. This is a precondition to apply the statistical methods.

3.1. Twentieth Century

Both precipitation and streamflow series between 1933 and 2009 are statistically independent. The results are organized in terms of region 1 (drier) and 2 (wetter) and presented in Figure 1, for the analyzed variable (precipitation and streamflow) and method (Mann-Kendall and Pettit). The X axis of the figures represents the years and the Y axis represents the statistic of the method. The figures also show the thresholds that indicate the limit value to consider that there is no trend change in the series. Figure 2 exhibits the results of both methods for precipitation series in the two regions and Figure 3 presents the results for streamflow time series. As can it be seen in the figures, the values of the statistics do not cross the thresholds represented by the horizontal black line. In other words the results show that there is no trend change in precipitation and streamflow in CRB during the period of analysis with significance level of 5%.

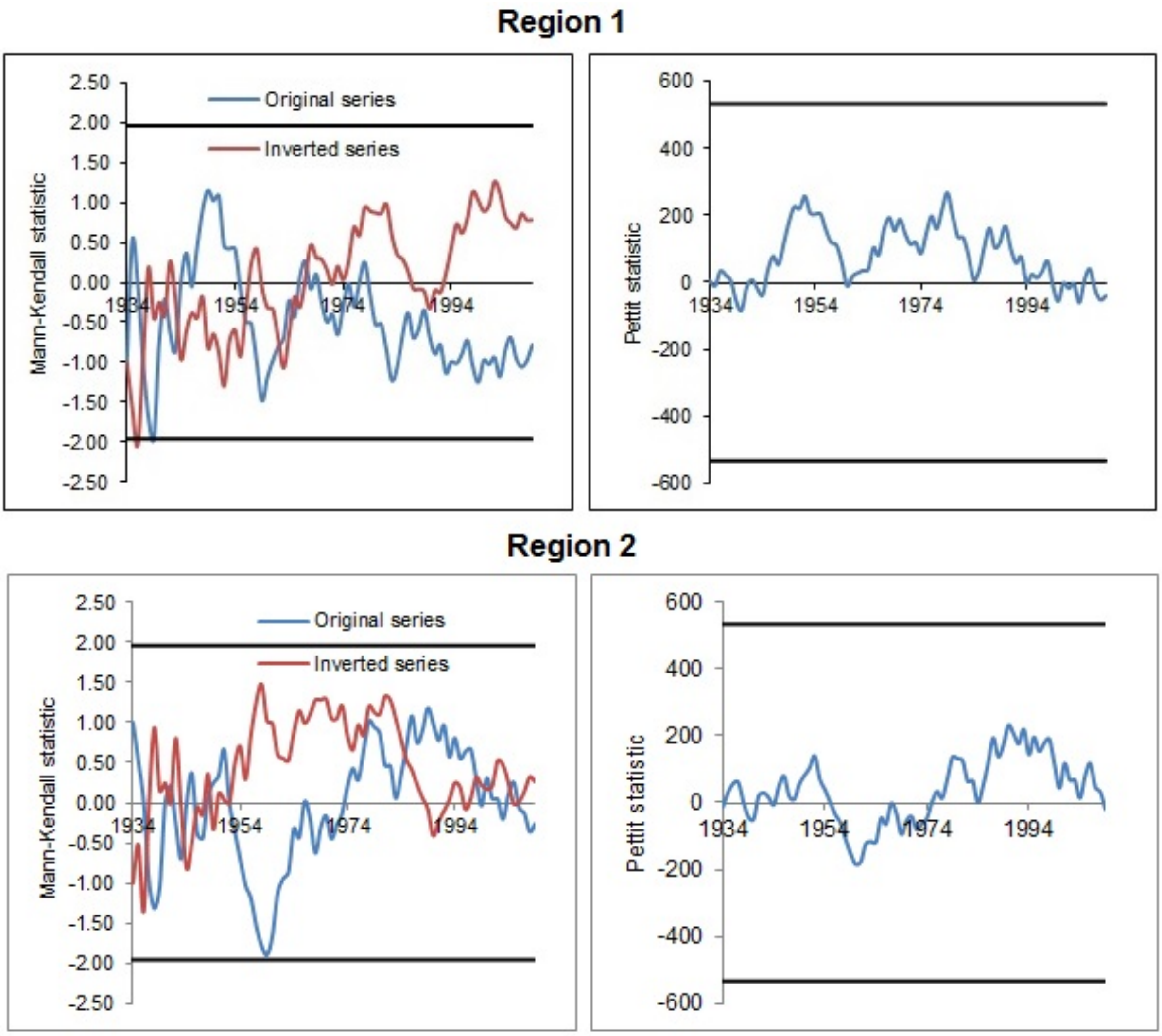

Figure 2 – Trend analyzes for precipitation time series in the 20th Century (the horizontal black lines represent the thresholds).

