

Rainfall trends in the Brazilian Amazon Basin in the past eight decades

Prakki Satyamurty · Aline Anderson de Castro ·
Julio Tota · Lucia Eliane da Silva Gularte ·
Antonio Ocimar Manzi

Received: 14 July 2008 / Accepted: 23 March 2009 / Published online: 18 April 2009
© Springer-Verlag 2009

Abstract Rainfall series at 18 stations along the major rivers of the Brazilian Amazon Basin, having data since 1920s or 1930s, are analyzed to verify if there are appreciable long-term trends. Annual, rainy-season, and dry-season rainfalls are individually analyzed for each station and for the region as a whole. Some stations showed positive trends and some negative trends. The trends in the annual rainfall are significant at only six stations, five of which reporting increasing trends (Barcelos, Belem, Manaus, Rio Branco, and Soure stations) and just one (Itaituba station) reporting decreasing trend. The climatological values of rainfall before and after 1970 show significant differences at six stations (Barcelos, Belem, Benjamin Constant, Iaurete, Itaituba, and Soure). The region as a whole shows an insignificant and weak downward trend; therefore, we cannot affirm that the rainfall in the Brazilian Amazon basin is experiencing a significant change, except at a few individual stations. Subregions with upward and downward trends are interspersed in space from the far eastern Amazon to western Amazon. Most of the seasonal trends follow the annual trends, thus, indicating a certain consistency in the datasets and analysis.

1 Introduction

We know now that the CO₂ concentration in the atmosphere has increased during the last century from less than 260 ppm to nearly 380 ppm (IPCC, 2007). The projections for the future indicate that the anthropogenic forcing will increase the CO₂ concentration to 720 ppm in 2100 (Li et al. 2008). We also observe that the Amazon jungle has been depleted by about 30% due to economic activity in the region in the latter half of the XX century (Artaxo et al. 2006) and, in all likelihood, will be depleted by another 30% in the present century. Many modeling studies examined possible changes in the rainfall pattern over the Amazon basin due to changes in land cover (Sud et al. 1993, Oliveira et al. 2007) and due to changes in the composition of the atmosphere (Chen et al. 2003). These studies predicted reduction in precipitation and a rise in temperature. Sud et al. (loc. cit) and Costa and Foley (2000) explain that replacing forests with pastures reduces evapotranspiration and the strength of tropical convection. Consequent changes in energy and water balance lead to significant reduction in rainfall and an increase in temperature. The question is whether we are able to observe any significant trend or change in the observed rainfall over the Amazon basin as predicted by the modeling studies.

Marengo (2004) presented an analysis of the trends of rainfall during the second half of the last century in the Amazon basin. He showed that the northern Amazon and southern Amazon regions presented opposite tendencies in the rainfall indices during the 50-year period from 1950 to 2000. Li et al. (2008) observed a significant negative trend in the standard precipitation index over the southern Amazon region during the 30-year period 1970–1999. Marengo (2004) worked with five different datasets. He found a large discrepancy between the National Centers for Environmental Prediction (NCEP) data and the other

P. Satyamurty (✉) · A. A. de Castro · J. Tota · A. O. Manzi
LBA Program,
Instituto Nacional de Pesquisas da Amazônia (INPA),
Manaus, Brazil
e-mail: prakki.satyamurty@cptec.inpe.br

L. E. da Silva Gularte
Instituto Nacional de Meteorologia (INMET),
Manaus, Brazil

P. Satyamurty
Centro de Previsão de Tempo e Estudos Climáticos (CPTEC),
Instituto Nacional de Pesquisas Espaciais (INPE),
São José dos Campos, Brazil

datasets. In fact, his analysis showed large and opposite trends with NCEP and CPC Merged Analysis of Precipitation (CMAP) datasets for All Amazonia and southern Amazonia. He also correlated the changes in Amazon precipitation with global indices like SST in the Pacific and in the Atlantic. He attributed the interdecadal variability in rainfall to the frequency of El Niño events.

We examine, in the present study, data at individual rain gauge stations, thereby avoiding possible inhomogeneities among the datasets. However, analysis for the whole Brazilian Amazon region is also presented to verify the trends on the regional basis. The objective is to detect if there are any significant trends in the rainfall regimes of the stations in the Brazilian Amazon Basin in, approximately, the last 80 years, considering that the rain gauge data at the stations are more homogeneous than a mixture of data from different sources.

2 Data and methodology

2.1 Precipitation data sets

Monthly data of 18 rain gauge stations in the Brazilian Amazon basin, shown in Fig. 1, are used to study the trends in rainfall. The rain gauge stations with less than 45 years of data during the period 1925–2007 are not considered. The data are obtained from the Instituto Nacional de Meteorologia (INMET). The stations are spread from west to east along the major rivers, Rio Negro, Rio Solemoes, and Rio Amazonas (not shown), over the region 48–73° W and 1–10° S. The stations far from the two rivers do not have sufficient lengths of historical data for a climate change study. The INMET has been steadily replacing the rain gauge stations in the Brazilian Amazon region by

automatic stations since 2007, and the data after the replacement may present sudden changes in magnitude, rendering the climate change assessment difficult. Therefore, the periods of data considered in this study, i.e., up to 2007, have the maximum possible length. There is no information available on the homogenization process of the historical data in the records and files at the INMET office in Manaus, AM, Brazil, except for a remark in the preface of the publication “1961–1990 Meteorological Normals” stating that “the calculations of the climatological normals include an analysis of homogeneity of the data.”

For each station, the 4-month dry and wet seasons are determined by preparing monthly rainfall climatologies (not presented here). The four consecutive months with the largest accumulated climatological rainfall are considered to be the rainy season. The four consecutive months with the smallest accumulated rainfall are considered to be the dry season. Table 1 presents the location of the stations and the seasons. Table 2 shows the periods of the datasets and the gaps therein. Except Macapa station, all others have data prior to 1931. Manaus, with 83 years of uninterrupted data from 1925 to 2007, and Sao Gabriel de Cachoeira station, with 82 years of data in the same period, has the longest datasets. Rio Branco, Tefe, and Macapa stations, having data for 46, 50, and 51 years, respectively, are the shortest datasets. We can see that most of the stations experience January through April (JFMA) as the rainy season and June through September (JJAS) or August through November (ASON) as the dry season.

