The Relationship Between The Atlantic Multidecadal Oscillation and The Urucuia Aquifer System Recharge

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Abstract

This study investigates and detects links between the precipitation characteristics with meteorological systems and teleconnections around the Urucuia Aquifer System (UAS). Several studies show the influence of meteorological systems and teleconnections on the volume and intensity of precipitation in South America, mainly the Atlantic Multidecadal Oscillation (AMO), the El Niño South Oscillation (ENSO), and the Pacific Decadal Oscillations (PDO). Then, the precipitation series' statistical characterization impacted the aquifer system's recharge from 1973 to 2006. Monthly and annual series were analyzed and tested the correlation analysis with the indexes of the AMO, PDO, and ENSO. Finally, the series of maximum daily rainfall on the UAS was determined, and the 15 largest events were chosen to analyze the retroactive trajectories of air masses and thus try to estimate which atmospheric systems was acting and their origin. It concluded that the total annual precipitation data indicated a decreasing linear trend and that external climatic phenomena can influence precipitation characteristics. The correlation with the AMO index revealed a potential teleconnectivity between climate circulation patterns with average annual precipitation over the UAS ($p\text{-value} \leq 0.03$). Moreover, the analysing of precipitation trajectories observed a greater amount of specific humidity in the atmosphere during the AMO negative period concerning the AMO positive period. Also, the negative AMO phase's trajectories had higher latitudes closer to the Intertropical Convergence Zone, as opposed to the positive AMO phase, where the trajectory altitudes were lower and closer to the Capricorn tropic.

Highlights

- Potential teleconnectivity between patterns of climatic circulation and precipitation.
- No significant correlation was verified between precipitation and the Pacific Decadal Oscillation (PDO) index or Southern Oscillation Index (SOI) or the Multivariate El Niño South Oscillation (ENSO) index.
- The regulatory reserve of the Urucuia Aquifer System (UAS) is constituted exclusively from the infiltration of rainwater.
- It was not possible to correlate the high daily rainfall rates with the occurrence of a predominant atmospheric system.

Introduction

Current studies demonstrate that climate change causes warming or cooling in the atmosphere, which causes changes in moisture retention at high heights, influencing the rainfall regime over various planet regions.

In the central part of South America, normally, the observed rain is characterized by tropical and subtropical precipitation, with a marked seasonal cycle over the continent. In winter, it experiences its dry season, and, in the summer, a low-pressure zone located approximately at latitude of 25°S forces the east winds over the Amazon basin to turn south. These winds channel the wet masses between the eastern hillslope of the Andes and the Brazilian Plateau, which feed the convective summer storms over the subtropical plains to latitudes of 35°S (Garreaud et al. 2009). Thus, creating the South America Monsoon System which marks a well-defined rainy season in the summer and a season with little rainfall in winter (Liebmann and Mechoso 2011).

Associated with this monsoon system, there are the minimum pressure belt and the intense low-level convergence of trade winds over the equatorial oceans, which cause a band of clouds with great vertical development. This system surrounds the globe close to the equator, forming storm activities, generated due to solar heating and the vertical movement of trade winds, corresponding to the Intertropical Convergence Zone (ITCZ), where the active precipitation is mostly of a convective nature, produced by deep cumulus-nimbus (Garreaud et al. 2009). It is important to note that the ITCZ has more zonal behavior between November and December over the southern hemisphere when it starts moving south.

The monsoon systems of South America and ITCZ, acting together, make Brazilian southeast that are close to the Tropic of Capricorn not to have characteristics of arid and dry areas, such as the Sahara, Atacama, Kalahari, and Australia. The air

masses' dynamics create the meteorological system called the South Atlantic Convergence Zone (SACZ), which is a typical summer system. This system is characterized by a band of cloudiness oriented in the northwest-southeast direction, whose area of operation encompasses the center-south of the Amazon and the center-west and southeast regions of Brazil, and can also reach the center-south of Bahia, the north of Paraná and extend to the South Atlantic Ocean (between the latitudes of 15S and 25S - southeast region of Brazil), associated with a convergence zone of the flow of humidity in the lower troposphere (Reboita et al. 2012).

These systems have already been extensively studied and had their influence on rainfall occurrence (Marengo and Dias 2006; CEPED 2012; Reboita et al. 2012; Marshall et al. 2014; Gan et al. 2015; Escobar et al. 2016; Nielsen et al. 2019; Rodrigues et al. 2019).

However, several current studies show that climate change impacts the rainfall pattern in the central part of South America (Ouachani et al. 2013; Ríos-Cornejo et al. 2015; Zhong et al. 2017; Silva et al. 2020), and also indicate that changes are influenced by teleconnections, which are trends in associations between the variability of atmospheric pressure and circulation patterns that occur in one location, with their effect elsewhere (Limberger 2016).

These studies show the relationship between teleconnections and precipitation in South America, with several modes of variability. The climatic teleconnections more studies are (IPCC 2007):

- Atlantic Multidecadal Oscillation (AMO): natural variability based on average anomalies of sea surface temperatures (TSM) in the North Atlantic.
- El Niño Southern Oscillation (ENSO): natural variability over the tropical Pacific Ocean, which originates when El Niño and the Southern Oscillation co-occur, with El Niño being a process of high pressure and heating of sea temperatures, and the Southern Oscillation an atmospheric component, associated with changes in sea temperature.
- Pacific Decadal Oscillation (PDO): pattern of climatic variability centered in the North Pacific Ocean, which occurs due to the variation in the temperatures of the Pacific Ocean, whose positive phase provides an increase in temperature, decrease in humidity and increase numbers of occurrences and the intensity of El Niño, and in the negative phase, a consequent decrease in temperatures, an increase in air humidity and a greater incidence and intensity of La Niña.

In Figure 1, the areas of teleconnection indexes presented the area for identifying teleconnection standards, adapted from <https://meteorologia.unifei.edu.br/teleconexoes/>, (Souza and Reboita 2021) and the location of the UAS area.

For example, the relationship of Atlantic Multidecadal Oscillation and El Niño Southern Oscillation and its influence on rainfall in South America, analyzed by Kayano and Capistrano (2014), showed that El Niño events, concomitant with the Cold AMO (CAMO) phase, are generally stronger than events in the Warm AMO (WAMO) phase due to negative temperatures in the inter-Pacific-Atlantic sea surface (Kayano and Capistrano 2014).

Another example is the study in Chile, that showed that the relationships between low-frequency variability of precipitation and the PDO are significant for the north of the country, while connections with the AMO are significant for the north and also for the south and that this low-frequency variability in Chile appears to be largely linked to PDO and AMO modulation (Valdés-Pineda et al. 2018).