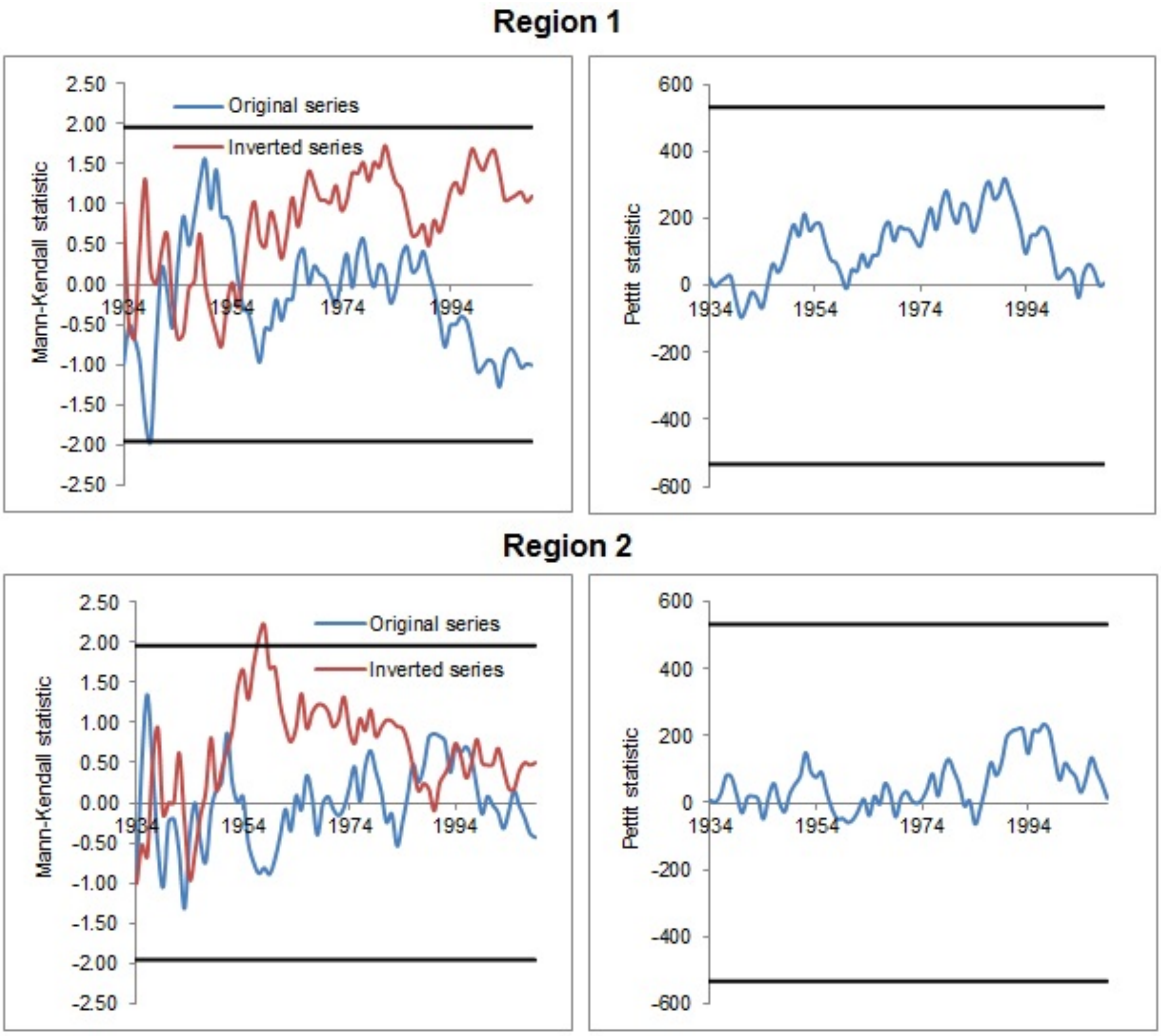

Figure 3 – Trend analyzes for streamflow time series in the 20th Century (the horizontal black lines represent the thresholds).