The gaps in the datasets are attributed to (1) lack of trained manpower during some years/periods, (2) malfunctioning of the rain gauge instruments, (3) loss of original registers, and (4) illegible entries in the registers (Senna, R., Personal Communication). The gaps are sometimes just a

Fig. 1 Location of the 18 stations in the Brazilian Amazon basin used to study rainfall trends. Upward and downward trends are indicated by the letters *U* and *D*, respectively

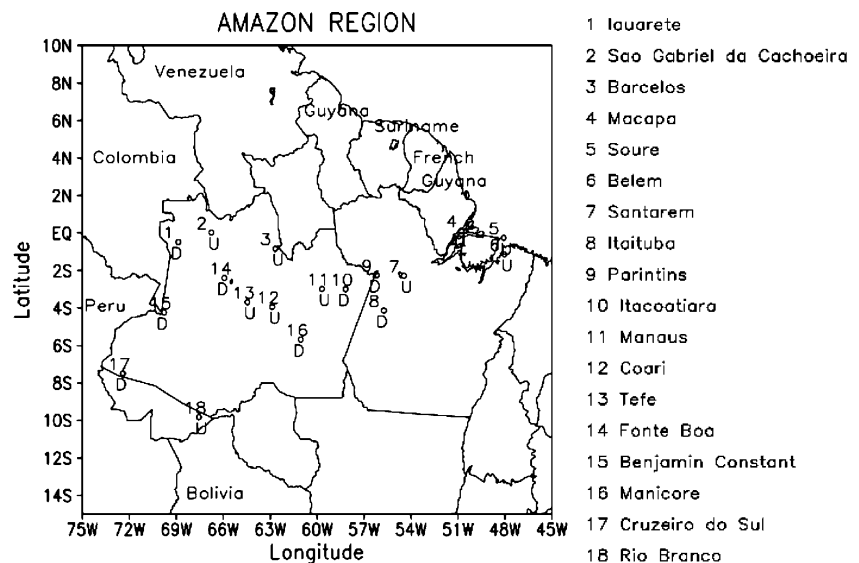


Table 1 Rain gauge stations, positions (latitude, longitude), and wet and dry seasons

Station number	Station	Lat	Long	Wet season	Dry season
3	Barcelos-AM	00:58 S	62:55 W	MAMJ	NDJF
6	Belém-PA	01:27 S	48:28 W	JFMA	ASON
15	Benjamin Constant-AM	04:23 S	70:02 W	NDJF	JJAS
12	Coari-AM	04:05 S	63:08 W	JFMA	JJAS
17	Cruzeiro do sul-AC	07:38 S	72:40 W	JFMA	JJAS
14	Fonte Boa-AM	02:32 S	66:10 W	JFMA	JASO
1	Iauaretê-AM	00:37 S	69:12 W	AMJJ	NDJF
10	Itacoatiara-AM	03:08 S	58:26 W	JFMA	JASO
8	Itaituba-PA	04:27 S	55:29 W	JFMA	JJAS
4	Macapá-AP	00:02 S	51:03 W	FMAM	ASON
11	Manaus-AM	03:07 S	59:57 W	JFMA	JJAS
16	Manicoré-AM	05:49 S	61:18 W	JFMA	JJAS
9	Parintins-AM	02:38 S	56:44 W	JFMA	ASON
18	Rio Blanco-AC	09:58 S	67:48 W	NDJF	JJAS
7	Santarém-PA	02:25 S	54:42 W	FMAM	ASON
2	S. G. da Cachoeira-AM	00:07 S	67:00 W	MAMJ	ASON
5	Soure-PA	00:40 S	48:33 W	JFMA	ASON
13	Tefê-AM	03:50 S	64:42 W	JFMA	JASO

The seasons are indicated by the first letters of the months of the year

month long and sometimes last for several years. When the gap is just for a month, it is filled by an arithmetic mean of the previous and succeeding months. If a gap lasts for 2 months or longer, no interpolation is attempted to avoid

introducing highly spurious data. That is, the totals for such years or seasons are left blank. It is important to remember that, in a given year, the rainfall of a season (wet or dry) may have data while the annual rainfall presents a gap.

Table 2 Data periods and gaps in the datasets

Station	Period	Gaps		
		Wet Season	Dry Season	Annual
Barcelos-AM	1928–2007 (06)	1949; 1953; 1963–64; 1991	1954; 1963–64; 1991	1949; 1953; 1963–64; 1990–91
Belém-PA	1925–2007 (03)	1965	1964; 2007	1964; 1965; 2007
Benjamin Constant-AM	1931–2007 (8)	1938; 1971; 1977; 1982; 1991	1938; 1970; 1971; 1976–77; 1981	1938; 1970; 1971; 1976; 1977; 1981–82; 1990
Coari-AM	1924–2007 (8)	1958–61; 1964; 1991	1958–61; 1990	1958–61; 1963–64; 1990–91
Cruzeiro do Sul-AC	1928–2007 (12)	1952; 1960–61; 1963–70	1952; 1959–61; 1963–70	1952; 1959–61; 1963–70
Fonte Boa-AM	1927–2007 (09)	1931; 1959; 1963; 1968; 1972; 1991–92	1954; 1959; 1963; 1967–68; 1972; 1991–92	1931; 1954; 1959; 1963; 1967–68; 1972; 1991–92
Iauaretê-AM	1931–2007 (01)	1968	1968	1968
Itacoatiara-AM	1928–2007 (16)	1938–39; 1959–61; 1963–70; 1975	1938–39; 1956; 1959–60; 1962; 1963–70; 1974; 1975	1938–39; 1956; 1959–60; 1962; 1963–70; 1974; 1975
Itaituba-PA	1931–2004 (04)	1937; 1977	1936–37; 1977; 2004	1936–37; 1977; 2004
Macapá-AP	1954–2005 (01)	Complete	2004	2004
Manaus-AM	1925–2007 (00)	Complete	Complete	Complete
Manicoré-AM	1928–2007 (22)	1928; 1937–38; 1950; 1952–67; 1969	1935; 1937–38; 1950; 1952–66; 1969	1928; 1935; 1937–38; 1950; 1952–67; 1969
Parintins-AM	1923–2001 (06)	1939; 1943; 1960	1939–40; 1959; 2001	1939–40; 1943; 1959; 1960; 2001
Rio Branco-AC	1929–2005 (31)	1929; 1933–48; 1959–69	1932–48; 1954; 1957–68	1932–48; 1954; 1957–69
Santarém-PA	1919–1996 (01)	1995	Complete	1995
S. G. da Cachoeira-AM	1925–2007 (01)	Complete	1991	1991
Soure-PA	1930–2000 (02)	Complete	1989–90	1989–90
Tefê-AM	1930–2007 (28)	1931; 1994–70; 1991–92	1930–31; 1948–69; 1991–93	1930–31; 1947–69; 1991–93

Number of years of missing data in the period is given in parentheses in column 2. The gaps in the seasonal and the annual datasets are shown in columns 3, 4, and 5

Three datasets, one each for the rainy-season rainfall, the dry-season rainfall, and the annual rainfall are prepared, for each station and for the whole region. The aerial average rainfall for the whole region is obtained by simply taking an arithmetic mean of the 18 stations, taking properly into account the gaps in the datasets.

