ELSEVIER

Journal of Arid Environments 58 (2004) 575–596

Journal of Arid Environments

www.elsevier.com/locate/jnlabr/yjare

On climate variability in Northeast of Brazil

Vicente de Paulo Rodrigues da Silva*

Department of Atmospheric Sciences, Federal University of Campina Grande, Av. Aprígio Veloso, 882, Bodocongó, 58, Campina Grande, PB 109-970, Brazil

Received 25 February 2003; accepted 8 December 2003

Abstract

The time-series (annual period and dry- and wet-season) of eight climatic variables were analysed to ascertain the existence of climate variability in Northeast of Brazil. Results indicated generally increasing trends in most of these variables (statistically significant at $p < 0.01$ or < 0.05) by Mann–Kendall test. However, relative humidity and rainfall presented decreasing behavior. The study showed that most of the stations studied are going through a process of environmental dryness. The results also suggest that the historical trends may be related to climate variability in Northeast of Brazil, which affects both semi-arid and coastal part of the region.

Keywords: Reference evapo-transpiration; Class A pan evaporation; Rainfall,air temperature; Relative humidity; Aridity index; Trend

1. Introduction

Deforestation by cutting and burning, unsuitable use and soil degradation by man have reduced the quantity of water vapor that returns to the atmosphere by evapo-transpiration process (Silva et al., 1998). Anthropogenic interference in the environment is one of the greatest causes of the process of climatic change in several regions of the world. This complex phenomenon, which includes natural and human processes, depends on a multiplicity of factors and is an almost irreversible scenario (Nimer, 1988).

*Tel.: +55-83-310-1202; fax: +55-83-310-1202.
E-mail address: vicente@dca.ufcg.edu.br (V.P.R. da Silva).

0140-1963/$ - see front matter
doi:10.1016/j.jaridenv.2003.12.002

Climatic change results essentially from man's action on the ecosystems that degrade very quickly but recover very slowly and lose biodiversity. Climatic change strongly influences the process of desertification by its impact on the vegetation, soil and hydrological cycle (Pimenta et al., 1998). Currently, one of the great problems that affects humanity is the possibility of a global climate change with unpredictable consequences on natural resources, especially on the quality and quantity of potable water (OMM, 1992).

Among the direct effects of climate change are changes in temperature, rainfall and wind speed (Schwalm and Ek, 2001). However, climate variability and climate change have been researched recently based on the analysis of different climatic variables. The most common are: class A pan evaporation (Balling and Brazel, 1987; Cohen et al., 2002); the aridity index (Elagib and Abdu, 1997); and reference evapotranspiration (Hupet and Vanclooster, 2001; Kipkorir, 2002). Indeed, temperature and rainfall time-series are much used in climate variability analysis (see e.g. Elagib and Mansell, 2000; Lázaro et al., 2001; Moonen et al., 2002; Morrison et al., 2002; Velichko et al., 2002). Recently, the climatic scenario projection for the future has also encouraged several investigations (Sefton and Boorman, 1997; Arnell, 1999; Chang, 2002; Lasch et al., 2002; Tao et al., 2002).

The droughts that periodically affect Northeast of Brazil are phenomenona that cause great social, economic and environmental impacts. The population of this region does not live satisfactorily with the climatic instability, making the suffering from the drought a great problem in government policy. The main consequences of the droughts are related to low crop production and water supply to the urban centers and rural communities.

The atmosphere over Northeast of Brazil presents mean stability conditions that inhibit large-scale convective processes, caused by the descending branch of the Walker circulation cell. The permanent South Atlantic anticyclone induces a mean situation of atmospheric stability. The disturbances from the east create instability and rain. A possible mechanism for the occurrence of severe droughts over Northeast of Brazil is the establishment of a thermally direct local circulation which has its ascending branch at about 10°N and its descending branch over Northeast of Brazil and the adjoining oceanic region (Moura and Shukla, 1981). Some studies show that the sea-surface temperature anomalies of the Pacific and Atlantic oceans are associated with droughts in Northeast of Brazil (Moura and Shukla, 1981; Roucou et al., 1996).

Many investigators have studied climatic changes in various regions of the world including: United States (Balling and Brazel, 1987; Comrie and Broyles, 2002); Philippines (Jose et al., 1996); Bahrain (Elagib and Abdu, 1997); Europe (Arnell, 1999; Velichko et al., 2002); Kenya (Kipkorir, 2002); Arab Region (Abahussain et al., 2002); Taiwan (Chang, 2002; Yu et al., 2002); Israel (Cohen et al., 2002); and Italy (Moonen et al., 2002). On the other hand, Nimer (1988) and Silva et al. (1998) studied the problems of desertification and rainfall trends in Brazil, respectively. Thus, given the relevance of the climate change in the world, the present paper aimed to ascertain the occurrence of climatic variability in Northeast of Brazil, particularly in the semi-arid region.

2. Study area

2.1. Site description

Northeast of Brazil covers an area of about 1.5 million square kilometers. It is bounded to the north and east by the Atlantic Ocean (Fig. 1). The semi-arid part of this region corresponds to approximately 60% of the total area of Northeast of Brazil. This extensive area is inhabited by more than 30 million people and the economy is mainly based on subsistence rain-fed crop production. Northeast of Brazil is strongly affected by human actions and contains much semi-arid environment. This region is extremely vulnerable to climatic variations where the periodicity of the droughts especially affects subsistence agriculture (Pimenta et al., 1998). Therefore, the large variability in both inter-annual and spatial rainfall often leads to devastating suffering and occasional mass migration problems.

2.2. Climate, soil and vegetation

Northeast of Brazil suffers the influence of several large-scale precipitation mechanisms because of its large area and location, including most importantly: intertropical convergence zone, upper air cyclonic vortex and cold fronts (Roucou et al., 1996). This region is characterized by low rainfall levels and high evaporation rates. At the same time, in semi-arid zones the rainfall is highly variable in space and time. The low rainfall indexes registered in the north-eastern, especially in the semi-arid region, have considerably damaged the local economy. Although it rains as much as in many other areas of the world, this semi-arid region is periodically

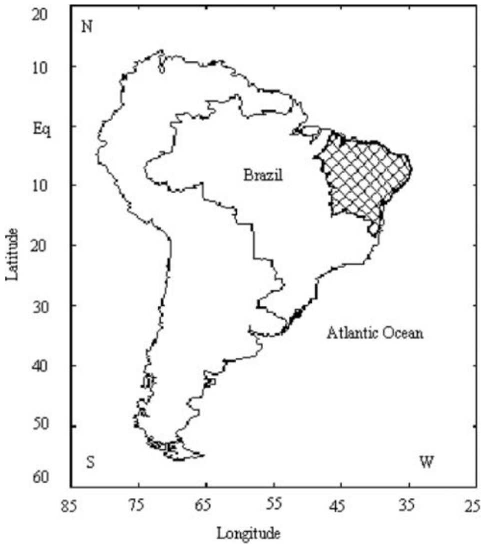

Fig. 1. Map of South America. Northeast of Brazil is represented by the striped area.

affected by drought, with partial or total loss in agriculture, which also damages water supply to the population. The high evaporative demand of this region produces evaporation rates that can surpass 10 mm day^{-1}. The mean deviation of the rainfall compared to the climatological normal is greater than 25%. The climate on the coast of the region is hot and humid while in the semi-arid is hot and dry.

The wet-season in Northeast of Brazil is generally between January and June and the dry-season between July and December (Table 1). The rainy season is centered upon March, April and May. The normal annual rainfall ranges from 1800 mm on the coast to less than 400 mm in the center of the NEB (Table 5). Annual average temperature varies between 20.7°C (Guaramiranga) and 27.4°C (Apodi), while the

Table 1
Weather station and period of record of the maximum air temperature (T_{max}), minimum air temperature (T_{min}), mean air temperature (T_{mean}), relative humidity (R_h), class A pan evaporation (E_p), reference evapo-transpiration (ET_o), aridity index (A_i) and rainfall in Northeast Brazil