3.2. Twenty-first Century

As explained before, the 21st Century analysis used four time series from the HadCM3-Eta-CPTEC runs. The evaluation of the independence of the series is showed in Table 1. It is clear the influence of the scenario of increasing of the greenhouse gases concentration. Fifty percent of the series are not independent and 50% are independent. It is only possible to identify trend change for the precipitation data from the simulation with the set of MIDI parameters for region 1 and LOW and MIDI for region 2. For streamflow series, it is only possible to identify for CTRL, HIGH and MIDI in Region 1 and CTRL and LOW for Region 2. In order to present the results in the same way of the 20th Century, we chose the member with the greatest number of independent series.

Figures 4 and 5 show the graphs with the statistics of the methods for the simulation of the member MIDI. The moment when occurs the trend change with Mann-Kendall method corresponds to the intersection between the curves of the original and inverted series immediately before the original series curve cross the threshold. For the Pettit method, the changing point corresponds to the maximum value of the statistic.

Considering the precipitation, the trend change occurs between 2050 and 2058 in the region 1 and 2047 in the region 2. For the streamflow time series, the trend change occurs between 2052 and 2062 in the region 1 and between 2041 and 2051 in the region 2, approximately 10 years earlier than in region 1.

Table 1 – Independency of the series

Precipitation				
	CTRL	HIGH	LOW	MIDI
Region 1	No	No	No	Yes
Region 2	No	No	Yes	Yes
Streamflow				
	CTRL	HIGH	LOW	MIDI
Region 1	Yes	Yes	No	Yes
Region 2	Yes	No	Yes	No