2.2 Linear trend analysis

2.2.1 Linear trend line

Those datasets are subjected to linear trend analysis. That is, a straight line of best fit of the form $Y=ax+y_0$ is found. In this equation, $Y(x)$ is the expected rainfall if the trend is linear, x is the number of years since the beginning of the series, a is the trend, and y_0 is the value of rainfall in the beginning of the series according to linear-trend line. The slope of the trend line indicates if there is a positive or a negative trend in the dataset considered and the magnitude of the change in the data period. Li et al. (2008) obtained the trend from the spatially averaged rainfall for the Amazon region south of 5° S. In the present study, the trends are calculated at each of the 18 stations shown in Table 1. This will allow us to obtain the spatial distribution of the trends along the major rivers of the Brazilian Amazon basin. To get a gross idea of the regional changes, trend analysis is applied to the datasets for the whole region also.

2.2.2 Strength of the trend

The magnitude of the trend is important and is compared with the interannual variability of the variable, as measured by standard deviation, σ , in order to consider it strong or weak. Here, we consider the trend to be strong if the change in 70 years or more is larger than 50% of the standard deviation. If the change is equal to or larger than 100% of the standard deviation, the trend is considered very strong. Before this comparison is made, the variance of the series is corrected by subtracting the variance due to the linear trend.

The rainfall series at a given station can be expressed as

$$y(x) = Y(x) + y'(x) = y_0 + ax + y'(x) \quad (1)$$

where $y(x)$ is the observed rainfall, y_0+ax represents the linear-trend line, and $y'(x)$ is the deviation from the trend line. Considering that the interannual variations (y') are randomly distributed with respect to x and x^2 , the variance of y is given by

$$S(y) = S(y') + a^2D^2/3 \quad (2)$$

where D is the duration of the series. $S(y')$ represents the variance due to the interannual variability, $a^2D^2/3$ is the

variance due to linear trend and $S(y)$ is the total variance. The variances for a continuous function of x are given by

$$S(y) = (1/D) \int (y - \bar{y})^2 dx; \quad (3)$$

$$S(y') = (1/D) \int (y - Y)^2 dx = (1/D) \int y'^2 dx$$

where \bar{y} is the mean of y in the interval D over which integration is performed. Accordingly, the uncorrected and corrected standard deviations are given by $\sigma=[S(y)]^{1/2}$ and $\sigma'=[S(y')]^{1/2}$, respectively. In practice, we use equivalent expressions, for discrete y , using summation in the place of the integral.

The change in rainfall due to linear trend in the period D is simply $a(D-1)$. For example, if we have data for 80 years at a station where the trend is a , the change in rainfall at that station is $79a$. Thus, the criteria for measuring the significance, for $D \geq 70$ years, become:

$$\begin{aligned} |a(D-1)| &\geq [S(y')]^{1/2} = \sigma' \rightarrow \text{very strong trend} \\ |a(D-1)| &\geq (1/2)[S(y')]^{1/2} = (1/2)\sigma' \rightarrow \text{strong trend} \\ |a(D-1)| &< (1/2)[S(y')]^{1/2} = (1/2)\sigma' \rightarrow \text{weak trend.} \end{aligned} \quad (4)$$

2.2.3 Change in climatology

The climatologies or mean values of rainfall for the periods up to 1970 and for 1971–2007 are calculated and their difference is tested for statistical significance using the z statistic (Wilks 2006, p140, 141) given by

$$z = (\bar{y}_1 - \bar{y}_2) / \sqrt{[(S_1/n_1) + (S_2/n_2)]} \quad (5)$$

where \bar{y}_1 and \bar{y}_2 are the climatological rainfalls before and after 1970, and n_1 and n_2 are the numbers of years of data before and after 1970, respectively. The magnitude of z tells us if there is a significant change in rainfall after 1970 as compared to the climatology before 1970. Actually, for reasonable sizes of n_1 and n_2 , $|z| \geq 2$ means that \bar{y}_1 and \bar{y}_2 are significantly different, and we may say that there is a change in rainfall climate before and after 1970. It has to be remembered that $z < 0$ means that there is a decrease in the rainfall climatology after 1970, and vice versa.

The rainfall series before and after 1970 are tested for the hypothesis that the two series are drawn from distributions with equal medians using rank sum test (Statistics Toolbox, Hollander and Wolfe, 1973). A product of the test is the probability, p , of observing the given result by chance if the null hypothesis, H_0 , is true. The null hypothesis here is that the two series are drawn randomly from a single series. Small values of p cast doubt on the validity of the null hypothesis, and thus may indicate

a change in the rainfall regime at the station after 1970. Mahli and Wright (2004) suggested that temperature changes over the tropical forests have been positive since the mid-1970s. In the same way, the present study may show the rainfall changes over the Brazilian Amazon basin in the period after 1970 as compared to the period before 1970.

Firstly, the rainfall climatologies for the period before 1970 and after 1970 are calculated to gauge the change from the first period to the second and then z statistic and p are obtained. For $p \leq 5\%$ the climatologies are considered significantly different and H_0 is rejected.

2.2.4 Statistical significance of linear trend

Finally, a nonparametric statistical significance test for linear trend commonly used in geophysical sciences, the Mann–Kendal test, as described in Xu et al. (2003) and Partal and Kahya (2006), is applied for the rainfall series. The products of the test are the test statistics S and Z_c . A positive value of S indicates upward trend and a negative value a downward trend while Z_c determines the significance or the acceptance or rejection of the null hypothesis, H_0 , which states that the dataset is formed by n independent and identically distributed random variables. When H_0 is rejected at a given significance level, α , one can say that the dataset has a significant trend. Further details can be obtained in the two papers cited above. We adopted 95% significance level in this study.