Station	Latitude (°S)	Longitude (°W)	Altitude (M)	Period of record	Dry-season	Wet-season
(a) T_{max}, T_{min}, T_{mean}, R_h, E_p, ET_o and A_i						
Fortaleza	03°44′	38°32′	26	1961–1990	Jun/Nov	Dec/May
Sobral	03°42′	40°21′	75	1961–1990	Jul/Dec	Jan/Jun
Guaramiranga	04°17′	39°00′	872	1961–1997	Jul/Dec	Jan/Jun
Crateus	05°11′	40°40′	275	1964–1993	Jul/Dec	Jan/Jun
Quixeramobim	05°12′	39°18′	187	1961–1991	Jul/Dec	Jan/Jun
Apodi	05°40′	37°48′	305	1964–1993	Jul/Dec	Jan/Jun
Tauá	06°01′	40°26′	356	1964–1993	Jul/Dec	Jan/Jun
Florânia	06°07′	36°49′	210	1963–1993	Jul/Dec	Jan/Jun
São Gonçalo	05°20′	38°44′	120	1961–1990	Jul/Dec	Jan/Jun
Campos Sales	07°04′	40°23′	551	1964–1993	Jun/Nov	Dec/May
Picos	07°04′	41°28′	195	1966–1997	May/Oct	Nov/Apr
João Pessoa	07°07′	34°53′	5	1961–1997	Sep/ Feb	Mar/ Aug
Campina Grande	07°13′	35°52′	508	1961–1990	Aug/Jan	Feb/ Jul
Triunfo	07°50′	38°07′	1010	1961–1990	Jun/Nov	Dec/May
Surubim	07°50′	35°45′	380	1961–1995	Aug/Jan	Feb/ Jul
Monteiro	07°53′	37°07′	590	1964–1993	Jul/Dec	Jan–Jun
Recife	08°02′	34°53′	4	1962–1997	Sep/ Feb	Mar/ Aug
Floresta	08°36′	38°35′	317	1961–1990	May/Oct	Nov/Apr
Petrolina	09°23′	40°30′	376	1970–2001	May/Oct	Nov/Apr
(b) Rainfall						
Terezina	05°05′	41°24′	250	1913–1990	Jul/Dec	Jan/Jun
Quixeramobim	—	—	—	1911–1988	—	—
Tauá	—	—	—	1912–1990	—	—
Amarante	06°15′	42°51′	72	1911–1990	May/Oct	Nov/Apr
Catolé do Rocha	06°21′	37°45′	250	1911–1990	Jul/Dec	Jan/Jun
Campina Grande	—	—	—	1912–1990	—	—
Jaicos	07°22′	41°08′	255	1911–1990	May/Oct	Nov/Apr
Recife	—	—	—	1911–1990	—	—
Paulistana	08°05′	41°08′	375	1912–1990	May/Oct	Nov/Apr
S.R. Nonato	09°01′	42°41′	386	1910–1990	May/Oct	Nov/Apr
Petrolina	—	—	—	1911–1989	—	—
Mocambo	10°33′	37°38′	206	1912–1990	Sep/Feb	Mar/ Aug
Jacobina	11°10′	40°31′	460	1911–1990	May/Oct	Nov/Apr
Castro Alves	12°46′	39°25′	265	1915–1990	Jul/Dec	Jan/Jun

mean maximum temperature can reach up to 33.8°C (Apodi) and the mean minimum temperature 16.8°C (Triunfo) (Table 2).

Tropical thorn forest (caatinga) is the predominant vegetation type in the semi-arid part of Northeast of Brazil (for details see Tabarelli et al., 2003). The predominant soil is fairly diversified, formed mainly by lithosoils, regosoils, latosoil and sandy soils (Sampaio, 1995, pp. 35–63). In the semi-arid part of the region the ideal soil for agriculture is very shallow, varying from 40 to 60 cm in depth.

3. Materials and methods

This study analysed time-series (annual period and dry- and wet-season) of the maximum, minimum and mean daily air temperatures, relative air humidity, class A pan evaporation, reference evapo-transpiration and aridity index of 19 weather stations and the annual rainfall totals of 14 stations in Northeast of Brazil (Table 1). The other climatic variables were also analysed in five of these 14 stations (Quixeramobim, Tauá, Campina Grande, Recife and Petrolina). The monthly mean wind speed, at 2 m height, maximum and minimum air temperature, relative humidity and sunshine hours were used to obtain the reference evapo-transpiration and aridity index. Least-squares linear regression was used to evaluate increasing or decreasing slope of trends in the climate variables. It used data records length of 30 years or at most 37 years, except that the rainfall time-series was approximately 80 years. According to Stewart (1988), it is needed at least 30 years of climate data for an accurate analysis of climatic trends in tropical regions.

3.1. Aridity index

The monthly aridity index (A_i) of the stations studied was obtained according to the following expression (Allen et al., 1998):

$$A_i = \frac{(ET_o)_{obs}}{(ET_o)_{T_{dew}}} - 1, \quad (1)$$

where $(ET_o)_{obs}$ and $(ET_o)_{T_{dew}}$ referred to the reference evapo-transpiration obtained on the basis of the relative humidity and dew point temperature, respectively. For the same period, the minimum air temperature (T_{min}) was used as an estimate of the T_{dew}. This index is based on the supposition that air might not be saturated at T_{min} in arid and semi-arid regions, which, depending on the location, can be greater than the T_{dew}. The difference between T_{min} and T_{dew} can reach 2°C or 3°C (Allen et al., 1998). If this difference is small, A_i tends to zero, otherwise it assumes values different to zero. Thus, an A_i value greater than zero characterizes an environmental dryness trend and less than zero an environmental well-watered trend.

Table 2
Time-series of the climatic variables of the stations in Northeast of Brazil (annual period)[a]

Station	T_{max} (°C)			T_{min} (°C)			T_{mean} (°C)			R_h (%)			E_v (mm)			ET_o (mm)			A_i (adimensional)		
	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (% year^{-1})	σ	μ	Trend mm year^{-1}	σ	μ	Trend mm year^{-1}	σ	μ	Trend annual
Fortaleza	0.39	30.1	0.018*	0.40	23.6	0.025**	0.34	26.7	0.015*	2.90	78.7	0.06	19.8	123.2	0.29	0.33	4.66	0.003	0.04	0.04	0.001
Sobral	0.99	33.4	−0.010	0.85	22.3	0.041**	0.63	27.1	0.007	6.15	68.7	−0.08	18.9	057.2	1.45*	0.66	5.20	0.027**	0.06	0.01	0.002*
Guaramiranga	0.88	25.4	−0.014	0.73	17.8	0.057**	0.40	20.7	0.002	3.61	85.8	−0.12	43.1	152.8	2.51**	0.28	3.16	0.001	0.07	−0.08	0.001
Crateus	0.94	32.8	0.032**	0.71	21.6	0.019*	0.99	26.7	0.032**	6.04	61.8	−0.11	63.1	255.5	4.34**	0.54	5.68	0.014	0.07	0.09	0.002*
Quixeramobim	0.78	32.5	0.017*	0.45	22.7	0.009	0.66	26.8	0.030**	4.26	64.9	−0.04	46.2	173.8	1.36*	0.53	5.79	0.021*	0.05	0.11	0.001
Apodi	0.73	33.9	0.032**	0.55	22.8	0.026**	0.61	27.4	0.036**	3.65	66.9	−0.20*	32.6	186.5	0.80	0.43	5.56	0.028**	0.04	0.02	0.002*
Tauá	0.73	31.9	0.018*	0.77	21.3	0.044**	0.99	25.9	0.063**	6.56	61.3	−0.39*	55.4	215.8	2.23**	0.49	5.38	0.005	0.08	0.10	0.004**
Florânia	1.36	31.9	0.048**	0.74	21.1	0.050**	0.75	26.1	0.031**	3.72	64.2	−0.02	49.1	210.0	2.11**	0.48	5.75	−0.011	0.05	0.07	0.001
São Gonçalo	0.56	32.8	−0.012	0.55	21.1	0.049**	0.47	26.6	0.016*	3.89	61.1	−0.30**	39.4	186.2	2.91**	0.54	5.61	0.043**	0.05	0.06	0.005**
Campos Sales	0.97	30.8	0.001	0.71	20.0	0.015*	0.94	24.7	0.008	7.52	63.9	−0.26*	76.5	225.7	1.87*	0.53	5.72	0.004	0.08	0.07	0.004**
Picos	1.15	32.3	0.032**	3.65	20.7	0.027**	1.31	26.4	0.023*	7.46	68.7	−0.24*	45.7	134.2	0.06	0.56	4.69	0.001	0.06	0.01	0.002*
João Pessoa	0.33	29.2	0.016*	0.64	22.9	0.044**	0.47	26.2	0.023*	2.41	77.1	−0.13*	44.2	136.4	2.54**	0.44	4.24	0.018*	2.78	−0.47	0.005**
Campina Grande	0.67	27.7	0.057**	0.83	19.2	0.077**	0.48	22.6	0.048**	3.07	80.7	−0.28*	25.7	123.1	−0.46	0.31	3.95	0.032**	0.04	−0.08	0.003*
Triunfo	0.67	26.3	−0.012	0.34	16.8	0.008	0.47	21.1	0.007	3.48	73.1	−0.10	23.6	124.7	1.02*	0.26	4.17	0.005	0.04	−0.02	0.002*
Surubim	0.64	29.3	0.011	0.40	19.7	0.011	0.32	23.7	−0.005	2.91	75.4	0.09	25.5	151.3	−0.15	0.37	4.23	0.019*	0.04	−0.05	−0.002*
Monteiro	0.80	30.4	0.024*	0.61	18.1	0.049**	0.44	23.7	0.025**	3.81	68.9	−0.23*	22.9	197.9	0.39	0.35	4.70	0.022*	0.03	−0.04	0.003*
Recife	0.29	29.1	0.016*	0.54	21.9	0.029**	0.30	25.5	0.021*	1.04	79.6	−0.03	36.3	115.7	2.43**	0.18	4.21	0.005	0.02	−0.01	0.001
Floresta	1.08	32.8	−0.05**	0.46	20.6	0.034**	0.79	26.5	−0.012	4.17	61.8	−0.10	39.5	176.9	1.51*	0.36	5.16	−0.010	0.04	0.03	0.003*
Petrolina	0.94	31.9	0.033*	0.85	20.6	0.028**	0.89	26.2	−0.021	5.17	65.7	0.14*	20.1	225.5	−0.33	0.39	4.97	−0.008	0.04	0.03	−0.001

**Trends statistically significant at $p<0.01$.

*Trends statistically significant at $p<0.05$.

[a] See text.