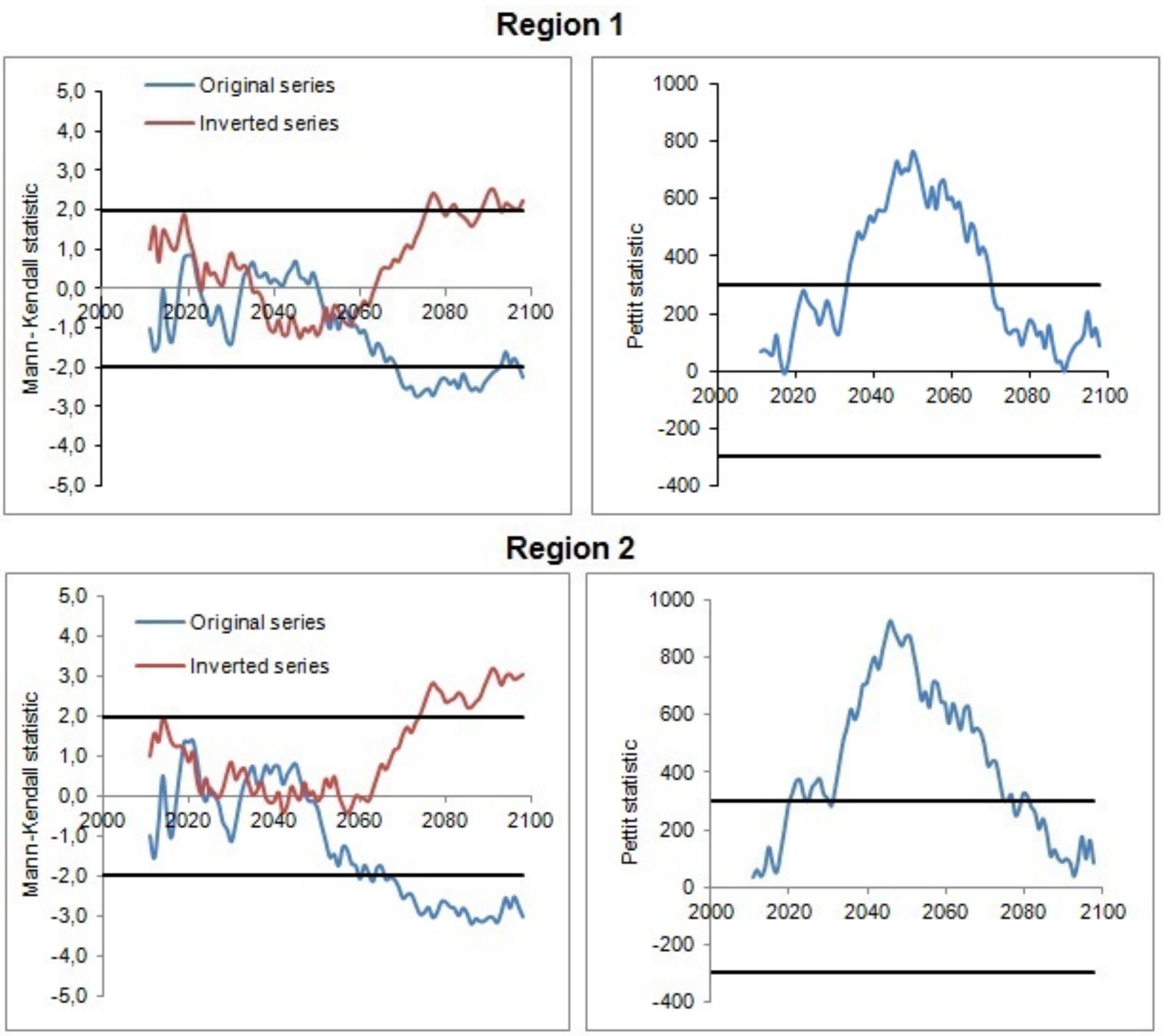

Figure 4 – Trend analyzes for precipitation time series (MIDI member) in the 21st Century (the horizontal black lines represent the thresholds).