3 Rainfall climatology

Table 3 shows the climatology of rainfall, considering the whole available periods of data at the 18 stations shown in Table 1. The highest annual rainfall is observed at Iauete station lying close to the equator. It receives nearly 3,480 mm of rainfall per year and has no clearcut dry season, which can be seen from the amount of rainfall expected during the so-called dry season. The interannual variability of rainfall at this station is large, nearly 600 mm/year. The Sao Gabriel de Cachoeira station, also close to the equator, presents a large annual mean and an even distribution over the seasons, and the interannual variability (σ') is very small compared to the Iauete station. The Rio Branco station in Acre state, receiving slightly less than 1,950 mm/year, is the least rainy station among the 18 studied. The rest of the stations receive an annual rainfall between 2,000 and 3,000 mm and some of them like Belem, Coari, and Manicore present reasonably well-defined wet and dry seasons. The seasonality and annual climatologies of rainfall observed here are in good agreement with Satyamurty et al. (1998).

4 Trends in annual and seasonal rainfalls

Table 4 shows the linear trend line equations and the changes in the annual and seasonal rainfalls during the periods of the datasets at the 18 stations studied. Figure 1 shows the geographical distribution of trends. It is important to note that the trends are negative in the far west represented by Iauete, Fonte Boa, Benjamin Constant, and Cruzeiro do Sul stations. To the east of this subregion lie positive trends at Sao Gabriel de Cachoeira, Barcelos, Manaus, Coari, and Tefe stations. Parintins, Itacoatiara, and Manicore stations present downward trends and in the easternmost part of the Amazon basin considered, Belem and Soure stations present upward trend. That is, decreasing and increasing trend subregions are interspersed from west to east over the Brazilian Amazon basin.

Figure 2 shows the rainfall sequences and the linear trend lines for the four stations, Itaituba, Benjamin Constant, Iauete, and Manicore, which have presented the largest negative trends among the stations with data length of 70 years or more. Figure 3 shows the rainfall sequences and the linear trend lines for the four stations Soure, Belem, Barcelos, and Rio Branco, which have the largest positive trends. These results are discussed below.

Itaituba station (Fig. 2) shows the largest decrease of rainfall, more than 1,000 mm/year in 75 years. This change is very strong according to the criterion given in Eq. 4. Benjamin Constant station shows a decrease in rainfall of 415 mm/year in 77 years, i.e., from 2,964 mm/year in 1931 to 2,549 mm/year in 2007. This change is strong. The change at Iauete station is also strong. But at Manicore, the change found according to the linear trend is less than $0.5\sigma'$, i.e., the change is weak. Consistent with the annual rainfall changes, the wet-season rainfalls of these stations demonstrate negative trends. The dry-season rainfalls also reveal decreasing trends, except at Itaituba station. It is interesting to note that Macapa station (figure not shown) presented the second largest negative trend, but it has data for just 52 years.

Soure rainfall (Fig. 3) registered a positive change of 671 mm/year in 70 years from 2,762 mm/year in 1928 to 3,433 mm/year in 2007, according to the linear trend line. Compared with the standard deviation of 383 mm/year, the trend is very strong. The rainfall increase at Belem in 82 years is 566 mm/year and is also considered very strong compared to the relatively small interannual variability. The changes at the other two stations (Barcelos and Rio Branco) are just strong. The seasonal rainfalls at all the four stations also showed positive trends.

Five out of the remaining nine stations (see Table 4) show very small positive changes and the four others show small negative changes in the annual rainfall from 1930s to the present. The seasonal rainfalls present strong changes at

Table 3 Wet-season, dry-season, and annual rainfall climatologies for the data periods given in Table 2

Station	Wet Season			Dry season			Annual		
	Mean	σ	σ'	Mean	σ	σ'	Mean	σ	σ'
Barcelos-AM	1085.6	261.8	244.3	628.0	242.1	241.5	2268.4	480.7	460.3
Belém-PA	1600.1	262.3	257.0	493.3	139.8	127.5	2910.2	407.5	372.0
Benjamin Constant-AM	1121.1	242.2	236.5	549.8	153.6	150.5	2759.4	467.4	450.2
Coari-AM	1054.9	248.9	248.4	389.7	115.5	114.9	2260.0	419.6	418.6
Cruzeiro do Sul-AC	985.4	213.5	213.5	358.7	110.4	106.5	2144.7	329.5	325.9
Fonte Boa-AM	1018.4	228.2	224.4	648.8	148.9	148.9	2585.6	439.1	434.5
Iauaretê-AM	1464.0	304.3	302.8	958.4	230.7	229.3	3479.4	600.7	591.5
Itacoatiara-AM	1323.5	311.2	309.8	350.6	148.6	148.5	2402.5	517.4	514.6
Itaituba-PA	1317.4	286.8	237.8	244.3	98.4	89.6	2392.9	460.8	345.3
Macapá-AP	1527.2	422.8	407.6	241.8	115.7	115.4	2648.8	613.2	596.5
Manaus-AM	1176.8	208.5	207.6	301.1	102.8	99.1	2211.2	310.2	304.0
Manicoré-AM	1311.1	265.9	260.6	338.2	132.3	132.2	2531.2	487.2	482.7
Parintins-AM	1282.7	329.4	328.2	311.2	122.7	122.4	2342.4	509.3	508.8
Rio Branco-AC	1020.8	190.7	182.4	210.0	85.5	85.4	1947.1	232.2	224.8
Santarém-PA	1276.2	237.5	236.2	211.8	112.5	112.4	2078.6	394.6	393.4
S. G. da Cachoeira-AM	1141.6	191.4	191.1	745.6	132.3	128.7	2921.8	353.5	352.4
Soure-PA	2145.0	542.7	521.8	169.3	80.7	82.0	3125.0	720.2	694.0
Tefê-AM	1077.5	234.2	233.9	484.0	165.5	165.4	2391.0	379.0	379.0
Whole Region	1267.3	106.6	105.3	434.4	48.7	48.1	2540.4	177.4	177.1