3.2. Reference evapo-transpiration

The monthly reference evapo-transpiration, based on the relative humidity—$(ET_o)_{obs}$ and on the dew point temperature—$(ET_o)_{dew}$, were obtained by Penman–Monteith approach. Thus, considering a hypothetical reference crop height 0.12 m, a fixed surface resistance of $70\,s\,m^{-1}$ and albedo of 23%, ET_o is given by the equation (Allen et al., 1994)

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\big(900U_2/T + 273\big)(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \tag{2}$$

where ET_o is the reference crop evapo-transpiration ($mm\,day^{-1}$), Δ is the slope vapor pressure curve ($kPa\,^\circ C^{-1}$), R_n is the net radiation ($MJ\,m^{-2}\,day^{-1}$), G is the soil heat flux ($MJ\,m^{-2}\,day^{-1}$), T is the average temperature at 2 m height, γ is the psychrometric constant ($kPa\,^\circ C^{-1}$), U_2 is the wind speed measured at 2 m height ($m\,s^{-1}$) and $e_s - e_a$ is the vapor pressure deficit for measurement at 2 m height (kPa). According to Allen et al. (1998) as the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it may be ignored (i.e. $G \cong 0$). All the variables involved in Eq. (2) were calculated according to the procedure given by Allen et al. (1998). FAO (Food and Agriculture Organization) considers the Penman–Monteith method as standard to estimate the reference evapo-transpiration.

3.3. Trend detection

The Mann–Kendall method has been suggested by the World Meteorological Organization to assess the trend in environmental data time-series (Yu et al., 2002). This test consists of comparing each value of the time-series with the others remaining, always in sequential order. The number of times that the remaining terms are greater than that under analysis is counted. The statistic S is the sum of all the counting, given as follows:

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

where $\operatorname{sign}(x_i - x_j)$ is

$$\begin{aligned} &-1 \quad \text{for } x_i - x_j < 0,\\ &0 \quad \text{for } x_i - x_j = 0,\\ &1 \quad \text{for } x_i - x_j > 0. \end{aligned}$$

The statistic S tends to normality for large n, with mean and variance defined as follows:

$$E[S] = 0, \tag{4}$$

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

where n is the length of the times-series, t_p is the number of ties for the pth value and q is the number of tied values (i.e. equals values). The second term represents an adjustment for tied or censored data. The standardized test statistic Z is given by

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0. \end{cases} \tag{6}$$

The presence of a statistically significant trend is evaluated using the Z value. This statistic is used to test the null hypothesis such that no trend exists. A positive Z indicates an increasing trend in the time-series, while a negative Z indicates a decreasing trend. To test for either increasing or decreasing monotonic trend at p significance level, the null hypothesis is rejected if the absolute value of Z is greater than $Z_{1-p/2}$, where $Z_{1-p/2}$ is obtained from the standard normal cumulative distribution tables. In this work, the significance levels of $p = 0.01$ and 0.05 was applied, and the significant level (p-value) was obtained for each analysed time-series. It is also possible to obtain a non-parametric estimate for the magnitude of the slope of trend (Hirsch et al., 1982)

$$\beta = \mathrm{Median}\left[\frac{(X_j - X_i)}{(j-i)}\right] \quad \text{for all } i < j, \tag{7}$$

where is the slope between data points X_j and X_i, measured at times j and i, respectively.

4. Results and discussion

The standard deviation (σ), mean (μ) and trend of the maximum (T_{max}), minimum (T_{min}) and mean (T_{mean}) temperatures, relative humidity (R_{h}), class A pan evaporation (E_{p}), reference evapo-transpiration ($\mathrm{ET_o}$) and aridity index (A_{i}) are specified in Tables 2–4. Actually, Table 2 show the climate variables of the annual period, while Tables 3 and 4 refers to the climate variables of the dry- and wet-season, respectively.

The air temperature time-series of Northeast of Brazil for the three periods analysed presented an increasing trend (statistically significant at $p < 0.01$ or < 0.05) in practically all the stations studied. However, some stations showed a declining trend (Floresta, Sobral, Guaramiranga, São Gonçalo, Campos Sales, Petrolina and Triunfo). Campina Grande station presented the greatest increasing trend in air temperature in the three periods analysed (annual period and dry- and wet-season). All the air temperature time-series of this station presented a statistically significant

Table 3
Time-series of the climatic variables of the stations in Northeast of Brazil (dry-season)[a]

Station	T_{max} (°C)			T_{min} (°C)			T_{mean} (°C)			R_h (%)			E_v (mm)			ET_o (mm)			A_i (adimensional)		
	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (% year^{-1})	σ	μ	Trend (mm year^{-1})	σ	μ	Trend (mm year^{-1})	σ	μ	Trend annual
Fortaleza	0.45	30.1	0.030**	0.39	23.4	0.029**	0.34	26.5	0.024*	3.15	76.1	0.08	20.7	146.7	0.74	0.31	5.1	0.004	0.05	0.06	0.001
Sobral	0.88	34.9	−0.03**	0.95	22.3	0.032**	0.65	27.7	−0.009	5.37	60.6	−0.04	24.8	76.2	1.77*	0.91	6.0	0.044**	0.06	0.06	0.003*
Guaramiranga	0.93	26.1	−0.016*	0.77	17.4	0.059**	0.48	20.5	0.001	3.88	82.4	−0.12	49.4	203.2	2.22**	0.33	3.5	0.006	0.06	−0.08	0.001
Crateus	0.78	34.1	0.032**	0.89	21.8	0.029**	0.86	27.6	0.027**	4.36	49.7	−0.20*	57.5	347.2	4.82**	0.59	6.9	0.016*	0.08	0.19	0.002*
Quixeramobim	0.63	33.5	0.011	0.51	22.6	0.011	0.68	27.1	0.022*	4.41	56.8	0.067	53.6	232.3	1.23*	0.62	6.8	0.008	0.07	0.18	0.001
Apodi	0.89	34.4	−0.003	0.65	22.4	0.031**	0.67	27.4	0.017*	4.61	63.1	−0.05	32.4	219.7	0.30	0.38	5.8	0.009	0.04	0.02	0.001
Tauá	0.58	32.9	0.008	1.04	21.2	0.070*	1.06	26.5	0.079**	6.85	53.0	−0.61**	62.7	260.6	4.15**	0.63	6.2	0.009	0.09	0.16	0.005**
Florânia	1.42	32.5	0.056**	0.84	20.9	0.060**	0.92	26.2	0.046**	3.68	58.6	0.02	57.7	261.4	2.03**	0.52	6.5	−0.022*	0.05	0.12	0.001
São Gonçalo	0.54	33.8	−0.015*	0.68	20.9	0.057**	0.49	27.1	0.017*	3.71	53.7	−0.30**	44.8	231.5	2.79**	0.72	6.3	0.053**	0.06	0.11	0.006**
Campos Sales	0.91	31.5	0.009	0.85	19.7	0.026**	9.30	56.1	−0.46**	9.30	56.1	−0.46**	136.9	297.8	1.54*	0.84	6.4	0.009	0.11	0.12	0.004**
Picos	0.81	34.4	0.023*	0.85	20.8	0.036*	0.81	27.5	0.031*	5.02	50.6	−0.25*	48.9	270.1	−0.39	0.61	6.3	0.011	0.07	0.13	0.002*
João Pessoa	0.38	29.6	0.009	0.71	23.6	0.052**	0.52	26.7	0.025**	3.01	73.9	−0.10	46.0	158.3	2.71**	0.60	4.6	0.022*	0.17	0.09	0.001
Campina Grande	0.80	28.3	0.060**	0.980	18.9	0.092**	0.615	22.5	0.053**	3.568	77.9	−0.30**	19.7	143.6	−0.11	0.43	4.4	0.043**	0.05	−0.07	0.004**
Triunfo	0.94	26.9	0.067**	0.60	16.3	0.052**	0.89	21.2	0.079**	5.37	68.6	−0.33**	37.1	157.2	2.48**	0.44	4.5	0.028**	0.05	−0.01	0.004**
Surubim	0.72	29.9	0.012	0.64	19.6	0.001	0.43	23.8	−0.009	2.83	73.3	0.09	27.3	178.8	−0.24	0.43	4.7	0.020*	0.04	−0.04	−0.002*
Monteiro	0.59	30.9	0.002	0.74	17.5	0.054**	0.48	23.7	0.023*	4.12	65.1	−0.24*	26.2	234.0	0.49	0.42	5.1	0.022*	0.05	−0.03	0.004**
Recife	0.37	29.7	0.014	0.64	22.1	0.038**	0.37	26.0	0.024*	1.49	75.8	−0.04	52.1	144.9	2.89**	0.23	4.9	0.002	0.03	0.03	0.001
Floresta	0.89	31.4	−0.006	0.56	19.3	0.047**	0.65	25.1	0.024*	4.10	62.8	−0.22*	42.3	176.0	1.75*	0.44	4.8	−0.007	0.05	0.02	0.005**
Petrolina	0.80	31.4	0.050*	0.89	19.6	0.033**	0.95	25.4	−0.029**	6.11	63.8	0.13*	21.2	230.5	−0.49	0.44	4.9	−0.006	0.07	0.03	−0.002*

**Trends statistically significant at $p<0.01$.
*Trends statistically significant at $p<0.05$.
[a] See text.

Table 4
Time-series of the climatic variables of the stations in Northeast of Brazil (wet- station)[a]