The AMO's impact in the summer monsoon of South America was investigated in the La Plata River Drainage Basin (Chiessi et al. 2009). The authors concluded that the sea surface temperature and the anomalies of atmospheric circulation triggered by AMO would control the variability of the South American Monsoon System (SAMS).

In Brazil, a study carried out in dry and rainy years in the Northeast of the country showed that the main difference in the anomaly patterns of sea surface temperature between the AMO phases is the differential positioning of the heating or cooling surface waters in the equatorial Atlantic. As a result, Hadley and Walker's anomalous circulations also show

differences between the phases of the AMO, justifying the precipitation anomalies observed in tropical South America (Kayano et al. 2016).

Therefore, to add more information about the climate interference on rainfall patterns, this study investigated the links between precipitation characteristics, especially volume and intensity, with meteorological systems and teleconnections. The objective is to detect correlations that help define better water availability scenarios, including assessing the issue of aquifer recharge, which has precipitation as a natural source. Because the regulatory reserve of aquifers is formed from the infiltration of rainwater.

The area chosen to carry out this study is located on the Urucuia Aquifer System (UAS), a region experiencing an accelerated commercial agriculture expansion that began 30 years ago, to the point that it is currently considered one of the most important centers of irrigated agriculture of the country. However, the inherent scenario of high surface and underground water demand is accompanied by changes in vegetation cover, notably the suppression of extensive areas of Cerrado forest, and a high risk of contamination by fertilizers and pesticides, in addition to the inevitable urban expansion of certain outbreaks. Therefore, it is essential to know the region's water availability, considering the part of precipitation that will contribute to its recharge, influencing the regulatory reserve. If the meteorological systems and teleconnections influence the volume and intensity of precipitation, they must be considered in the management of water availability in the region of the UAS.

The Urucuia Aquifer System - Uas

The UAS is a groundwater reservoir located between latitudes 9°25'38" and 16°15'00" and longitudes 47°41'42" and 43°46'43" (Figure 2a), under the geomorphological unit called Western Bahia Plateau or São Francisco Plateau (IBGE 2006). In an area of 121,653 km², this aquifer has altitudes ranging from 300 to more than 1000 m above sea level (Figure 2b) with steep escarpments and the presence of colluviums, comprising essentially sandy soils (Figure 2c).

The climate in this region is classified as Tropical Savanna Climate (Aw), according to Köppen. It presents a wet season (excess water) corresponding to the summer, which occurs between October and April when the volume of precipitation is greater than evapotranspiration (Gaspar 2006). The dry season occurs from May to September, encompassing the whole Winter in South Hemisphere, and evapotranspiration is greater than precipitation, causing water deficit (Gaspar 2006). Therefore, during the period from May to September, the rivers of the region are maintained by the base flow, which according to Gaspar (2006), corresponds to a mean value of 1,35x10⁹ m³/ano (42,8 m³/s), which on average is equal to 20% of the precipitation (6,86 x10⁹ m³/ano or 1.241 mm) and 91% of the total streamflow (1,48 x10⁹ m³/ano or 46,9 m³/s), based on a data series from 1982 to 2002. Also according to Gaspar (2006), the average temperatures vary annually between 26° and 20° C, and the relative humidity of the air varies between 80% (December) and 50% (August).

However, in recent years, there has been climatic alteration, which points to an increase in the intensity of droughts in the region, as shown by the Drought Monitoring Project's maps (Figure 3) from the National Water Agency (ANA 2018). The Figure 3 shows the spatial spread of the drought intensity over Brazil's northeast region in December of 2014, 2015, and 2016. The green rectangle highlights the area where the Urucuia aquifer is located. Comparing the spatial distribution along the years, we observed that the drought intensity has been increasing in the region.

Two hypotheses are considered to explain this pattern: just the effect of agricultural expansion in the region, or the climatic variation exerts influence too, whether to arising from Low-Frequency Variability associated with teleconnections, or global climate change. That is a point to be addressed in this work.

Materials And Methods

The average monthly rainfall series were initially obtained from the historical daily series of ten gauges in the area of the UAS. Table 1 displays general information on these. A simple descriptive statistical analysis was performed for these series to describe, evaluate, and summarize the data. Then, from these monthly precipitation data series, the annual precipitation data series for each station was defined and the representative regional monthly and annual precipitation series of the area.

Table 1
Information from the historical series of ten pluviometric stations installed over the Urucuia Aquifer System area.

Code	Name	Initials	Sub Basin	Municipality / State	Latitude (°)	Longitude (°)	Altitude (m)
01145013	Ponte Serafim – Montante	PSM	46	Barreiras / BA	-11.8961	-45.6119	713
01245014	Fazenda Johá	FJH	46	Barreiras / BA	-12.1256	-45.8108	725
01245015	Roda Velha	RVE	46	São Desidério / BA	-12.7653	-45.9439	761
01346006	Fazenda Planalto	FPL	45	Correntina / BA	-13.7519	-46.14	947
01346007	Fazenda Prainha (Faz. Antas)	FPR	21	São Desidério / BA	-13.3125	-46.0631	824
01347000	Cavalcante	CAL	21	Cavalcante / GO	-13.7969	-47.4617	821
01445000	Cajueiro	CAJ	45	Januária / MG	-14.8361	-45.1733	700
01447000	Alto Paraíso de Goiás	APG	20	Alto Paraíso de Goiás / GO	-14.1347	-47.5117	1197
01447002	São João D'Aliança	AJD	20	São João D'Aliança / GO	-14.7072	-47.5236	1009
01546005	Cabeceiras	CAB	43	Cabeceiras / GO	-15.8008	-46.9247	900

The region in which the UAS is characterized by the rainy period from October to March, as in April initiating the dry period when the rains begin to decrease. In this work, monthly precipitation average data from September 1973 to August 2006 were used. This period of precipitation data was selected with the intention of the time series had only 10% of failures in the daily data and without impacting the monthly and annual total values of the stations. Therefore, no other consistency analyses were performed and there was no a failure filling.