Units are in mm/year or mm/season

σ uncorrected standard deviations, σ' corrected standard deviations

Table 4 Rainfall trends over central and western Amazon basin

Station	Wet season		Dry season		Annual	
	Trend Line	Change	Trend line	Change	Trend line	Change
Barcelos-AM	$3.97x+927.9$	314	$0.76x+598.1$	60	$5.84x+2038.0$	462
Belém-PA	$2.17x+1511.1$	178	$2.40x+396.2$	196	$6.90x+2630.5$	566
Benjamin Constant-AM	$-2.50x+1217.0$	-190	$-1.61x+611.0$	-122	$-5.46x+2964.0$	-415
Coari-AM	$-0.60x+1079.6$	-50	$0.50x+369.2$	42	$1.15x+2213.0$	96
Cruzeiro do Sul-AC	$-0.20x+993.3$	-16	$-1.17x+405.9$	-93	$-1.92x+2222.0$	-152
Fonte Boa-AM	$-1.72x+1087.2$	-141	$-0.10x+652.9$	-8	$-2.61x+2690.3$	-214
Iauaretê-AM	$-1.36x+1515.7$	-103	$-1.12x+1001.0$	-85	$-4.66x+3656.7$	-354
Itacoatiara-AM	$-1.16x+1371.6$	-92	$-0.15x+356.9$	-12	$-2.09x+2489.0$	-165
Itaituba	$-7.46x+1591.9$	-545	$1.93x+174.5$	141	$-14.53x+2925.8$	-1061
Macapá-AP	$-7.25x+1719.9$	-370	$0.67x+224.4$	34	$-9.22x+2889.8$	-470
Manaus-AM	$0.77x+1136.3$	63	$1.14x+254.1$	94	$2.56x+2106.3$	210
Manicoré-AM	$-2.11x+1403.2$	-167	$-0.18x+345.9$	-14	$-2.64x+2648.2$	-209
Parintins-AM	$-1.20x+1329.9$	-87	$0.40x+295.6$	29	$-0.97x+2380.7$	-71
Rio Branco-AC	$2.74x+888.8$	214	$0.17x+201.8$	13	$2.85x+1806.3$	222
Santarém-PA	$1.04x+1234.4$	85	$0.24x+202.2$	19	$1.32x+2025.9$	107
S. G. da Cachoeira-AM	$0.44x+1123.5$	36	$1.42x+716.6$	116	$1.17x+2874.4$	96
Soure-PA	$8.07x+1871.8$	484	$0.80x+151.7$	48	$11.18x+2762.5$	671
Tefê-AM	$0.50x+1056.7$	39	$-0.23x+493.9$	-18	$0.80x+2309.4$	63
Whole Region	$-0.7x+1295$	-56	$0.3x+422$	25	$-0.4x+2557$	-33

The values are in mm/year or mm/season. Change (mm/year) is from the beginning to the end of the series, according to the trend line x number years since the beginning of the data period

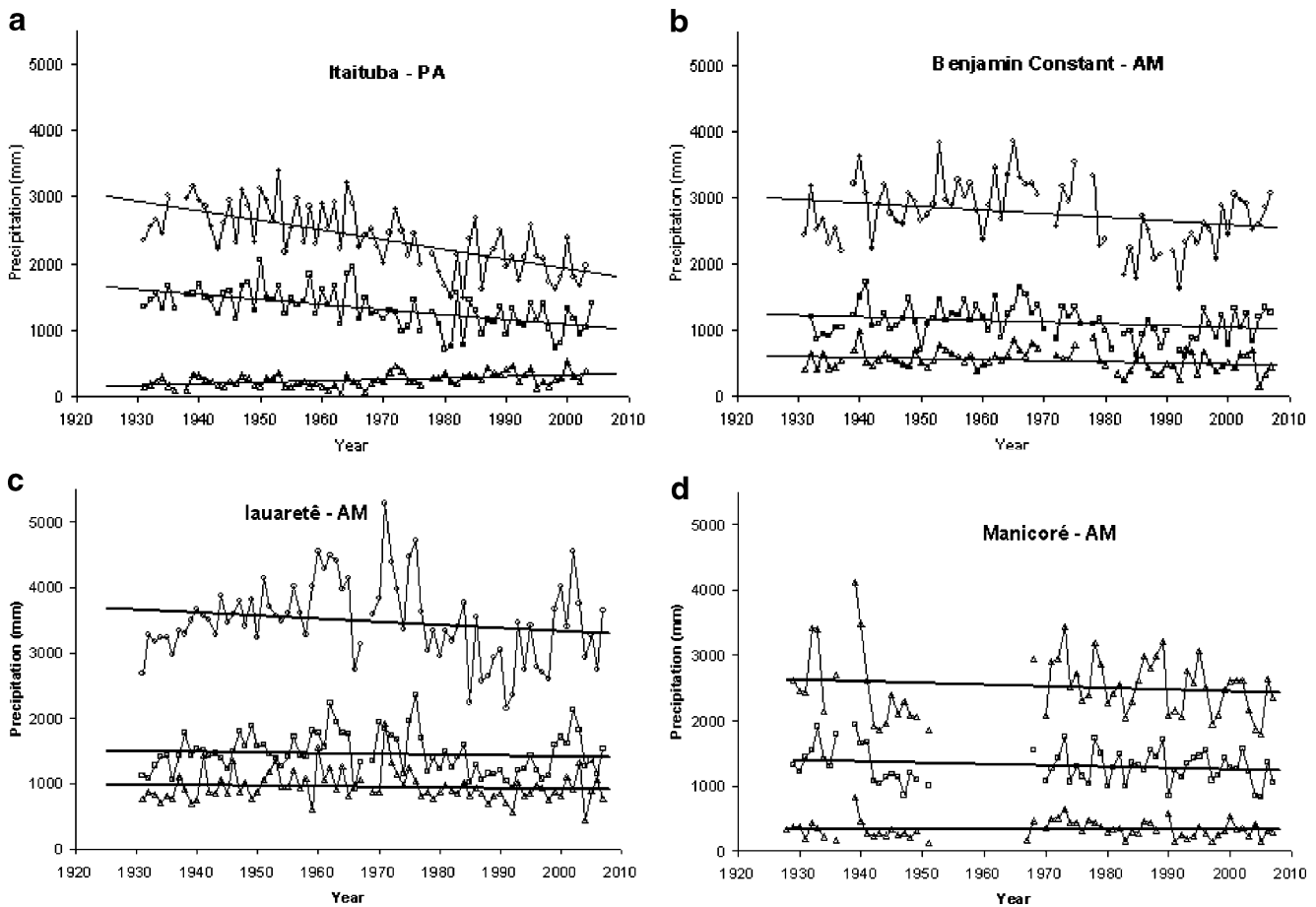


Fig. 2 Annual, wet-season, and dry-season rainfalls and trend lines for **a** Itaituba, **b** Benjamin constant, **c** Laurete, and **d** Manicore stations