Station	T_{max} (°C)			T_{min} (°C)			T_{mean} (°C)			R_h (%)			E_v (mm)			ET_o (mm)			A_i (adimensional)		
	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (°C year^{-1})	σ	μ	Trend (% year^{-1})	σ	μ	Trend (mm year^{-1})	σ	μ	Trend (mm year^{-1})	σ	μ	Trend annual
Fortaleza	0.46	30.2	0.010	0.47	23.9	0.023*	0.43	26.8	0.013	3.40	81.3	−0.03	25.4	101.5	0.22	0.44	4.30	0.008	0.05	0.01	0.002*
Sobral	1.08	32.0	−0.019*	0.85	22.4	0.037**	0.67	26.6	0.003	6.38	76.3	−0.09	17.2	39.1	1.07*	0.55	4.35	0.010	0.07	−0.03	0.001
Guaramiranga	0.79	24.7	−0.003	0.75	18.3	0.056**	0.33	20.7	0.005	3.55	88.9	−0.10	38.5	101.3	1.46*	0.29	2.82	−0.003	0.08	−0.08	−0.001*
Crateus	1.28	31.3	0.059**	0.72	21.5	−0.005	1.01	25.6	0.032**	7.36	73.4	−0.14*	61.1	151.3	2.16**	0.61	4.49	0.012	0.08	−0.01	0.002*
Quixeramobim	0.93	31.4	0.029**	0.49	22.7	0.005	0.72	26.3	0.036**	5.03	72.7	−0.14*	42.5	118.5	1.23*	0.59	4.76	0.038**	0.05	0.04	0.001
Apodi	1.08	33.2	0.051**	0.46	23.3	0.009	0.72	27.2	0.039**	5.06	71.8	−0.28*	37.1	139.5	1.17*	0.57	5.01	0.038**	0.04	0.02	0.002*
Tauá	1.07	30.8	0.037**	1.06	21.1	0.023*	1.06	25.2	0.045**	8.21	69.7	−0.20*	53.6	151.4	1.41*	0.62	4.55	0.001	0.10	0.03	0.002*
Florânia	1.42	31.3	0.068**	0.77	21.4	0.040**	0.77	25.8	0.035*	5.35	69.6	−0.07	52.7	157.6	2.58**	0.60	4.95	0.001	0.07	0.03	0.001
São Gonçalo	0.66	31.9	−0.006	0.50	21.3	0.040**	0.52	26.1	0.016*	4.93	68.3	−0.30**	42.1	140.5	3.07**	0.47	4.89	0.034**	0.05	0.02	0.004**
Campos Sales	1.14	30.2	0.040**	0.70	20.3	0.020*	0.97	24.4	0.031**	5.96	71.6	−0.34**	59.3	154.7	3.25**	0.61	5.03	0.014	0.08	0.02	0.005**
Picos	0.88	33.3	0.030**	0.60	22.5	0.033**	1.25	27.3	0.037**	6.77	65.6	−0.32**	40.5	152.8	1.69*	0.50	5.19	0.011	0.06	0.04	0.003*
João Pessoa	0.47	28.8	0.024*	0.66	22.1	0.038**	0.69	25.7	0.023*	2.92	80.0	−0.13*	26.8	109.8	1.99*	0.49	3.93	0.015*	5.55	−1.02	0.006**
Campina Grande	0.75	27.2	0.060**	0.82	19.4	0.068**	0.55	22.5	0.050**	2.82	83.4	−0.26*	14.6	89.7	0.12	0.25	3.51	0.021*	0.03	−0.09	0.003*
Triunfo	1.14	25.7	−0.09**	0.53	17.2	−0.036**	0.79	20.9	−0.062**	4.30	77.5	0.10	25.4	92.8	−1.12*	0.36	3.80	−0.017*	0.04	−0.04	0.001
Surubim	0.69	28.8	0.006	0.42	19.9	0.007	0.40	23.5	−0.004	3.40	77.7	0.13*	18.9	113.1	0.08	0.37	3.77	0.017*	0.05	−0.06	−0.002*
Monteiro	1.27	29.9	0.059**	0.68	18.7	0.047**	0.66	23.7	0.036**	4.29	72.8	−0.24*	33.1	158.4	1.02*	0.35	4.28	0.022*	0.03	−0.04	0.001
Recife	0.37	28.6	0.020*	0.38	21.9	0.011	0.33	25.0	0.019*	1.41	83.3	−0.04	25.5	87.4	1.99*	0.17	3.53	0.008	0.02	−0.05	0.001
Floresta	0.86	33.9	−0.05**	0.45	21.9	0.026**	0.62	27.5	−0.006	4.74	60.7	0.01	39.2	178.2	1.57*	0.36	5.49	−0.011	0.04	0.05	0.001
Petrolina	1.36	32.6	0.025*	1.04	21.7	0.023*	1.08	26.9	−0.008	4.88	67.2	0.11	22.6	222.7	−0.13	0.45	5.11	−0.003	0.05	0.02	0.001

**Trends statistically significant at $p<0.01$.
*Trends statistically significant at $p<0.05$.
[a] See text.

trend at $p<0.01$. However, the greatest was in the minimum air temperatures during the dry-season (Table 3), with a trend of 0.09°C year^{-1}. This trend corresponds to an increase of 2.7°C in the total period analysed (1961–1990) or to 14.28% of mean minimum temperature. Annual mean temperature trend was a little less (0.057°C year^{-1}) but it was still very strong (Table 2). The temperature increase corresponding to the total period was 1.71°C or 6.13% of annual mean temperature. The time behavior tendency is clearly shown in Fig. 2c. Jose et al. (1996) describe the impact of the climatic variability on the water resources in the Philippines, indicating

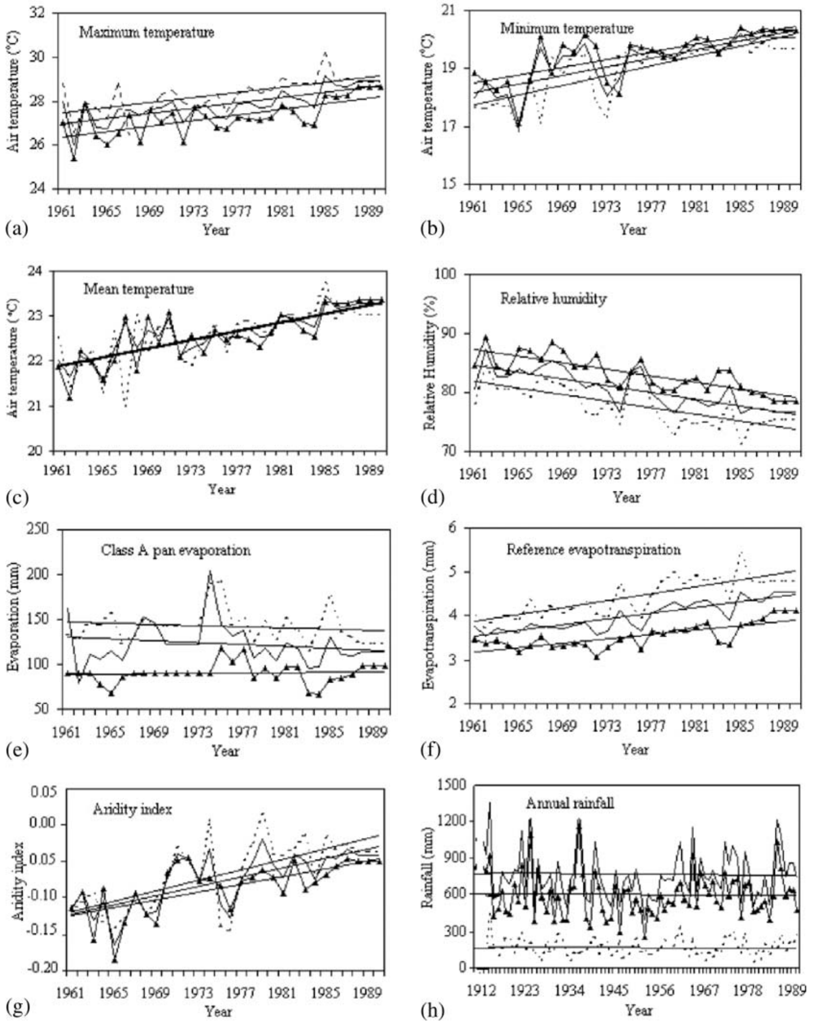

Fig. 2. Trends of the climatic variables to Campina Grande station. The continuous line indicates the mean annual trend, the dashed line indicates the mean trend of the dry-season and the line with triangles indicates the mean tendency of the wet-season.

an increasing trend in the time-series of the annual temperature anomalies of 0.18°C decade^{-1}. The widely accepted HadCM2 (coupled atmospheric–ocean general circulation model) predicts an increase between 2°C and 4°C trend in air temperature for Northeast of Brazil due to global warming for the second half of the 21st century (Azevedo, 1999). The analysis of data sets of the earth's surface temperature reveals an increase in the global mean temperature of about 0.5°C since the start of the 20th century (Koutsikopoulos et al., 1998).

The relative air humidity in Northeast of Brazil presented declining behavior in all the periods analysed and was generally statistically significant at $p<0.01$ or <0.05. However, contrary to most of the stations, there was increase in relative humidity in Petrolina station in the annual period and dry-season time-series (statistically significant at $p<0.05$). There was also an increase in relative humidity in the wet-season, but it was not statistically significant (Table 4). The increase in relative humidity in Petrolina station was accompanied by a reduction in class A pan evapo-transpiration, reference evapo-transpiration and aridity index. Fig. 4c show the decrease in the mean air temperature, while the Fig. 4h show the increase in the rainfall. The inverse behavior of the climatic variables in Petrolina station, compared with the other stations in Northeast of Brazil, is associated with the large expansion of the irrigated perimeter over middle reaches of San Francisco River Valley, where Petrolina is located. This region is the largest tropical fruit cultivation center in Brazil, where more than 100,000 ha are irrigated (Silva, 2000). The great quantity of water exposed to the atmosphere by the irrigation process has kept this region with moistened atmospheric air. This becomes more evident with the decreasing behavior of A_i (Fig 4g). During the period studied (1970–2001) the minimum air temperature came sufficiently close to the dew point temperature.