Then, a local frequency analysis used in the precipitation series for each station and the regional averages (monthly and yearly) to assess the fulfilment of the criteria of independence, homogeneity, stationarity, and randomness, which are essential to verify whether the results are statistically valid (WMO 2009). These criteria will be evaluated by the following non-parametric tests (Naghetini and Pinto 2007). Randomness of values suggested by the test of NERC (1975), which indicates the presence of a structure or intervention of a non-random nature; Independence of values is assessed with the test proposed by Wald and Wolfowitz (1943), which verifies that no observation can influence the occurrence, or non-occurrence, of the next observation; Homogeneity of the sample is analyzed through the test by Mann and Whitney (1947), which considers an homogeneous sample when all elements come from one and identical population; and the Stationarity of a series is verified by the Spearman test described by NERC (1975), which is associated with the non-alteration of statistical characteristics over time, which means that there are no trends, jumps and other properties.

Besides the adjustments of the series to the Log-Normal distribution (Naghetini and Pinto 2007), which presents good results for annual values averages (Pinto and Alves 2001), were evaluated by the Anderson-Darling (AD) adherence test, at the 5% level of significance, calculated by:

$$P(X < x) = \int_0^x \frac{1}{x\sigma_{\ln(x)}\sqrt{2\pi}} e^{-\frac{1}{2}\left[\frac{\ln(x)-\mu_{\ln(x)}}{\sigma_{\ln(x)}}\right]^2} dx \quad (1)$$

where P is the probability of $X < x$, X é random variate (RV), x is a value of RV, σ is the standard deviation of $\ln(x)$, μ is the mean of $\ln(x)$.

The empirical distribution estimate was performed with descending order of the series and the calculation of the plot position using the Weibull formula:

$$(P > p) = \frac{m}{N + 1}$$

(2)

Where: m is the order number and N the sample size. For the annual series, the hydrological year starting in September and ending in August was considered, and the data dates from September 1973 to August 2006, a total of 33 years.

With the distribution adjusted, it is possible to determine the return period of an observed rain height. The following correlation estimates the recurrence time or return period (T):

$$T = \frac{1}{(P > p)} = \frac{1}{1 - (P < p)} \quad (3)$$

The return period is associated with the probability that an event will be equalled or exceeded in any given year.

Then, the values of monthly and annual precipitation average representative of the area were correlated with the respective indexes of teleconnections, AMO, PDO, and ENSO, obtained from the NOAA website (NOAA 2019a, b, c).

AMO is an index of natural variability, generated from anomalies in the sea surface temperature of the North Atlantic Ocean, in an interval of 5 to 8 decades (Santos et al. 2016), which cause changes in atmospheric circulation, based on three main processes: the atmospheric waves, the continuity of mass and the change of phases of the water (gaseous to liquid or solid). These anomalies are measured using the AMO Index, proposed by Raa et al. (2009) and (Oldenborgh et al. 2012), and makes it possible to evaluate the occurrence of gradients responsible for generating the phenomena called Atlantic dipole, which can be of positive or negative phase (Kayano and Andreoli 2009). The AMO Index monthly series is calculated from 1856 to 2020 (NOAA 2019b).

Similar to AMO, the PDO teleconnection consists of a climatic phenomenon observed in the North Pacific Ocean, where a Sea Surface Temperature (SST) pattern is identified for 20 to 30 years, and which seems to coincide with the cooling periods (negative values) and warming (positive values) of the waters. It results in changes in marine ecosystems, in addition to affecting the currents' trajectories (Ndehedehe and Ferreira 2020) as it affects the temperatures of the coastal sea and the continental surface air from Alaska to California. This variability is verified by the Decadal Oscillation Index, which is a function of the monthly anomalies of the sea surface temperature over the North Pacific (about 20°N) after removing the global average temperature of the sea surface (Molion 2005; Buffon and Binda 2014). The PDO Index monthly series was considered in this study from 1854 to 2020 (NOAA 2019c).

ENSO is a periodic variation in the tropical Pacific Ocean of winds and sea surface temperature, which occurs in the warming phase and accompanies the high pressure of the air surface (Walker cell changes), affecting the climate of a large part of the tropics and subtropics. ENSO can be assessed by the Southern Oscillation Index, which is a standardized index based on the differences in sea level pressure observed between Tahiti and Darwin in Australia, and the prolonged periods of negative oscillation values coincide with ocean waters abnormally warm throughout the eastern tropical Pacific, typical of El Niño episodes. The South Oscillation Index (SOI) series obtained was monthly from 1951 to 2020 (NOAA 2019a).

It was also used to characterize the intensity of an ENSO event, the multivariate index, which consists of a complex interaction of a variety of climatic systems, and which is considered the most comprehensive index for monitoring El Niño,

as it combines the analysis of multiple meteorological and oceanographic components (Mazzarella et al. 2013). The series of the Multivariate Index (MI) obtained was monthly from 1979 to 2020 (NOAA 2019a).

Therefore, due to the data available at NOAA for each teleconnection, the period from September/1963 to August/2006 was used to relate the AMO, PDO, SOI (for ENSO) with the historical precipitation series. But to relate with MEI (for ENSO) was used the serie from September/1979 to August/2006.

The climate indices were correlated with monthly and annual precipitation data from stations located in the UAS, in pairs, and for periods defined based on the phases of each index. The correlation was evaluated by analyzing the significance of the differences and using the Student's t-test, and the results were considered statistically significant with a p-value ≤ 0.05 . This is because the p-value depends directly on the data series and presents a quantitative measure that assists the decision-making process as evidence that if the null hypothesis (H_0) is true, then the chance of random variation will be the only explanation for sample differences.

Therefore, a reasonable interpretation of the p-value (Arsham 1988) shows that there is robust evidence against H_0 if $P < 0.01$; if $0.01 \leq P < 0.05$ there is moderate evidence against H_0 ; if $0.05 \leq P < 0.1$ there is suggestive evidence against H_0 ; but if $P \geq 0.10$ there is little or no real evidence against H_0 .

After analysing the correlation of the monthly and annual precipitation data with the values of the climate indices, the series of maximum daily rainfall over the Urucuia Aquifer System was determined, and the 15 largest events were chosen to analyse the retroactive trajectories of the air masses, and so try to estimate which atmospheric systems are operating and their origin.

The retroactive trajectories of the air masses were estimated by the Lagrangian approach, which determines the water balance (Evaporation – Precipitation), for a given period of time, from the sum of the humidity changes (Sodemann; Schwier; Wernli, 2008), that is:

$$\frac{Dq}{Dt} \approx \frac{\Delta q}{\Delta t} = E - P$$

(4)

Knowing that the moisture content is interpolated to its position every time (Stohl and James, 2004), water vapour gains and losses are measured by changes in specific humidity (Δq) over time (Δt). The rates of increase (x) and reduction (y) of specific humidity occur with the gains and losses of water vapour along the particle's trajectory ($\Delta q = x - y$).