a few of these nine stations. Considerable values are observed in the wet-season rainfalls at Macapá and Fonte Boa and dry-season rainfalls at Sao Gabriel Cachoeira and Cruzeiro do Sul. The rest of the values are weak according to the criterion shown in Eq. 4. The whole-region annual and wet-season rainfalls show slight downward trends and the dry-season rainfall a very slight upward trend.

Summarizing the trend line equations and changes in rainfall from the beginning of the series to 2007 given in Table 4, we may argue that the stations indicate mixed trends in rainfall in the past 70 to 80 years. The spatial distribution of trends (Fig. 1) shows that the upward and downward-trend regions are interspersed from east to west. But when the whole region studied is considered (Fig. 4), it is difficult to discern a significant trend.

Table 5 shows the rainfall climatologies before and after 1970 and their respective z and p values. Magnitudes of z greater than or equal to 2.0 are observed at six stations (Barcelos, Belem, Benjamin Constant, Iauete, Itaituba, and Soure) for the annual rainfall, at five stations (all the above except Iauete) for the wet-season rainfall and at five stations for the dry-season rainfall. The rest of the values are less than 2.0, some of them close to zero. Small values of p (<5%) are

obtained for changes in the annual rainfall at six stations (exactly those with $|z| \geq 2.0$) where the H_0 is rejected.

Table 6 shows the Mann-Kendal statistics and hypothesis tests for the series at the 18 stations. The test indicates that at six stations the trend is significant ($h=1$) for the annual rainfall. At the same six stations, the trends in the wet season rainfalls are also significant. It is interesting to note that the stations with large changes in their climatologies from before 1970 to after 1970 also present high values of the Z statistic.

Some of the increasing trends at the major cities like Manaus, Belem, and Santarem in both the seasons and for the annual rainfalls are perhaps due to the intensification of the local atmospheric circulations attributed to deforestation in and around the city as is argued by (Correia et al. 2007).

5 Conclusion and discussion

The rainfall trends at 18 rain gauge stations along the major rivers in the Brazilian Amazon basin in the past eight decades show mixed signs. Except for six stations, the trends in the annual rainfall are not significant. Almost the same conclusion

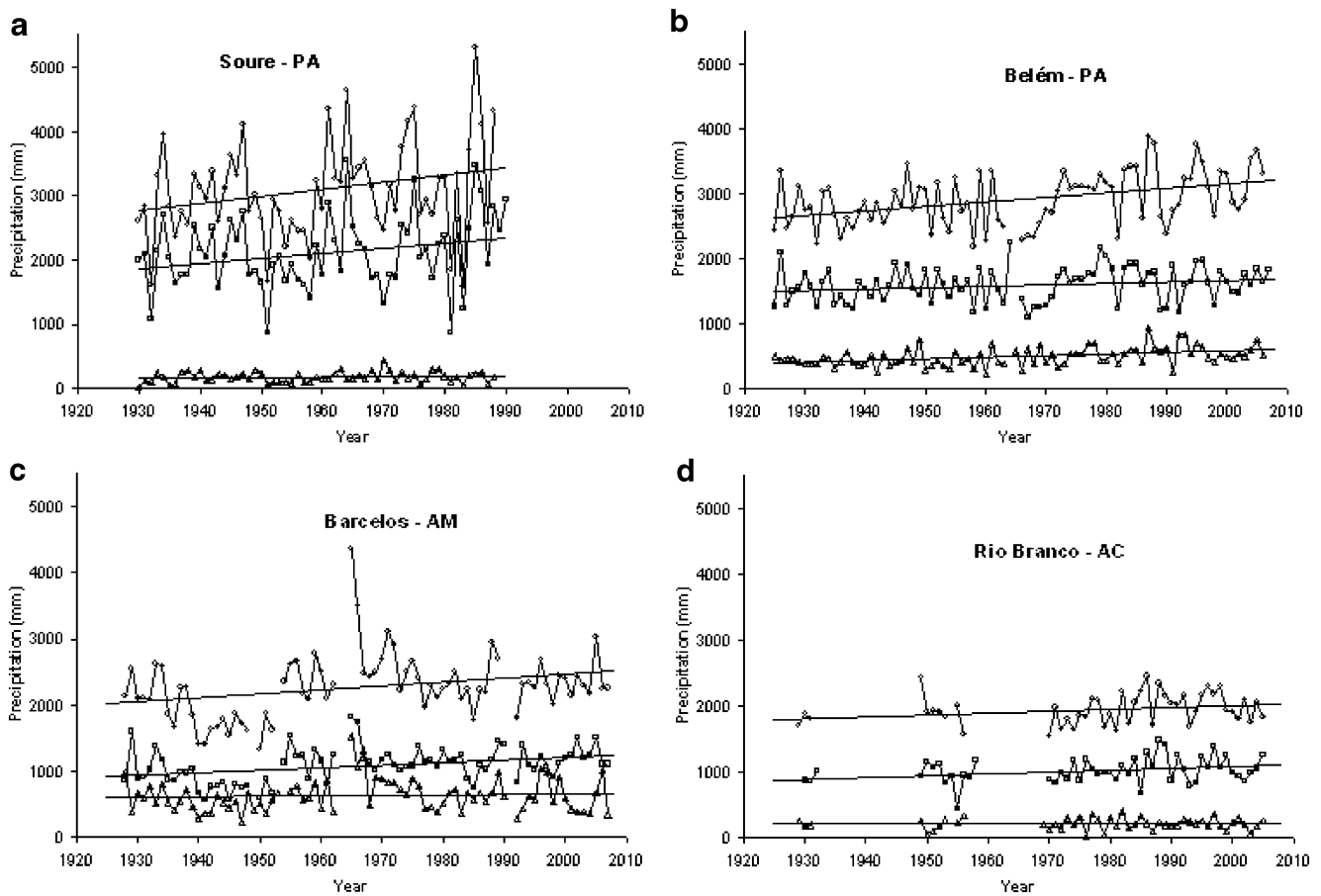


Fig. 3 Annual, wet-season, and dry-season rainfalls and trend lines for **a** Soure, **b** Belém, **c** Barcelos, and **d** Rio Branco stations

is reached by comparing the climatological values of rainfall before 1970 and after 1970. The z statistic and the rank sum test for the rainfall series before and after 1970 also confirm the same result. The annual and seasonal rainfalls for the whole Amazon show insignificant negative trends. That is, it is difficult to affirm that there are significant changes in the