Most of the stations studied, A_I, presented an increasing trend, and many of them were statistically significant at $p<0.01$ or <0.05 (Tables 2–4). This result suggests that these stations are going through an environmental dryness process caused by the climate variability in the region. Elagib and Abdu (1997) observed that Lagn's index (P/T, where P is the annual rainfall and T the mean annual temperature) increased with the increase of rainfall in Bahrain.

The performance of the mean temperature and relative humidity is physically consistent in the stations studied. The increase in air temperature, over the period studied, was accompanied by reduced relative humidity. While the relative humidity decreased, the class A pan evaporation, reference evapo-transpiration and aridity index showed increasing trends in all the stations studied, except Petrolina. This is consistent since at low relative humidity the evaporative demand of atmospheric increases and, consequently, the variables under its influence are also increased. Balling and Brazel (1987) also found evidence for an increase in the local pan evaporation in all month of year, in Phoenix, Arizona. The decreasing trend in relative humidity in the dry-season was most accentuated in the Campos Sales station (Table 3). The decrease was 0.46% year^{-1} in the whole period studied (1964–1993).

The class A pan evaporation presented an increasing trend in most of the stations studied. The strongest trend of 4.82 mm year^{-1} was detected during the dry-season in

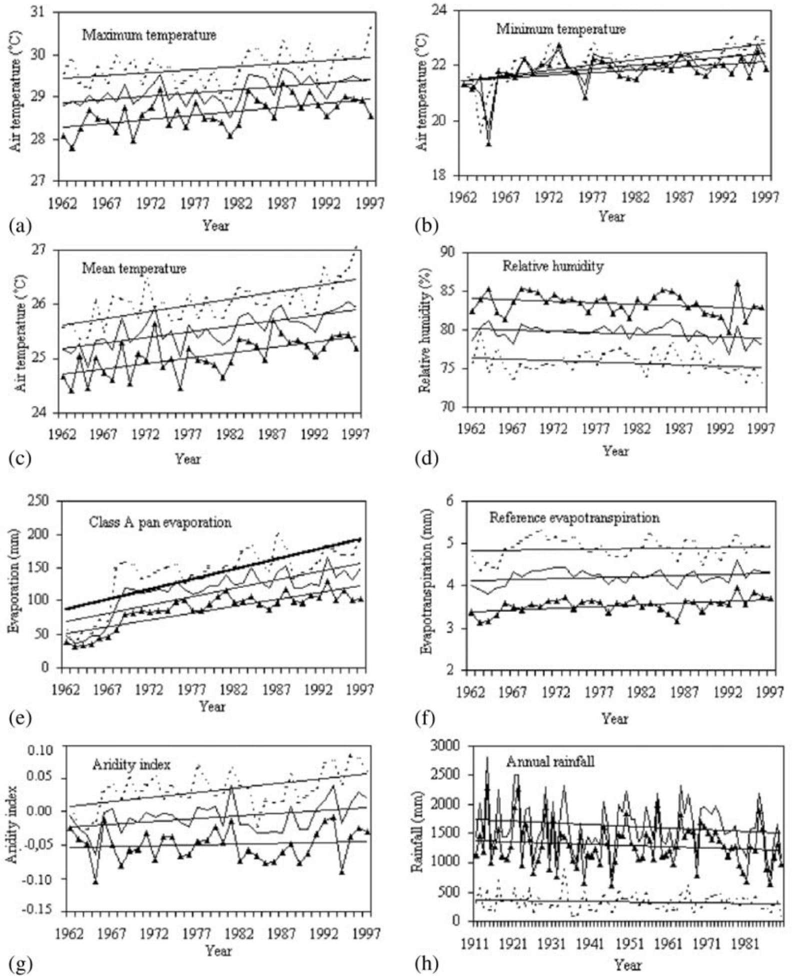

Fig. 3. Trends of the climatic variables to Recife station. The continuous line indicates the mean annual trend, the dashed line indicates the mean trend of the dry-season and the line with triangles indicates the mean tendency of the wet-season.

Crateús station (Table 3). This trend corresponded during the period analysed (1964–1993) to an increase of 144.6 mm or to 41.6% of climatological mean, that is 347.2 mm. This value is greater than that reported by Cohen et al. (2002) when they analysed climatic changes in Israel and detected a trend of 7% decade^{-1}. The results presented in this paper do not conflict with those by Cohen et al. (2002) because the evaporation rates in mean latitudes are, obviously, much lower than those detected in tropical regions. Furthermore, this paper shows that there is a strong increase in the evaporative demand in the region analysed. The mean annual total evaporation can surpass 3000 mm in the semi-arid of Northeast of Brazil (Silva, 2000) and in Israel it is 1683 mm (Cohen et al., 2002).

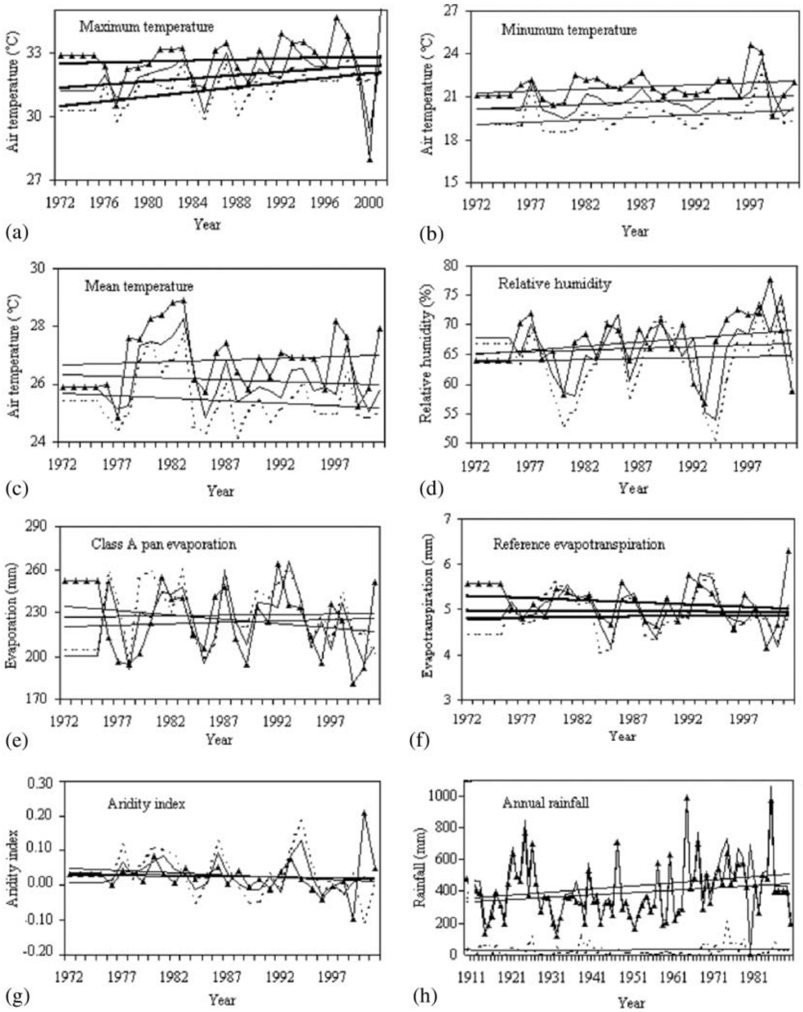

Fig. 4. Trends of the climatic variables to Petrolina station. The continuous line indicates the mean annual trend, the dashed line indicates the mean trend of the dry-season and the line with triangles indicates the mean tendency of the wet-season.

Northeast of Brazil also presented an increasing trend in reference evapotranspiration in nearly all the stations analysed. According to Allen et al. (1998), ET_o is a climatic variable and expresses the evaporation power of the atmosphere at a specific location and time of the year. Thus, the evaporative power of the air in the atmosphere in Northeast of Brazil is increasing, as a consequence of a climate variability in progress. The ET_o in São Gonçalo station presented an increasing trend in the annual period and the dry- and wet-season, which was statistically significant at $p < 0.01$. The trend was 0.053 mm year^{-1} in the dry-season (Table 3).

This value corresponds to an increase of 1.59 mm during the period studied or to 25.2% of the climatological mean. Cohen et al. (2002) reported that the measured annual pan evaporation increased at Bet Dagan, Israel; over the same period there was no significant change in the calculated open water evaporation and reference evapo-transpiration.

Table 5 shows some statistical aspects of the rainfall in the Northeast of Brazil. The mean annual rainfall is over 1000 mm in the coastal stations (Terezina, Amarante and Recife) and in the south station (Jacobina). The annual rainfall totals of the semi-arid stations are less than 800 mm (Quixeramobim, Tauá, Campina Grande, Jaicos, S.R. Nonato, Petrolina, Mocambo and Paulistana), except in Catolé do Rocha and Castro Alves. The rainfall standard deviation in Northeast of Brazil is very high. Most of the rain is concentrated in the wet-season, and can reach 94% of the total (e.g. Paulistana station).