So, for a large number of particles (K) passing over an area (A), the equation of (4) can be written as follows:

$$E - P = \frac{\sum_{k=1}^K (x - y)}{A}$$

(5)

This Lagrangian modelling for trajectory determination was performed using the HySplit model (Stein et al. 2015), which uses the data set of the reanalysis project carried out by NOAA to produce new atmospheric analyzes using historical data (from 1948) and also produce analyzes of the current atmospheric state (Climate Data Assimilation System).

The model estimates (at 1-degree resolution) and reports the position of the air packages (latitude, longitude, and height), pressure, and specific humidity in grams of water vapour per kilogram of air (g/kg), thus forming the trajectories of the air masses (Santos and Lima 2019).

The trajectories were calculated for the days that precipitation occurred above 125 mm in the Urucuia aquifer region, a criterion of rainfall greater than the 3rd quartile of the data series, which corresponds to a limit commonly used in similar

studies (Kim et al. 2004; Amato and Hopke 2012; Alves et al. 2018). The trajectories were started at heights from 10 to 6010 m, at intervals of 400 m, above ground level, and at the times of 12 h, 18 h of the previous day and 0 h and 06 h of the day of measurement, because all the measurements take place at 07 h and refer to the accumulated rainfall of the last 24 hours. The heights were defined based on previously performed works (Santos et al. 2018). The trajectories were simulated retroactively in time, that is, from the specification of the destination coordinates (sampling point) the trajectories are plotted from the possible points of origin, depending on the climatic conditions, in a specified time interval (1-hour interval for 10 days or 240 hours), to the destination (Back Trajectory). The trajectory data show, for each storm, the path that the particle travelled defined considering time, latitude, longitude, and heights of the trajectory, informing the respective pressure and specific humidity of the particle, which allows a better analysis of the data.

In other words, the HySplit model informs the rainfall trajectories according to the time, day and location, so it was necessary to evaluate the daily precipitation at the stations to detect the highest daily rainfall and where it occurred. It analyzed 22,400 trajectories (350 dates * 16 times * 4 times). However, only 15 daily rainfall records were higher than 122 mm, which was equivalent to 10% of the region's average annual rainfall in a single day. Therefore, it analyzed with more detail to understand if their occurrence derives from the presence of any specific atmospheric system.

Results

Characterization of precipitation variability in the Urucuia Aquifer System region

The region in which the UAS is inserted is characterized by the rainy period from October to April, but in April, the rains begin to decrease, initiating the dry period, as can be seen in the (Figure 4), where monthly precipitation average data from September 1973 to August 2006 were used, in 94 pluviometric stations located on and near the area. The wettest quarter is December to February with a quarterly average of 619 mm, and the driest is from June to August with a quarterly average of 10 mm. The precipitation in the region begins in September, but the rainiest period occurs between October to April. The greatest precipitated volumes occur from west to east. The largest rainfall was observed in Ponte Alta do Bom Jesus station, located in the Tocantins River's Hydrographic Region. Over Urucuia Aquifer System, the average annual precipitation is equal to 1220.8mm, defined between 1973 and 2006.

This temporal variability of precipitation was analyzed by the spatialization of precipitation information from the National Hydrometeorological Network stations, from September 1973 to August 2006. This spatialization resulted in a surface or "raster", where monthly rainfall estimates are made for all cells to generate a continuous map. In this work, the Kriging method was chosen, which according to Murara (2019), is the most used method for spatialization of climatic data since it creates more uniform variations, not presenting variations and smoothing its representation since it homogenizes the information presented. After using the Rainfall Anomaly Index (RAI) methodology, proposed by (Rooy 1965), which characterizes the existence of dry periods (precipitation below the historical average) and rainy periods (annual precipitation above average), in addition to the intensity of the phenomenon in the period (Kraus 1977; Souza et al. 1980; Freitas 1998; Araújo et al. 2009; Cruz et al. 2013; Moraes 2014; Alves and Araújo 2015; Dutta et al. 2015; Noronha et al. 2016; Hänsel et al. 2016; Cerqueira et al. 2018; Lima et al. 2019; Surendran et al. 2019), the analysis showed 12 rainy years and 21 dry years in the region, considering the hydrological year beginning in September and ending in August of the following year, since 98.6% of the rain that occurred in the region above 2 mm, occurred between September to May of the following year and, besides, evaluating the precipitated volume throughout the period only 0.95% fell on UAS, between May and August.

The isohyets map of annual rainfall average in the region (Figure 4) assists in the evaluation of the behavior of annual rainfall average, showing that the rainfall in the western part of the UAS is higher, especially in the area of the "Ponte Alta do Bom Jesus" station, which presents a higher value of average annual precipitation compared to the other values of the

analyzed rainfall stations. In contrast, the eastern part presents precipitation with lower annual averages, reaching values below 1000 mm in the vicinity of the area in which the aquifer is located. This spatial variation in rainfall is attributed to the orographic control of rainfall in which air masses are discharged progressively from west to east. It presents a niche of the greatest rainfall occurring around Ponte Alta do Bom Jesus Station, which reaches an average annual rainfall of 2,033 mm, much higher than the region's average of 1,200 mm.

Considering as a dry year, the years with annual precipitation below the historical average, and the years with annual precipitation above, such as rainy years, the variability of the spatialization of the precipitated volume in the dry and rainy years was analyzed, and the result showed that the spatialization of the rains demonstrated no difference between the dry or rainy years (Figure 5) in the region. Observe the comparison of the average annual rain's spatialization between dry and rainy years. In reference to the monthly historical average, dry years were lower monthly rainfall, and in rainy years observed higher monthly rainfall. Not observed differences between the occurrences of rains regardless of the dry or rainy year.

Moreover, from the evaluation of the precipitation spatialization in all months of the year, observing the existence of variability between the rainy and dry months, it is concluded that in the driest period of the year, between May and September, there is no variation in the spatialization of rain in the region, that is, it is uniform in the investigated area. However, in the wettest period of the year, between October and April, it is observed that the western region presents a greater volume of precipitation, especially in the region around the municipality of Ponte Alta do Bom Jesus (Figure 6).

However, concerning the precipitation of the "Ponte Alta do Bom Jesus" station (code: 01246000), where the concentration of precipitation occurs (Figures 4, 5 and 6), it was observed that the behaviour of precipitation is different, with different mean and variance, such as show the daily hyetograms that compare the rainfall on the UAS and with that observed at the "Ponte Alta do Bom Jesus" station – code: 01246000. In Figure 7, note through the daily hyetograms that precipitation over the Urucuia aquifer system is different from the frequency observed on the station, which is installed around the UAS region, not on it. Also, analyzing the series statistically by the t-test, assuming different variances, the results show that the data did not present correlation ($p\text{-value} \gg \gg 0.05$).