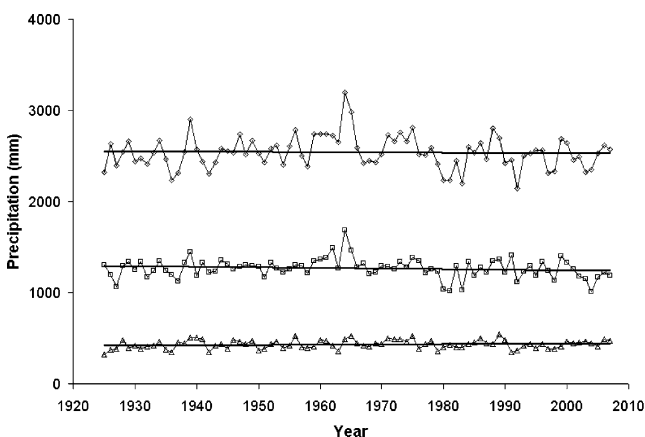


Fig. 4 Whole Region average annual and wet-season (JFMA) precipitation series and their linear-trend lines

rainfall regime in the Brazilian Amazon basin in the past 70 to 80 years.

If the deforestation of Amazon basin can cause reduction in rainfall over the region as is predicted by modeling studies (Correia et al. 2007), this effect is not yet observed. Contrary to the modeling study results, some stations in the central and eastern parts of the region studied have shown increasing in their rainfalls. However, this result should not be used to let the deforestation proceed as it has been in the last half a century because the modeling study of Oliveira et al. (2007) has shown that the changes in the climate, especially those in the rainfall regime, are increasingly felt for deforestation beyond 50% the area. The decrease in rainfall may start appearing later.

It is surprising to note that the stations in the extreme western parts of the region (e.g., Iauarete and Benjamin Constant), where the forest is still preserved, show decreasing trend and the stations in the eastern portion (e.g., Soure and Belém), where the forest is depleted, show increasing trend. A slight increase in rainfall due to enhanced local or mesoscale circulations caused by partial deforestation is also found in the modeling studies. The deforested areas lying side by side with forested areas generate breeze from the forest to the deforested

Table 5 Rainfall climatology (mm/season or mm/year) for the periods before and after 1970, and its statistical significance

Station	Wet season					Dry season					Annual				
	M1	M2	<i>z</i>	<i>p</i> (%)	<i>h</i>	M1	M2	<i>z</i>	<i>p</i> (%)	<i>h</i>	M1	M2	<i>z</i>	<i>p</i> (%)	<i>h</i>
Barcelos - AM	1021	1156	2.6	1	1	632	624	0.3	80	0	2184	2362	2.1	4	1
Belém - PA	1531	1685	2.8	1	1	442	558	3.9	0	1	2734	3126	4.2	0	1
Benjamin Constant - AM	1205	1025	-2.9	0	1	591	502	-2.2	2	1	2936	2543	-3.4	0	1
Coari - AM	1038	1074	0.1	89	0	368	415	2.1	3	1	2162	2372	1.9	6	0
Cruzeiro do Sul - AC	1002	971	0.2	83	0	383	338	1.7	9	0	2219	2082	1.6	11	0
Fonte Boa - AM	1046	986	-1.1	27	0	640	659	0.8	45	0	2603	2566	0.0	99	0
Iauaretê - AM	1514	1412	-1.9	6	0	980	935	-1.0	33	0	3601	3351	-2.1	4	1
Itacoatiara - AM	1341	1310	-0.6	56	0	336	362	-1.0	31	0	2402	2403	-1.7	9	0
Itaituba - PA	1478	1128	-5.2	0	1	199	300	4.2	0	1	2665	2069	-5.5	0	1
Macapá - AP	1656	1459	0.6	53	0	241	242	-0.2	87	0	2812	2560	0.4	67	0
Manaus - AM	1168	1188	0.4	71	0	273	336	2.6	1	1	2156	2280	1.6	12	0
Manicoré - AM	1343	1292	0.3	78	0	321	349	-1.1	26	0	2520	2538	-0.8	43	0
Parintins - AM	1304	1254	0.0	99	0	300	327	0.7	47	0	2346	2338	0.7	48	0
Rio Branco - AC	940	1053	-1.6	11	0	197	215	-0.6	55	0	1861	1974	-1.4	17	0
Santarém - PA	1259	1299	0.3	76	0	209	216	-0.2	85	0	2059	2104	0.1	95	0
S. G. da Cachoeira - AM	1134	1151	0.2	85	0	715	784	2.1	4	1	2908	2940	0.1	96	0
Soure - PA	2016	2321	2.6	1	1	171	167	0.0	97	0	2978	3340	2.2	3	1
Tefê - AM	1077	1078	-0.1	91	0	490	481	-0.4	70	0	2365	2404	-0.8	42	0
Whole Region	1290	1238	-1.9	6	0	429	441	1.1	28	0	2562	2513	-0.7	49	0

h=1 indicates the means are statistically different

z statistic of difference, *p* probability that the two means are not different

area during the day and in the opposite direction during the night. The “forest-breeze” during the day causes low-level convergence and convection over the deforested area within and around large cities, thus, increasing the rainfall locally.