The time behavior of the annual rainfall totals in the stations analysed is generally decreasing, except in Quixeramobim, S.R. Nonato and Petrolina. The trends are statistically significant in few stations and are greatest in Recife, Jacobina and Castro Alves. Fig 3h show a decreasing trend of the annual rainfall in Recife station. The trend line is also drawn indicating an average increase of about 2.88 mm year^{-1} (Table 5). This trend corresponded to a decrease of 103.7 mm in the period studied (1911–1990) or to 6.4% of climatological mean. Kertész and Mika (1999) also detected a decreasing rainfall trend of 2.30 mm year^{-1} in Pécs, south-eastern Europe, statistically significant at $p<0.05$. On the other hand, according to Aragão (1986) the climate variability in the Northeast of Brazil is attributed to a large extent of the El

Table 5
Time-series of the annual totals of rainfall in Northeast of Brazil (annual, dry- and wet-season)[a]

Station	Annual			Dry-season			Wet-season		
	σ	μ	Trend (mm year^{-1})	σ	μ	Trend (mm year^{-1})	σ	μ	Trend (mm year^{-1})
Terezina	579.5	1299.7	−0.691	142.2	193.4	0.279	489.4	1106.4	−0.970
Quixeramobim	295.9	767.5	1.159	47.8	68.0	0.249	290.2	699.5	0.910
Tauá	230.2	624.9	−0.769	53.0	73.9	−0.237	228.9	551.0	−0.532
Amarante	640.7	1474.0	−1.215	143.1	188.4	−0.278	556.1	1285.6	−0.937
Catolé do Rocha	501.3	896.9	−0.682	61.8	66.8	0.257	476.0	830.1	−0.938
Campina Grande	230.2	772.7	−0.199	76.5	172.1	−0.096	208.4	600.6	−0.104
Jaicos	211.8	695.0	−0.393	37.6	54.2	−0.168	205.5	641.5	−0.223
Recife	486.0	1623.7	−2.881*	166.5	336.9	−0.866	401.1	1286.8	−2.014*
S.R. Nonato	191.5	691.0	0.279	58.9	63.1	−0.058	180.8	627.9	0.337
Petrolina	149.6	392.9	2.174*	32.4	33.0	0.088	145.3	360.0	2.073*
Mocambo	281.5	698.0	−1.911	112.0	194.1	−0.710	215.4	503.9	−1.201
Jacobina	313.1	1016.7	−3.979**	114.8	373.1	−2.313*	257.7	643.6	−1.666
Castro Alves	191.6	917.0	−3.803**	157.6	483.4	−1.791	140.2	521.1	−2.012*
Paulistana	173.4	604.8	−0.671	31.5	34.0	−0.056	172.5	570.8	−0.615

**Trends statistically significant at $p<0.01$.
*Trends statistically significant at $p<0.05$.
[a] See text.

Niño/southern oscillation (ENSO) phenomenon activities. The rainfall in Northeast of Brazil shows a cyclical trends of 13 and 26 years as a consequence of ENSO phenomenon, which causes droughts in Northeast and floods in South of Brazil (Kane and Souza, 1988; Silva, 1992).

The values of the statistics S, variance Var(S) and significance level (p-value) corresponding to the climatic variables trend analysed in this study were presented in the Tables 6–9. In some cases, the Var(S) has the same value once the time-series have same length and no tied values (i.e. equals values). The positive and negative values of the statistics S are indicators of increasing and decreasing trends, respectively. The increase of the p-value is a function of statistics S reduction and vice versa. As an example, for the annual period, the maximum temperature at Campos Sales station presented statistics $S = 5$ and $p = 0.9442$, while at Apodi station those values were $S = 210$ and $p = 0.0002$ (Table 6). According to Burn and Elnur (2002) the significance level indicates the trend's strength and the slope magnitude indicates the direction as well as magnitude of the trend. On the other hand, Yue et al. (2002) observed that the power of the Mann–Kendal test is an increasing function of the absolute slope of the trend and of the significance level for a given n. For significance levels $p < 0.10$, others time-series would present statistical significance, mainly in the dry-season (Table 7). Also, Table 9 shows that rainfall trend in Mocambo station, for annual ($p = 0.0588$) and dry-season ($p = 0.0784$) periods, is very close to the rejection region of the null hypothesis (i.e. there is a trend).

5. Summary and conclusions

This study investigated climatic variability in Northeast of Brazil based on maximum, minimum and mean air temperatures, relative air humidity, class A pan evaporation, reference evapo-transpiration, aridity index and rainfall. It emphasizes that the time-series of these climatic variables in Northeast of Brazil presented an increasing trend (statistically significant at $p < 0.01$ or < 0.05) for almost all stations. Moreover, the relative humidity and rainfall trend is inverse, that is, decreasing over time, also statistically significant in most stations. The time behavior pattern of the relative humidity is physically consistent with the behavior of the other climatic variables analysed. The decrease in the relative humidity is generally accompanied by reduced rainfall, while the temperature, evaporation, reference evapo-transpiration and aridity index have increased.

Unlike the other stations in Northeast of Brazil, Petrolina station manifested in an increase of the rainfall and relative humidity and at the same time decrease in the mean temperature, evaporation, evapo-transpiration and aridity index. This result suggests that in the last decades there has been a sharp increase in the air humidity content because of the expansion of the irrigated perimeter in São Francisco River Valley. Our study also showed that the annual and dry- and wet-season time-series of maximum and minimum temperatures presented an increasing trend.

Table 6

Summary of the statistic S, variance (Var (S)) and significance level (p-value) of the climatic variables (maximum, minimum and mean temperatures; relative humidity; class A pan evaporation; reference evapo-transpiration and aridity index) in Northeast of Brazil (annual period)[a]

Station	T_{max} (°C)			T_{min} (°C)			T_{mean} (°C)			R_h (%)			E_v (mm)			ET_o (mm)			A_i (adimensional)		
	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value
Fortaleza	129	3141	0.0226	167	3141	0.0030	118	3141	0.0444	65	3141	0.2542	29	3141	0.6242	19	3141	0.7490	17	3141	0.7794
Sobral	−13	3141	0.8336	170	3141	0.0026	27	3141	0.6242	−42	3141	0.4654	122	3141	0.0286	150	3141	0.0072	110	3141	0.0478
Guaramiranga	−66	5846	0.3844	250	5846	0.0012	58	5846	0.4594	−115	5846	0.1310	257	5846	0.0008	−28	5846	0.7040	132	5846	0.0836
Crateus	147	3141	0.0094	119	3141	0.0444	159	3141	0.0050	−42	3141	0.4472	178	3141	0.0016	49	3141	0.3954	112	3141	0.0478
Quixeramobim	121	3461	0.0424	60	3461	0.3174	172	3461	0.0036	−13	3461	0.8104	81	3461	0.1700	118	3461	0.0466	27	3461	0.6600
Apodi	210	3141	0.0002	197	3141	0.0004	219	3141	0.0002	−117	3141	0.0444	110	3141	0.0524	201	3141	0.0004	115	3141	0.0424
Tauá	118	3141	0.0376	159	3141	0.0050	155	3141	0.0062	−111	3141	0.0466	165	3141	0.0036	26	3141	0.6600	187	3141	0.0010
Florânia	163	3461	0.0060	154	3461	0.0094	155	3461	0.0088	−30	3461	0.6030	172	3461	0.0036	−44	3461	0.4472	40	3461	0.5092
São Gonçalo	−46	3141	0.4238	153	3141	0.0062	134	3141	0.0164	−216	3141	0.0002	195	3141	0.0004	200	3141	0.0004	185	3141	0.0004
Campos Sales	5	3141	0.9442	111	3141	0.0466	39	3141	0.4778	−114	3141	0.0444	117	3141	0.0444	43	3141	0.4354	188	3141	0.0008
Picos	173	3802	0.0054	180	3802	0.0038	126	3802	0.0384	−152	3802	0.0132	103	3802	0.0930	66	3802	0.2938	126	3802	0.0434
João Pessoa	178	5846	0.0208	244	5846	0.0016	180	5846	0.0192	−167	5846	0.0286	241	5846	0.0018	161	5846	0.0366	249	5846	0.0012
Campina Grande	193	3141	0.0006	201	3141	0.0004	187	3141	0.0018	−139	3141	0.0128	−56	3141	0.3124	189	3141	0.0008	130	3141	0.0214
Triunfo	−47	3141	0.4122	45	3141	0.4122	24	3141	0.6600	−46	3141	0.4238	109	3141	0.0500	8	3141	0.8728	140	3141	0.0120
Surubim	60	4958	0.4066	72	4958	0.3174	−81	4958	0.2460	109	4958	0.1260	−1	4958	0.9840	176	4958	0.0132	−164	4958	0.0208
Monteiro	113	3141	0.0466	155	3141	0.0062	160	3141	0.0046	−109	3141	0.0500	28	3141	0.6312	116	3141	0.0404	135	3141	0.0168
Recife	153	5390	0.0384	270	5390	0.0004	156	5390	0.0348	−119	5390	0.1032	222	5390	0.0026	86	5390	0.2502	90	5390	0.2262
Floresta	−191	3141	0.0006	155	3141	0.0054	−9	3141	0.8886	−91	3141	0.1096	112	3141	0.0444	−19	3141	0.7490	129	3141	0.0204
Petrolina	156	3802	0.0120	166	3802	0.0076	−24	3802	0.6892	129	3802	0.0384	−13	3802	0.8494	17	3802	0.9803	−64	3802	0.3078

[a] See text.