Geographically, the "Ponte Alta do Bom Jesus" station is not located on the UAS. However, on the slope area, which circulates the entire plateau, it was understood that the meteorological systems phenomena, which may influence and/or generate precipitation at this point, are not the same as those acting in the rains over the aquifer. Therefore, the precipitation in this place must be analyzed separately.

Another issue is that, depending on the location of this station, the rains that occur in this location should not contribute to the recharge of the Regional Free Aquifer, which occupies the largest area in the basin, since the variable static level of this subsystem, varies from 4 to about 50 meters.

The "Ponte Alta do Bom Jesus" station is located at an altitude of 518 meters, while the height of the plateau closest to this location is at an altitude of 903 meters, another at an elevation of 385 meters. Therefore, if the rain in this place contributes to the UAS recharge, it will only be for the free Deep Aquifer subsystem's recharge, which can reach depths greater than 100 m.

Annual and monthly rainfall averages over the UAS area

The monthly precipitation series over the Urucuia aquifer show that the differences between the means and the variances are not significant, according to the tests for samples assuming equivalent means (z test) and equivalent variances (t-test), with the true null hypothesis (H_0) claims that random variation will be the only explanation for sample differences ($p\text{-value} < 0.05$). But, when we compare the monthly flows series of one station with the other stations series, the results found were not statistically significant ($p\text{-value} \geq 0.05$), because the lowest p-value found was equal to 0.057.

The stations' series of monthly data were correlated in pairs through the coefficient of determination (R^2) to adjust a generalized linear statistical model. Thus, it was found 45 R^2 values for correlations with monthly data, with the lowest value being 0.6564 and the maximum 0.8336, for an average R^2 of 0.7455, which allows to conclude that there is a good correlation between the series of monthly precipitation of the stations located on the UAS in the period of 33 years (1973 to 2006), which represents the main source of recharge for this aquifer.

Therefore, the station series of monthly precipitation data showed equivalent averages and variances, in addition to a good correlation, when correlated with the regional monthly precipitation series, which the lowest R^2 found was 0.8352, indicating a good correlation.

Evaluated by the series formed by each month, the monthly data were divided into twelve series for each station. The series was assembled month by month. That is 120 series analysed. Nine series did not approve: three in independence teste (July series from Ponte Serafim – Montante station, July series from Fazenda Johá station and June from Fazenda Prainha station); two in randomness test (May and June series from Cabeceiras station); and four in stationarity test (June series of Ponte Serafim – Montante station, and October series of Cavalcante, Alto Paraíso de Goiás, and São João d'Aliança stations).

The homogeneity test as not evaluated due to the small size of the series. However, even passing the criteria of independence, randomness, and stationarity, all series from May to September were not accepted by the Anderson-Darling (AD) adherence test, at the 5% significance level, to be modelled due to the Log-Normal distribution, this occurs precisely due to the occurrence of the dry season in the region, where rainfall is not frequent.

In May and September, which are the months of the beginning of the descent and rise of precipitated volumes, it was possible to adjust Gumbel extremes' distribution, being accepted by the Anderson-Darling (AD) adhesion test, to the level of 5% of significance. For the series of November, December, January, and February, the null hypothesis was accepted by the AD test for 5% of significance, showing that the Log-Normal distribution can model the series of these months.

Also, analyzing the series of mean data on the UAS, month by month, it was observed that the Log-Normal distribution could also model the series for December, January, February, March, and April since the null hypothesis was accepted by the AD adherence, at the 5% level. The data of the descriptive statistics of the monthly precipitation series are shown in Figure 8. The higher monthly rainfall totals range from 524 mm to 780 mm. However, most of the observed precipitations are less than 250 mm.

The total annual precipitation data series of each station on the UAS, in addition to the series of regional annual total precipitation, over the period of 33 years, were also evaluated.

It is concluded that the series are independent and stationary, except for the “Fazenda Planalto” station (code: 01346006), which presented dependent values and presented non-stationary values on “São João d'Aliança” station series (code: 01447002) and regional annual totals series (Figure 9 and Table 2).

Table 2

Descriptive statistics of the ten series of annual rainfall data for stations installed over the Urucuia Aquifer System area and the series of regional annual total precipitation.

Code Station	Name Station	Initials	Test statistics		Test result	
			Independence	Stationary	Independence	Stationary
01145013	PONTE SERAFIM - MONTANTE	PSM	1.09	-1.56	Independent Observations	Stationary Observations
01245014	FAZENDA JOHÁ	FJH	-1.81	0.09	Independent Observations	Stationary Observations
01245015	RODA VELHA	RVE	-1.51	-1.22	Independent Observations	Stationary Observations
01346006	FAZENDA PLANALTO	FPL	-2.04	-0.05	Dependent Observations	Stationary Observations
01346007	FAZENDA PRAINHA (FAZ.ANTAS)	FPR	0.80	-0.90	Independent Observations	Stationary Observations
01347000	CAVALCANTE	CAL	0.91	-1.39	Independent Observations	Stationary Observations
01445000	CAJUEIRO	CAJ	-0.71	-0.69	Independent Observations	Stationary Observations
01447000	ALTO PARAÍSO DE GOIÁS	APG	1.39	-0.81	Independent Observations	Stationary Observations
01447002	SÃO JOÃO D'ALIANÇA	SJA	-0.33	-2.79	Independent Observations	No Stationary Observations
01546005	CABECEIRAS	CAB	0.56	-0.59	Independent Observations	Stationary Observations
ANNUAL MEAN REGIONAL SERIES			1.46	-2.61	Independent Observations	No Stationary Observations

Nevertheless, all the annual totals indicated a linear downward trend, represented by the hyetogram of the series of regional annual total precipitation (Figure 10). The Mann-Kendall test was applied to define whether there is a statistically significant time trend, where the p-value of the test less than the level of significance (0.10, 0.05 and 0.01), indicates statistically significant evidence to reject the null hypothesis H_0 , which indicates an increasing trend in the data (positive S) or decreasing (negative S) (WMO 2000; Chiew and Siriwardena 2005). And results indicated that there is and that a large part of the differences between the values in the time series was negative, pointing to a downward trend over time ($S = -172$ and $p\text{-value} = 0.004$). So, the series of annual totals indicated a linear downward trend, represented by the hyetogram of the series of regional annual total precipitation. This downward trend was also observed in the precipitation series between 1980 and 2015 (Costa et al. 2019).