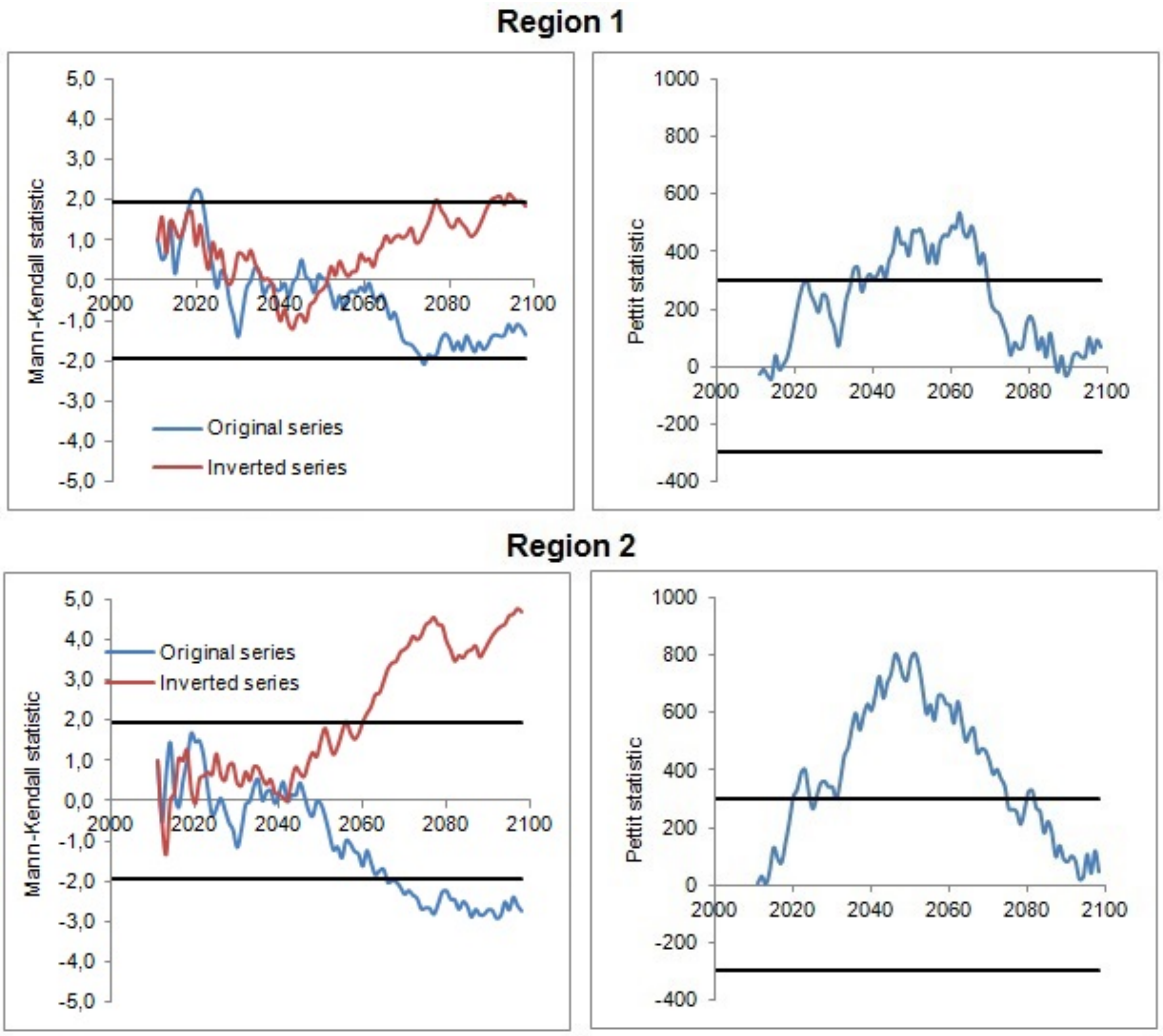

Figure 5 – Trend analyzes for streamflow time series (MIDI member) in the 21st Century (the horizontal black lines represent the thresholds).

In order to evaluate the results considering all members with independent series (without autocorrelation), Figures 6 and 7 exhibit the graphs of the Pettit method. The maximum values in the graphs varies between the years 2046 and 2062 considering all members, both variables (precipitation and streamflow) and both regions. This is similar to the variation identified with member MIDI in both methods as shown before.

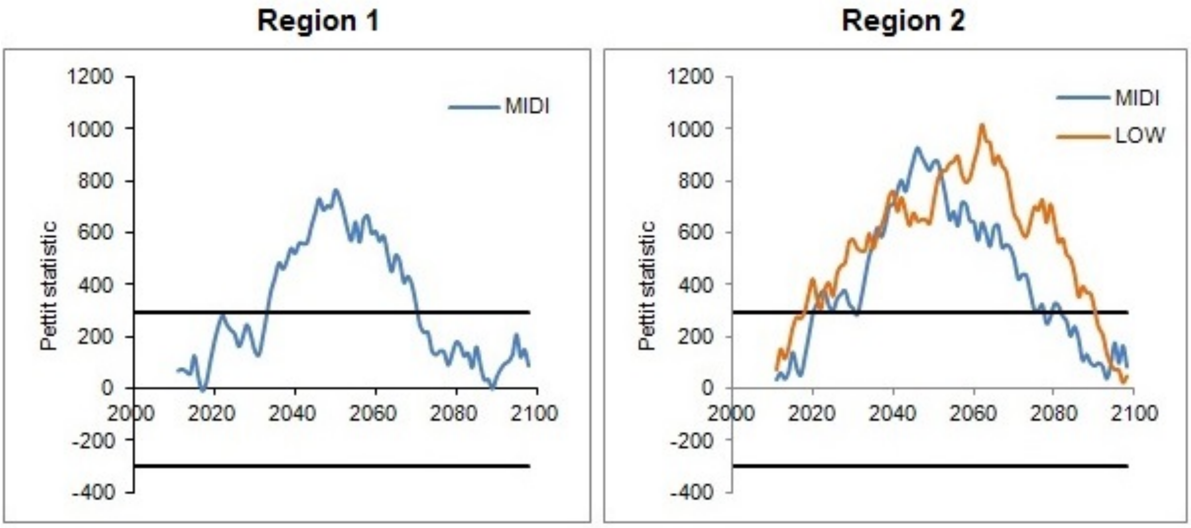

Figure 6 – Pettit method with independent precipitation series.