Table 7
Summary of the statistic S, variance (Var (S)) and significance level (p-value) of the climatic variables (maximum, minimum and mean temperatures; relative humidity; class A pan evaporation; reference evapo-transpiration and aridity index) in Northeast of Brazil (dry-season)[a]

Station	T_{max} (°C)			T_{min} (°C)			T_{mean} (°C)			R_h (%)			E_v (mm)			ET_o (mm)			A_i (adimensional)		
	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value
Fortaleza	162	3141	0.0042	185	3141	0.0008	139	3141	0.0138	50	3141	0.3844	101	3141	0.0750	27	3141	0.6456	51	3141	0.3734
Sobral	−158	3141	0.0052	165	3141	0.0436	−10	3141	0.8728	−44	3141	0.4472	108	3141	0.0574	154	3141	0.0064	114	3141	0.0444
Guaramiranga	−168	5846	0.0292	219	5846	0.0044	24	5846	0.7642	−108	5846	0.1646	202	5846	0.0090	36	5846	0.6528	54	5846	0.4902
Crateus	164	3141	0.0038	168	3141	0.0030	163	3141	0.0038	−115	3141	0.0424	179	3141	0.0016	123	3141	0.0300	131	3141	0.0208
Quixeramobim	10	3461	0.8808	60	3461	0.3174	129	3461	0.0300	74	3461	0.2040	147	3461	0.0132	29	3461	0.6384	29	3461	0.6384
Apodi	−61	3141	0.2846	185	3141	0.0010	138	3141	0.0150	−104	3141	0.0672	102	3141	0.0718	98	3141	0.0836	108	3141	0.0574
Tauá	38	3141	0.5092	124	3141	0.0286	151	3141	0.0076	−155	3141	0.0062	154	3141	0.0064	21	3141	0.7264	169	3141	0.0028
Florânia	159	3461	0.0074	167	3461	0.0066	155	3461	0.0090	32	3461	0.6030	175	3461	0.0032	−166	3461	0.0052	15	3461	0.9818
São Gonçalo	−134	3141	0.0178	200	3141	0.0004	135	3141	0.0762	−216	3141	0.0020	203	3141	0.0004	189	3141	0.0008	203	3141	0.0004
Campos Sales	24	3141	0.6818	158	3141	0.0052	−168	3141	0.0030	−163	3141	0.0038	122	3141	0.0316	21	3141	0.7264	196	3141	0.0006
Picos	129	3802	0.0384	128	3802	0.0404	126	3802	0.0434	−136	3802	0.0292	−117	3802	0.0602	80	3802	0.2006	136	3802	0.0292
João Pessoa	138	5846	0.0734	250	5846	0.0012	199	5846	0.0072	−93	5846	0.2302	281	5846	0.0004	208	5846	0.0070	104	5846	0.1802
Campina Grande	182	3141	0.0012	211	3141	0.0002	220	3141	0.0002	−182	3141	0.0012	−48	3141	0.4066	206	3141	0.0002	174	3141	0.0020
Triunfo	179	3141	0.0016	235	3141	0.0002	230	3141	0.0002	−150	3141	0.0080	190	3141	0.0008	158	3141	0.0052	206	3141	0.0002
Surubim	53	4958	0.4654	38	4958	0.6030	−116	4958	0.1032	131	4958	0.0658	−30	4958	0.6818	165	4958	0.0204	−155	4958	0.0292
Monteiro	4	3141	0.9602	159	3141	0.0050	125	3141	0.0272	−115	3141	0.0424	4	3141	0.9602	139	3141	0.0138	161	3141	0.0044
Recife	126	5390	0.0892	250	5390	0.0004	162	5390	0.0286	−80	5390	0.2846	240	5390	0.0012	38	5390	0.6170	104	5390	0.1616
Floresta	−8	3141	0.9044	173	3141	0.0022	124	3141	0.0286	−126	3141	0.0258	142	3141	0.0120	−31	3141	0.5962	173	3141	0.0022
Petrolina	151	3802	0.0150	185	3802	0.0028	−169	3802	0.0066	128	3802	0.0394	−15	3802	0.8180	−39	3802	0.5352	−153	3802	0.0138

[a] See text.

Table 8
Summary of the statistic S, variance (Var (S)) and significance level (p-value) of the climatic variables (maximum. minimum and mean temperatures; relative humidity; class A pan evaporation; reference evapo-transpiration and aridity index) in Northeast of Brazil (wet-season)[a]

Station	T_{max} (°C)			T_{min} (°C)			T_{mean} (°C)			R_h (%)			E_v (mm)			ET_o (mm)			A_i (adimensional)		
	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value
Fortaleza	64	3141	0.2628	129	3141	0.0226	58	3141	0.3124	−16	3141	0.7872	13	3141	0.8336	47	3141	0.4122	112	3141	0.0478
Sobral	−121	3141	0.0324	157	3141	0.0054	16	3141	0.7948	−21	3141	0.7188	123	3141	0.0292	60	3141	0.2938	20	3141	0.7338
Guaramiranga	−6	5846	0.9322	282	5846	0.0002	102	5846	0.1868	−107	5846	0.1676	179	5846	0.0204	−60	5846	0.4412	−188	5846	0.0146
Crateus	153	3141	0.0068	−34	3141	0.5552	146	3141	0.0096	−123	3141	0.0300	154	3141	0.0064	45	3141	0.4354	123	3141	0.0300
Quixeramobim	143	3461	0.0160	21	3461	0.7338	157	3461	0.0080	−122	3461	0.0404	131	3461	0.0272	173	3461	0.0036	67	3461	0.2628
Apodi	192	3141	0.0006	99	3141	0.0818	206	3141	0.0002	−128	3141	0.0238	135	3141	0.0168	212	3141	0.0020	131	3141	0.0208
Tauá	157	3141	0.0054	118	3141	0.0376	172	3141	0.0022	−133	3141	0.0188	143	3141	0.0114	9	3141	0.8886	125	3141	0.0272
Florânia	168	3461	0.0046	168	3461	0.0046	121	3461	0.0414	−41	3461	0.5028	158	3461	0.0076	20	3461	0.7490	64	3461	0.2846
São Gonçalo	−5	3141	0.9442	214	3141	0.0002	125	3141	0.0272	−153	3141	0.0068	199	3141	0.0004	207	3141	0.0002	251	3141	0.0002
Campos Sales	151	3141	0.0076	123	3141	0.0292	169	3141	0.0028	−171	3141	0.0024	158	3141	0.0052	44	3141	0.4472	184	3141	0.0012
Picos	168	3802	0.0070	199	3802	0.0014	171	3802	0.0060	−175	3802	0.0066	127	3802	0.0140	80	3802	0.2006	136	3802	0.0292
João Pessoa	159	5846	0.0394	279	5846	0.0002	179	5846	0.0204	−182	5846	0.0178	238	5846	0.0020	184	5846	0.0168	244	5846	0.0016
Campina Grande	145	3141	0.0076	181	3141	0.0014	211	3141	0.0002	−124	3141	0.0286	7	3141	0.9124	132	3141	0.0198	138	3141	0.0146
Triunfo	−184	3141	0.0012	−163	3141	0.0038	−183	3141	0.0012	56	3141	0.3270	−135	3141	0.0168	−118	3141	0.0366	8	3141	0.9044
Surubim	36	4958	0.6242	87	4958	0.2224	−35	4958	0.6312	157	4958	0.0272	20	4958	0.7872	148	4958	0.0376	−146	4958	0.0404
Monteiro	164	3141	0.0038	153	3141	0.0068	172	3141	0.0022	−141	3141	0.0128	134	3141	0.0178	118	3141	0.0376	62	3141	0.2802
Recife	164	5390	0.0264	142	5390	0.0548	167	5390	0.0238	−137	5390	0.0644	149	5390	0.0444	104	5390	0.1616	18	5390	0.2186
Floresta	−152	3141	0.0072	155	3141	0.0062	−28	3141	0.6312	37	3141	0.5222	129	3141	0.0226	−31	3141	0.5962	63	3141	0.2714
Petrolina	128	3802	0.0394	142	3802	0.0226	29	3802	0.6528	99	380 2	0.1118	−79	3802	0.2076	−99	3802	0.1142	67	3802	0.2846

[a] See text.

Table 9
Summary of statistic S, variance (Var (S)) and significance level (p-value) of the annual totals of rainfall in Northeast of Brazil (annual, dry- and wet-season)[a]

Station	Annual			Dry-season			Wet-season		
	S	Var (S)	p-value	S	Var (S)	p-value	S	Var (S)	p-value
Terezina	−70	53720	0.7466	74	53720	0.7466	−78	53720	0.7338
Quixeramobim	134	53720	0.5620	218	53720	0.3472	103	53720	0.6600
Tauá	−195	55800	0.4122	−221	55800	0.3524	−111	55800	0.6456
Amarante	−84	57933	0.7264	−32	57933	0.8966	−114	57933	0.6384
Catolé do Rocha	79	57933	0.7490	158	57933	0.5156	26	57933	0.9204
Campina Grande	99	55800	0.6818	−30	55800	0.8966	152	55800	0.6778
Jaicos	−215	57933	0.3734	−285	57933	0.2380	−163	57933	0.4966
Recife	−495	57933	0.0394	−205	57933	0.3954	−501	57933	0.0376
S.R. Nonato	28	60120	0.9124	−23	60120	0.9204	64	60120	0.8026
Petrolina	511	55800	0.0316	114	55800	0.6384	508	55800	0.0324
Mocambo	−446	55800	0.0588	−415	55800	0.0784	−341	55800	0.1498
Jacobina	−662	57933	0.0060	−503	57933	0.0366	−205	57933	0.3954
Castro Alves	−633	49716	0.0046	−411	49716	0.0672	−529	49716	0.0182
Paulistana	−185	55800	0.4354	−173	55800	0.4716	−145	55800	0.5418

[a] See text.