From the total annual rainfall series evaluated by the Anderson-Darling (AD) adherence test, at the 5% level of significance, eight accepted to modelled by the log-normal distribution (Naghettini and Pinto 2007), with the parameters of position (β) and form (α) calculated by the L-moment method (Hosking and Wallis 1997).

This information makes it possible to calculate the quartiles associated with different return times or calculate the return time for each annual quartile, as shown in Table 3.

Table 3

Local frequency analysis results of the annual rainfall series from the stations installed over the Urucuia Aquifer System area and of the regional annual total precipitation series.

Code Station	Initials	Parameters of the log-normal distribution model		Annual Precipitation for Return Time Equal 100 Years	Average Annual		Maximum Annual		Minimum Annual	
		Location	Scale							
		ξ	α		P (mm)	Tr (years)	P (mm)	Tr (years)	P (mm)	Tr (years)
01145013	PSM	7.0560	0.2205	1937.4	1186.7	2	1732	29	762.4	1
01245014	FJH	7.1140	0.1805	1870.3	1247.7	2	1781	51	824.3	1
01245015	RVE	7.1102	0.2465	2172.5	1258.2	2	1856	22	660.8	1
01346007	FPR	7.1656	0.1719	1930.6	1311.4	2	1659	13	907.5	1
01347000	CAL	7.4922	0.1642	2628.3	1817.4	2	2679	137	1311.6	1
01445000	CAJ	7.0428	0.2188	1904.2	1170.5	2	1810	55	765.7	1
01447000	APG	7.2830	0.2040	2339.4	1485.4	2	2431	168	964.3	1
01546005	CAB	7.2315	0.2261	2339.0	1415.6	2	2337	99	921.1	1

Failure in the independence and stationarity tests implies the non-acceptance to model by the log-normal distribution; therefore, “Fazenda Planalto” and “São João d’Aliança” stations do not appear in Table 3. The statistical tests showed that the annual precipitation series is independent and stationary.

Nevertheless, when dividing the series half, with 1989/1990 hydrological year of as the series center, the analysis shows that up to 1989/1990, 73% of the rainfall had a return time of up to 5 years and 27% greater than six years. After this hydrological year, 92% of the rainfall had a return time of up to five years and only 8% greater than six years. That represents an 18% decrease.

Analyzing also the average of all annual rainfall, it is observed that there is a significant difference between the period up to the hydrological year 1989/1990 and the subsequent period, which leads to the assumption that the existence of external climatic phenomena may influence some of the precipitation characteristics, mainly volume and intensity, such as, for example, meteorological systems and teleconnections, which would imply considerable changes in water availability, even so, the issue of aquifer recharge.

Comparison of total regional precipitations (annual and monthly) with Climate Indexes

Analyzing the North Atlantic SST anomaly time series, Enfield et al. (2001) found that the positive (warm) AMO phase occurred during the periods 1860-1885 and 1925-1965 and the negative (cold) AMO phase, during the periods 1895-1924 and 1970-1990. And the downward trend, shown in the hyetogram in Figure 10, shows that the greatest amounts of rainfall occurred between 1973 and 1990, a period in which the negative (cold) phase of the AMO occurred, according to other studies (Raa et al. 2009; Oldenborgh et al. 2012), and for this reason, this was the first teleconnection, whose index was compared with regional precipitation data.

However, analysis of the AMO index series showed that the negative AMO phase occurred until 1993 and, only in 1994, a positive AMO phase started, a fact confirmed in other studies too (Valdés-Pineda et al. 2018). Thus, and considering that the series are independent and stationary, the analyzes used the complete series to compare the indexes without links to the hydrological year of 1989/1990.

The analysis compared the precipitation annual with the average AMO index by means of correlation analysis, and the results showed statistical significance ($p\text{-value} \leq 0.03$), revealing the potential teleconnectivity of the climatic circulation patterns with average annual precipitation over the UAS. Correlating also the monthly precipitation average values in the region with the AMO indices values (Figure 11), a $p\text{-value}$ less than 0.001 is obtained for the regional data series and less than 0.025 for the series of monthly data of the stations, proving a strong correlation between this teleconnection and precipitation in the region. Therefore, these results suggest a correlation between AMO and total annual and monthly rainfall in the region where the Urucuia aquifer occurs.

Searching for more evidence of this correlation, the series of monthly rainfall that occurred when the AMO index was positive was compared with the series of rainfall that occurred when this index was negative, using the t-test at the 0.05 level of significance. In this case, it is concluded that there is a significant difference between the averages of precipitation that occur when the oscillation index is positive or negative ($p\text{-value} < 0.008$).

Based on this evidence, the boxplot graph was proposed (Figure 12), where the differences between the means (123.3 and 94.9 mm), the 3rd Quartiles (207.5 and 166.9 mm), and the 1st Quartiles (15.3 and 2.7 mm) can be observed, that suggest interference of AMO in the negative and positive phase of the dipole. The medians (99.5 and 51.9 mm) also show this difference. This means that there is, in the positive phase of the dipole, inhibition of cloud formation, decreasing precipitation, and causing dry periods. This is because the North Tropical Atlantic waters become warmer, and the Equatorial Atlantic and Tropical South waters become colder. In contrast, in the negative phase of the dipole, the North Tropical Atlantic waters become colder and the waters of the South Tropical Atlantic warmer, generating an increase in upward movements over these regions, intensifying the formation of clouds and increasing rainfall.

Regarding the PDO phenomenon, the mean precipitation series over the UAS did not show any correlation (Figure 13), as the results were not statistically significant, neither with the annual data, where $p\text{-values}$ greater than 0.7 were observed nor with the data monthly, whose lowest $p\text{-value}$ was greater than 0.1, since $p\text{-values} \geq 0.10$ indicate little or no real evidence of correlation (Arsham 1988). Still looking for some correlation, the series analysis was performed according to the hot or cold phase of the PDO.

As several authors (Mantua et al. 1997; Molion 2005; Kayano and Andreoli 2009; Alves 2012) stated that the cold phase of the PDO occurred between 1947 and 1976 and the warm phase between 1977 and 1998, it was correlated monthly and annual rainfall with the PDO index for the period between 1947 and 1976, then for the period between 1977 and 1998, but no correlation was also obtained, resulting in a $p\text{-value} \geq 0.8$.