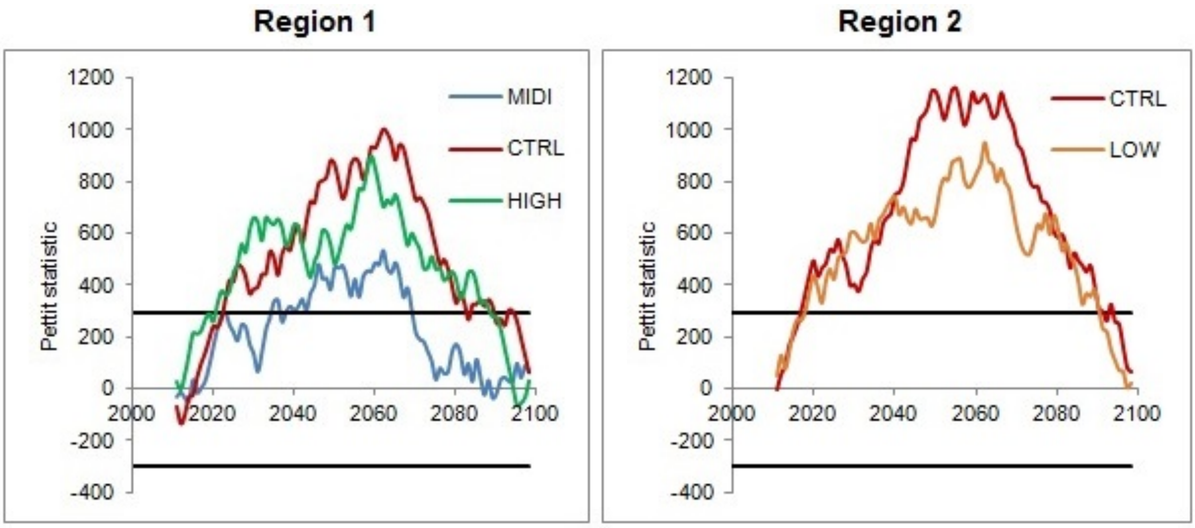

Figure 7 – Pettit method with independent streamflow series.

In order to consider all the simulations, Table 2 shows the year of occurrence of the trend change. Despite the statistic independence in the streamflow time series of the member CTRL, it is not possible to use Mann-Kendall method because the intersection between original and inverted series occurs beyond the significance level. In general, Mann-Kendall method found trend changes earlier than Pettit method. The former varies between 2025 and 2052 while the latter varies between 2046 and 2062 considering all members, both variables (precipitation and streamflow) and both regions. In that cases when the series of both variables are independent for the same member, it was not observed significant difference in the identification of the year (MIDI-Region 1 and LOW-Region 2). Similarly, there is no significant difference between the regions.

Table 2 – Years of occurrence of the trend changes.

Mann-Kendall				
Precipitation				
	CTRL	HIGH	LOW	MIDI
Region 1	-	-	-	2050
Region 2	-	-	2030	2047
Streamflow				
	CTRL	HIGH	LOW	MIDI
Region 1	-	2025	-	2052
Region 2	2041	-	2028	-
Pettit				
Precipitation				
	CTRL	HIGH	LOW	MIDI
Region 1	-	-	-	2058
Region 2	-	-	2062	2046
Streamflow				
	CTRL	HIGH	LOW	MIDI
Region 1	2062	2059	-	2062
Region 2	2055	-	2062	-

3.3. Discussion

The definition of "Detection" of change for IPCC is the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change (Bindoff et al., 2013). Statistical methods may be an important tool to support the search for detection of change in hydrological systems.

Salviano, Groppo and Pellegrino (2016) applied the Mann-Kendall method for the period 1961-2011 and the variables precipitation, air temperature, relative air humidity and potential evapotranspiration in the entire Brazilian territory. All variables presented significant trends in all months, especially air temperature, which showed a significant positive trend in most of the Brazilian territory throughout the year.

Marengo et al. (2007) characterized the climate in Brazil for the XX and XXI Centuries. According to the analysis, after 1970`s, the volume of precipitation in Northeast Brazil (same region of CRB) has been lower in relation to previous periods. The same variability has been observed in the streamflow of the São Francisco River, the most important river in the Northeast. The present work did not find trend changes in the precipitation nor streamflow in the CRB.

For the XXI Century, the simulation with HadCM3-Eta-CPTEC-MODHAC in the present work found a reduction in the average streamflow of about 60% in the entire basin until the end of the century. The application of the statistical methods clearly showed the existence of a trend change and the moment of its occurrence. Other studies detected precipitation and streamflow reduction in the Northeast Brazil (Milly et al., 2005; Montenegro and Ragab, 2012; Marengo et al., 2009; Fung et al., 2011), but none of them evaluated the trend change.

4. CONCLUSIONS

The results obtained for the 20th century indicated no trend change during the period of 1933 to 2009. On the other hand, according to the IPCC scenarios generated by the HadCM3 and Eta-CPTEC models for the Capibaribe River Basin, it was possible to verify the existence of a change in both rainfall and streamflow in the XXI Century. The year of occurrence of the trend change identified by Mann-Kendall method was earlier than Pettit method. Precipitation and streamflow series had similar behavior in terms of year of occurrence. The use of one regional climate model, but with four member representing different set of parameters can be a manner of considering the uncertainties in the model runs. The range of values obtained with the runs of Eta-CPTEC members covers part of the uncertainties observed in this kind of analysis.

The results did not show a remarkable difference between the region 1 (drier) and region 2 (wetter) despite the different climate conditions. The horizontal spatial resolution of the Eta-CPTEC model (40 km) may not have been able to totally capture the precipitation variability. The use of finer resolution will improve the evaluation of the impact on the regions and may show if the trend is stronger in one region than in other.

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