The rise in the temperature of the tropical forests in the latter half of the twentieth century found by Mahli and Wright (2004) may also have contributed to an increase in convective activity and consequently to a rise in precipita-

Table 6 Mann–Kendall *S* statistic

Station	Wet season			Dry season			Annual		
	<i>S</i>	<i>Z_c</i>	<i>h</i>	<i>S</i>	<i>Z_c</i>	<i>h</i>	<i>S</i>	<i>Z_c</i>	<i>h</i>
Barcelos-AM	716	3.27	1	96	0.43	0	506	2.36	1
Belém - PA	491	1.96	1	877	3.57	1	886	3.68	1
Benjamin Constant - AM	-283	-1.40	0	-280	-1.38	0	-302	-1.56	0
Coari - AM	-76	-0.33	0	337	1.45	0	199	0.91	0
Cruzeiro do Sul - AC	66	0.34	0	-424	-2.19	1	-180	-0.95	0
Fonte Boa - AM	-337	-1.57	0	-54	-0.25	0	-171	-0.83	0
Iauaretê - AM	-226	-1.01	0	-170	-0.76	0	-213	-0.95	0
Itacoatiara - AM	93	0.53	0	-1	0.00	0	159	0.96	0
Itaituba - PA	-989	-4.80	1	677	3.36	1	-1186	-6.01	1
Macapá - AP	-150	-1.28	0	35	0.30	0	-120	-1.06	0
Manaus - AM	163	0.67	0	497	1.95	1	420	1.65	1
Manicoré - AM	-203	-1.32	0	-89	-0.58	0	-129	-0.86	0
Parintins - AM	-54	-0.24	0	116	0.53	0	46	0.21	0
Rio Branco - AC	228	1.96	1	28	0.25	0	198	1.87	1
Santarém - PA	216	0.88	0	31	0.12	0	178	0.72	0
S. G. da Cachoeira - AM	55	0.21	0	485	1.97	1	98	0.39	0
Soure - PA	461	2.28	1	41	0.21	0	424	2.19	1
Tefê - AM	115	0.87	0	17	0.13	0	81	0.67	0
Whole Region	-361	-1.42	0	371	1.46	0	-47	-0.18	0

Z_c statistic and the test of hypothesis (*h*) of the linear trends given in Table 4; *h*=1 indicates that the trend is significant at 95% level of confidence

tion in the Amazon basin. Due to an increase in rainfall in the eastern and central parts of the Amazon basin, the moisture transport from the Atlantic to the western most parts of the basin is, perhaps, reduced causing a reduction in the rainfall there. This speculation can only be verified with calculations of moisture budget and hydrologic balance, for which long period wind and humidity data are needed.

As is concluded in Marengo (2004), the present study also shows a slight downward trend for the whole region considered (Fig. 4). Mixed upward and downward trends at individual stations make the interpretation difficult. However, the seasonal trends mostly follow the annual trends in rainfall at individual stations, and this shows that the datasets have certain internal consistency. As there are no records of the metadata of the stations, it is difficult to assess the impact of the changes in measurement techniques on the trend analyses.

One of the merits of the present study lies in the fact that rain gauge data at 18 stations for a period of nearly 80 years are used to analyze the trends and the whole dataset is from direct observations.

Acknowledgements The first author is supported by the “Amazonas Senior Fellowship” from FAPEAM in the period July 2007 through June 2008. The authors are grateful to David Adams for critically going through the manuscript and the Instituto Nacional de Meteorologia for providing the datasets used in this study.

References

- Artaxo P, Oliveira PH, Lara LL, Pauliquevis TM, Rizzo LV, Pires Junior C, Paixão MA (2006) Efeitos climáticos de partículas de aerossóis biogênicos e emitidos em queimadas na Amazônia. (Climatic effects of biogenic aerosols emitted in Amazon forest fires). *Revista Brasileira de Meteorologia* 21:168–222
- Chen, T. C., E. S. Takle, J. H. Yoon, K. J. Croix, and P. Hsieh, 2003: Impacts on South America rainfall due to changes in global circulation. In: proceedings of the *7th International Conference on Southern Hemisphere Meteorology and Oceanography*. Amer. Meteorol. Soc., Boston, USA. p 92-93
- Correia FWS, Alvalá RCS, Manzi AO (2007) Modeling the impacts of land cover change in Amazônia: a regional climate model (RCM) simulation study. *Theor Appl Climatol*. doi:10.1007/s00704-007-0335-z
- Costa MH, Foley JA (2000) Combined effect of deforestation and doubled atmospheric CO₂ concentrations on the climate of Amazonia. *J Climate* 13:18–34
- Hollander M, Wolfe DA (1973) *Nonparametric statistical methods*. Wiley, Hoboken, p 503 ISBN 047140635x
- IPCC (2007) *Climate change 2007: The physical science basis, summary for policy makers*. IPCC, Geneva
- Li W, Fu R, Negrón Juárez RI, Fernandes K (2008) Observed change of the standardized precipitation index, its potential cause and applications to future climate change in the Amazon region. *Phil Trans Roy Soc B363*:1767–1772. doi:10.1098/rstb.2007.0022
- Mahli Y, Wright J (2004) Spatial patterns and recent trends in the climate of tropical rainforest regions. *Phil Trans Roy Soc B359*:311–329. doi:10.1098/rstb.2003.1433
- Marengo JA (2004) Interdecadal variability and trends of rainfall across the Amazon basin. *Theor Appl Climatol*. doi:10.1007/s00704-004-0045-8
- Oliveira GS, Nobre C, Costa MH, Satyamurty P, Soares Filho BS, Cardoso M (2007) Regional climate change over eastern Amazônia caused by pasture and soybean cropland expansion. *Geophys. Res. Lett.* 34:L17709. doi:10.1029/2007GL030612
- Partal T, Kahya E (2006) Trend analysis in Turkish precipitation data. *Hydrol Process* 20:2011–2026
- Satyamurty, P., C. A. Nobre, P. L. Silva Dias, 1998: Tropics - South America. In: D. J. Karoly; D. G. Vincent. (Org.). *Meteorology and Hydrology of the Southern Hemisphere*. Boston: Meteorology Monograph, v. 49, p. 119-139
- Sud YC, Chao W, Walker G (1993) Dependence of rainfall on vegetation: Theoretical considerations, simulation experiments, observations, and inferences from simulated atmospheric soundings. *J Arid Environ* 25:5–18
- Wilks DS (2006) *Statistical methods in the atmospheric sciences*, 2nd edn. Elsevier, Amsterdam, p 627
- Xu ZX, Takeuchi K, Ishidaira H (2003) Monotonic trend and step changes in Japanese precipitation. *J Hydrol* 279:144–150