The regional monthly and annual precipitation series also did not correlate with the Southern Oscillation Index, as the results were also not statistically significant, with $p\text{-value} \geq 0.5$ for monthly data and $p\text{-value} \geq 0.3$ for the annual data (Figure 14). The Multivariate ENSO Index application also did not show any correlation since the $p\text{-values}$ were greater than 0.7. That is, they were not statistically significant.

This is a noteworthy point since no correlation was detected that indicated ENSO and PDOs influence on the precipitation of the studied area. However, some of the studies mentioned above indicate that the negative phase of these indices is favour precipitation over the Northeast of Brazil because there is an increase in rainfall intensity along the rainy season.

In their positive phase, the PDOs and ENSO there seems to occur a greater number of El Niño episodes and more intensely, and a lower number of La Niña events, which occur less intensely. The opposite occurs in the negative phase, where there is

a higher occurrence of La Niña episodes, which tend to be more intense, and a lower frequency of El Niños, which tend to be short and fast.

Comparison of the UAS total, annual, and monthly rainfall patterns with meteorological systems

Some of the studies previously mentioned have shown that the ENSO and PDO teleconnections also greatly influence meteorological systems, as they affect the longitudinal positioning of the ascending branches of the Walker Cell (Wang 2004). This is because, in the hot phase, its main ascending branch is positioned over the warm waters of the Pacific and causes subsidence and high pressure over the North of South America, blocking the Intertropical Convergence Zone further north and the cold Fronts of the Southern Hemisphere and the South Atlantic Convergence Zone (ITCZ) further south, which causes severe droughts in the region. In the cold phase, there is an intensification of the Walker Cell's ascending branches on the continents, increasing the rainfall totals. Therefore, if it was not possible to detect an influence between the ENSO and the PDOs with the precipitation series, it came up that it may be possible to define a relationship between the series and the meteorological systems that act on the UAS, which was investigated through simulation based on the HySplit model.

However, it is important to note that the HySplit model informs rain trajectories according to time, day, and location, so it was necessary to evaluate the daily rainfall in the stations to detect the greatest daily rainfall and where it occurred. In the assessment of the daily rain series, 12,053 days were analysed in 10 stations and found 24% of failures in the data series and 56.3% of the days have no rain occurrences (precipitation equal to zero).

For the other 19.7% of the data, on 54.7% of them precipitation were less than 10 mm, on 42.7% were greater than 10 mm and less than 60 mm and only 2.6% were greater than 60 mm. In other words, only 618 rain records greater than 60 mm verified on the UAS. In the period analysed from September 1973 to August 2006, there are only 49 rain daily records greater than 100 mm, equivalent to only 0.2% of observation records in the region (Figure 15).

To define from which precipitation value the daily data would be analyzed by the HySplit model, the series of maximum annual precipitation of the stations was evaluated, and it was found that for the recurrence time of 1 year, the rain would be 74 mm. Thus, all precipitations equal to or greater than 70 mm were analysed. That is, 22,400 trajectories were analyzed (350 dates * 16 times * 4 times).

With this assessment, it was possible to observe that the specific humidity of the air and the pressure decrease exponentially with the altitude, but in the period from 1973 to 1990 (negative AMO) the specific humidity was 26% higher than in the period from 1990 to 2006 (positive AMO), which shows a greater amount of water vapor in the atmosphere in the period of negative AMO concerning the period of positive AMO. The trajectory data showed no variation between the values of specific air humidity and atmospheric pressure with the increase or decrease in the total precipitation, as the results were not statistically significant, with a p-value ≥ 0.5 .

On average, the trajectories along the negative AMO phase were at higher latitudes closer to the ITCZ, showing that this atmospheric system may have an influence on precipitation during the negative phase of the AMO. However, in the phase of positive AMO, on average, the trajectories latitudes were lower, closer to the Tropic of Capricorn, suggesting that the rainfall received little influence from ITCZ in the phase of positive AMO, and perhaps more influence from the Atlantic Subtropical Anticyclone Sul (ASAS), which transport heat and humidity from the Atlantic Ocean to the interior of Brazil.

In the positive AMO phase, the trajectories presented anticlockwise snail aspects around the initial coordinates, mainly at higher altitudes, suggesting the presence of anticyclonic vortexes, which are high-pressure regions formed by a descending dry air mass, which due to its weight, force to descend. This dry air causes low relative humidity levels and prevents the formation of clouds and precipitation (Kousky and Alonso Gan 1981; Jury and Engert 1999). This type of trajectory suggests the influence of ASAS in its formation.

Figure 15 shows the sets of trajectories estimated for the 15 largest daily precipitation events in the area over the UAS. It is important to highlight that the color scale used is associated with each moment of the trajectories' specific moisture content. A more bluish coloration represents the trajectories that present the highest moisture content and are generally below 2000 m of altitude, corroborating with (Wallace and Hobbs 2006). The opposite occurs with the reddest trajectories, which have less moisture content and are generally at higher atmospheres levels.

Thais is, the color scale used is associated with the specific moisture content of each trajectories moment. A more bluish coloration represents the highest moisture content trajectories and is generally below 2000 m of altitude. The opposite occurs with the reddest trajectories, which have less moisture content and are generally at higher atmospheres levels. Moreover, it is possible to observe different types of storms generated by different atmospheric systems, but all coming from the South Tropical Atlantic Ocean. About the systems, observed indication a direct influence from the South Atlantic Convergence Zone, the predominance of the Amazon systems with a strong contribution from systems in the Equatorial Atlantic Ocean, the performance of High-Level Cyclonic Vortexes, and the performance of cold fronts from the Southern or Indian Ocean.

Also, in Figure 15, it is possible to observe different storms generated by different atmospheric systems. However, all coming from the South Tropical Atlantic Ocean, corroborating the hypothesis that AMO, in its cold (negative) phase, influences precipitation generated in the region.

Concerning the systems, it can be seen that the period from 1977 and 1988 had a direct influence from the South Atlantic Convergence Zone, but in 1978 one can assume the predominance of systems from the Amazon with a strong contribution from systems in the Equatorial Atlantic Ocean. In 1982, it suggested the performance of High-Level Cyclonic Vortexes. In 1976, there is an indication of cold fronts' performance from the Southern or Indian Ocean. Therefore, it was not possible to correlate the high daily rainfall with a predominant atmospheric system.

As the rain pattern distribution shows a decreasing trend in the amount of precipitation in the last 45 years in the Urucua Aquifer area it is expected a proportional reduction in groundwater recharge. This reduction is more important to the confined aquifer subsystem, but also may also affect the unconfined subsystems and must be considered when developing the management actions of the regional water resources.