Campina Grande station presented the greatest increasing trend in air temperature (annual period and dry- and wet-season) among all the stations studied. All these time-series were shown to be statistically significant at $p<0.01$. The greatest was the dry-season minimum air temperature, with a trend of $0.09^{\circ}C\,year^{-1}$. This corresponds to an increase of 2.7°C within the period analysed or of 14.28% of mean minimum temperature. The mean annual temperature trend was slightly less, but still very strong ($0.057^{\circ}C\,year^{-1}$). The class A pan evaporation trend in Crateus station during the dry-season was $4.83\,mm\,year^{-1}$. Throughout the period analysed, this trend corresponded to an increase of 144.6 mm or 41.6% of climatological mean. The very large increase in E_p, during the period analysed, was attributed to the strong increase in the evaporative demand in the region.

In this study the most significant trends detected in the annual time-series, besides those shown above, were the following: (i) *maximum temperature*: Florânia ($0.048^{\circ}C\,year^{-1}$ or 4.5% of climatological mean); (ii) *minimum temperature*: Guaramiranga ($0.057^{\circ}C\,year^{-1}$ or 11.8% of climatological mean); (iii) *mean temperature*: Tauá ($0.063^{\circ}C\,year^{-1}$ or 7.3% of climatological mean); (iv) *relative humidity*: Tauá ($-0.39\%\,year^{-1}$ or 19.1% of climatological mean); (v) *class A pan evaporation*: São Gonçalo ($2.91\,mm\,year^{-1}$ or 1.6% of climatological mean); (vi) *reference evapo-transpiration*: São Gonçalo ($0.043\,mm\,year^{-1}$ or 22.9% of climatological mean); (vii) *aridity index*: João Pessoa ($0.005\,year^{-1}$ or 39.4% of climatological mean); and (viii) *rainfall*: Jacobina ($-3.97\,mm\,year^{-1}$ or 31.2% of climatological mean). All these trends are statistically significant at $p<0.01$.

This study showed climate variability in most of the stations studied. This variability affects not only the semi-arid region of Northeast of Brazil but also the coastal part of the region.

Acknowledgements

The data used to carry out this research were provided by the Instituto Nacional de Meteorologia (INMET). The author thanks Dr. Pedro Vieira de Azevedo, Dr. Bernardo Barbosa da Silva, Dr. Francisco de Assis Salviano de Sousa and Dr. Enilson Palmeira Cavalcanti for their valuable suggestions and support for this paper.

References

Abahussain, A.A., Abdu, A.S., Al-Zubari, W.K., El-Deen, N.A., Abdul-Raheem, M., 2002. Desertification in the Arab Region: analysis of current status and trends. Journal of Arid Environments 51, 521–545.

Allen, R.G., Smith, M., Pereira, L.S., Perrier, A., 1994. An update for the calculation of reference evapotranspiration. ICID Bulletin 43 (2), 35–92.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, 301.

Aragão, J.O.R., 1986., A general circulation model investigation of the atmospheric to El Niño. Ph.D. Thesis, University of Miami, Coral Gables, 144pp.

Arnell, N.W., 1999. The effect of climate change on hydrological regimes in Europe: a continental perspective. Global Environmental Change 9, 5–3023.

Azevedo, J.R.G., 1999. Water resources and global warming for the São Francisco River in Brazil. Ph.D. Thesis, University of Southampton, Southampton, 193pp.

Balling Jr., R.C., Brazel, S.W., 1987. The impact of rapid urbanization on pan evaporation in Phoenix, Arizona. Journal of Climatology 7, 593–597.

Burn, D.H., Elnur, M.A.H., 2002. Detections of hydrologic trend and variability. Journal of Hydrology 255, 107–122.

Chang, C.C., 2002. The potential impact of climate change on Taiwan's agriculture. Agricultural Economics 27, 51–64.

Cohen, S., Ianetz, A., Stanhill, G., 2002. Evaporative climate change at Bet Dagan, Israel, 1964–1998. Agricultural and Forest Meteorology 111, 83–91.

Comrie, A.C., Broyles, B., 2002. Variability and spatial modeling of fine-scale precipitation data for the Sonoran Desert of south-west Arizona. Journal of Arid Environments 50, 573–592.

Elagib, N.A., Abdu, A.S.A., 1997. Climate variability and aridity in Bahrain. Journal of Arid Environments 36, 405–419.

Elagib, N.A., Mansell, M.G., 2000. Recent trends and anomalies in mean seasonal and annual temperatures over Sudan. Journal of Arid Environments 45, 263–288.

Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resources Research 18, 107–121.

Hupet, F., Vanclooster, M., 2001. Effect of the sampling frequency of meteorological variables on the estimation of the reference evapotranspiration. Journal of Hydrology 243, 192–204.

Jose, A.M., Francisco, R.V., Cruz, N.A., 1996. A study on impact of climate variability/change on water resources in the Philippines. Chemosphere 33 (9), 1687–1704.

Kane, R.P., Souza, E.G., 1988. Power spectrum analysis of various annual rainfall series in the Eastern part Brazil. Revista Brasileira de Meteorologia 3, 257–267.

Kertész, Á., Mika, J., 1999. Aridification—climate change in South-Eastern Europe. Physics and Chemistry of the Earth 24 (10), 913–920.

Kipkorir, E.C., 2002. Analysis of rainfall climate on the Njemps flats, Baringo District, Kenya. Journal of Arid Environments 50, 445–458.

Koutsikopoulos, C., Beillois, P., Leroy, C., Taillefer, F., 1998. Temporal trends and spatial structures of the sea surface temperature in the Bay of Biscay. Oceanologica Acta 21, 335–344.
Lasch, P., Lindner, M., Erhard, M., Suckow, F., Wenzel, A., 2002. Regional impact assessment on forest structure and functions under climate change—the Brandenburg case study. Forest Ecology and Management 5909, 1–14.
Lázaro, R., Rodrigo, F.S., Gutiérrez, F.D., Puigdefábregas, J., 2001. Analysis of a 30-year rainfall recorde (1967–19997) in semi-arid SE Spain for implications on vegetation. Journal of Arid Environments 48, 373–395.
Moonen, A.C., Ercoli, L., Mariotti, M., Masoni, A., 2002. Climate change in Italy indicated by agrometeorological indices over 122 years. Agricultural and Forest Meteorology 111, 13–27.
Morrison, J., Quick, M.C., Foreman, M.G.G., 2002. Climate change in the Fraser River watershed: flow and temperature projections. Journal of Hydrology 263, 230–244.
Moura, A.D., Shukla, J., 1981. On the dynamics of droughts in North-East Brazil: observations, theory and numerical experiments with a general circulation model. Journal Atmospheric Science 38, 2653–2675.
Nimer, E., 1988. Desertificação: realidade ou mito. Revista Brasileira de Geografia 50 (1), 1–39.
OMM, 1992. Cambios climaticos, medio ambiente y desarrollo. Opiniones de dirigentes del mundo. Secretaria de la Organización Meteorológica Mundial, Ginebra (OMM, 772) 171pp.
Pimenta, M.T., Santos, M.J., Rodrigues, R., 1998. A Susceptibilidade à Desertificação. Revista Florestal 11 (1), 27–33.
Roucou, P., Aragão, J.O.R., Harzallah, A., Fontaine, B., Janicot, S., 1996. Vertical motion, changes related to north-east Brazil rainfall variability: a GCM simulation. International Journal of Climatology 16, 879–891.
Sampaio, E.V.S.B., 1995. Overview of the Brazilian Caatinga. In: Bullock, S.H., Mooney, H.A., Medina, E. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, Cambridge, MA, 450pp.
Schwalm, C.R., Ek, A.R., 2001. Climate change and site: relevant mechanisms and modeling techniques. Forest Ecology and Management 150, 241–257.
Sefton, C.E.M., Boorman, D.B., 1997. A regional investigation of climate change impacts on UK streamflows. Journal of Hydrology 195, 26–44.
Silva, V.P.R., 1992. Comportamento Estatístico de Séries Temporais de Pluviometria no Nordeste do Brasil. M.Sc. Thesis, Universidade Federal da Paraíba, Campina Grande, 81pp.
Silva, V.P.R., 2000. Estimativas das necessidades hídricas da mangueira. Ph.D. Thesis, Universidade Federal da Paraíba, Campina Grande, 129pp.
Silva, V.P.R., Correia, A.A., Coelho, M.S., 1998. Análise de tendência das séries de precipitação pluvial do Nordeste do Brasil. Revista Brasileira de Engenharia Agrícola e Ambiental 2 (1), 111–114.
Stewart, J.I., 1988. Response Farming in Rainfed Agriculture. WHARF Foundation Press, Davis, USA.
Tabarelli, M., Vicente, A., Barbosa, D.C.A., 2003. Variation of sees dispersal spectrum of woody plants across a rainfall in north-eastern Brazil. Journal of Arid Environments 53, 197–210.
Tao, F., Yokozawa, M., Hayashi, Y., Lin, E., 2002. Future climate change, the agricultural water cycle, and agricultural production in China. Agriculture, Ecosystems and Environment 1979, 1–13.
Velichko, A.A., Catto, N., Drenova, A.N., Klimanov, V.A., Kremenetski, K.V., 2002. Climate change in east Europe and Siberia at the late glacial–holocene transition. Quaternary International 91, 75–99.
Yu, P.S., Yang, T.C., Wu, C.K., 2002. Impact of climate change on water resources in southern Taiwan. Journal of Hydrology 260, 161–175.
Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. Journal of Hydrology 259, 254–271.