Conclusions

In this work, ten series of total annual rainfall evaluated by the Anderson-Darling (AD) adherence test, at the 5% level of significance, but eight were accepted to be modeled by the log-normal distribution, with the position parameters (β) and shape (α) calculated by the L-moments method, namely: Ponte Serafim Montante (01145013), Fazenda Johá (01245014), Roda Velha (01245015), Fazenda Prainha (01346007), Cavalcante (01347000), Cajueiro (01445000), Alto Paraíso de Goiás (01447000) and Cabeceiras (01546005). It showed that rainfall values are independent and stationary, with no indication of abrupt changes to suggest interference of climate change.

However, analyzing the average of all annual rainfall, it is observed that there is a significant difference between the series' first 16 years and the series' last 16 years, which leads to considering that external climatic phenomena may influence mainly the volume and intensity of the precipitation.

And it was possible to observe that the total annual rainfall da series over the UAS indicates a downward linear trend, confirmed by the Mann-Kendall test (p -value = 0.004), which justify a decrease in the UAS recharge and, consequently, a decrease in the base flow from the aquifer.

This decrease in annual precipitation can be explained by the AMO phase change, because the correlation of the monthly and annual rainfall with the AMO index, were statistically significant, revealing the potential teleconnection of the sea

surface temperature of the North Atlantic Ocean with precipitation over the Urucuia Aquifer System.

Furthermore, the comparison between the monthly rainfall series that occurred when the AMO index was positive with the series of rainfall that occurred when this index was negative showed a significant difference between the average precipitation in the dipole's negative and positive phases.

Therefore, in the positive phase of the dipole, there is the inhibition of cloud formation, a decrease in precipitation, and, consequently, causing dry periods because the waters of the North Tropical Atlantic become warmer and the waters of the Equatorial Atlantic and Tropical South become colder. On the other hand, in the negative phase of the dipole, the North Tropical Atlantic waters become colder and the South Tropical Atlantic warmer waters, generating an increase in upward movements over these regions, intensifying the formation of clouds and increasing rainfall.

No correlation was found between precipitation over UAS and climate indices: Pacific Decadal Oscillation (PDO), Southern Oscillation Index (SOI), El Niño Multivariate Southern Oscillation Index (ENSO). However, the correlation between precipitation and PDO and ENSO teleconnections may not have occurred due to the indexes chosen to represent these phenomena, as there are several indexes that can be used in the analysis. Therefore, we indicate a more detailed exploratory analysis to conclude if the phenomena that occur in the Equatorial Pacific Ocean influence precipitation over the Urucuia Aquifer System.

Regarding the evaluation of the precipitation trajectories, it was observed that the specific humidity of the air and the pressure decrease exponentially with the altitude, but that the specific humidity in the period from 1973 to 1990 (negative AMO) was 26% higher than the specific humidity in the period of 1990 to 2006 (positive AMO), which shows a greater amount of water vapor in the atmosphere during the negative AMO period compared to the positive AMO period. However, the trajectory data show no variation between the values of specific air humidity and atmospheric pressure with the increase or decrease in the total precipitation, as the results were not statistically significant.

On average, the trajectories along the negative AMO phase, on average, occurred at greater latitudes and closer to the Intertropical Convergence Zone (ITCZ), showing that this atmospheric system can influence the precipitation during the negative phase of the AMO.

In contrast, in the positive AMO phase, on average, the latitudes of the trajectories were lower and closer to the Capricorn Tropic, suggesting that the rainfall received little influence from ITCZ in the phase of positive AMO, and perhaps more influence from the South Atlantic Subtropical Anticyclone (SASA).

In the phase of positive AMO, it was observed that the trajectories had snail aspects around the initial coordinates, mainly at higher altitudes, which may suggest the presence of high-level cyclonic vortex, as these are closed cyclonic circulations in the upper troposphere as shown by the atmospheric waves, whose intensity is higher in the upper troposphere and decreases towards the surface (Reboita et al. 2010).

It was also observed that different atmospheric systems generate the storms, but all coming from the South Tropical Atlantic Ocean, corroborating the hypothesis that AMO influences the precipitation in the region.

And, concerning the systems, it is possible to identify a possible performance of the South Atlantic Convergence Zone, of systems coming from the Amazon with a strong contribution from equatorial Atlantic Ocean systems, High-Level Cyclonic Vortexes, and cold fronts coming from the Antarctic or the Indian Ocean. But, it was not possible to correlate the high daily rainfall with a predominant atmospheric system.

Therefore, we conclude that as the precipitation pattern shows a decrease trend in the last decades it is expected a reduction in the aquifer recharge and in the water availability in the near future.

Declarations

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Figures

Figure 1

Area for identifying teleconnection standards (Adapted from <https://meteorologia.unifei.edu.br/teleconexoes/>). (Souza and Reboita 2021)

(a)

(b)

(c)

Figure 2

(a) Location of the Urucuia Aquifer System in central Brazil. (b) Digital Elevation Model of the Urucuia Aquifer System domain. (c) Altimetry of the Western Chapadão of Bahia geomorphological domain in different sections.

Figure 3

Classification of droughts in the Urucuia Aquifer System region (ANA 2018).

Figure 4

Analysis of Annual Precipitations Average in the Urucuia Aquifer System region (1973 to 2006).

Figure 5

Analysis of Annual Precipitations Average in the Urucua Aquifer System region.

Figure 6

Analysis of Monthly Precipitations Average in the Urucuia Aquifer System region.

Figure 7

Daily hyetograms comparing the precipitation on the Urucuia aquifer System and that observed at “Ponte Alta do Bom Jesus” station (code: 01246000).

Figure 8

Box Plot of the ten series of monthly rainfall data for stations installed over the Urucuia Aquifer System area.

Figure 9

Box Plot of the ten series of annual rainfall data for stations installed over the Urucuia Aquifer System area.

Figure 10

Hyetogram of annual rainfall average at the Urucuia Aquifer System.

Figure 11

Graph of monthly rainfall in the Urucuia Aquifer System region and of the monthly values of the AMO Index.

Figure 12

Boxplot illustrating monthly precipitation for positive and negative AMO Index values.

Figure 13

Graph of monthly precipitation in the Urucua Aquifer System region and of the monthly values of the PDO Index.

Figure 14

Graph of monthly precipitation in the Urucuia Aquifer System region and of the monthly values of the Southern Oscillation Index and the Multivariate ENSO Index.

Figure 15

Trajectories determined by the HySplit model of the 15 largest daily precipitation events on the Urucuia Aquifer System.

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