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Extreme temperature trends in the equatorial region of Brazil: Case study of the State of Ceará¹

Tendência das temperaturas extremas em região equatorial brasileira: estudo de caso do Estado do Ceará

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Abstract - Despite uncertainties as to the real causes, there is a large amount of evidence of climatic change on Earth. With the objective of investigating changes in extreme air temperatures, as well as the local effects of these changes, eight data sets, collected throughout the State of Ceará in Brazil, were analyzed. Four series of data were obtained from the semi-arid region, three from the coastal zone, and one from a mountainous region. To quantify the changes that occurred during the study period, variations in maximum and minimum temperatures were calculated in relation to the mean of each data series. The annual rates of temperature increase were estimated from the angular coefficients of the best-fit lines. The results showed that although there are differences in trends between stations, there was a systematic increase in the maximum and minimum temperature in the nineties, which was especially evident in the following decade. The highest rates of increase were recorded for the minimum temperatures (from 9.0 to 8.3 °C per century) for the stations at Guaramiranga and Crateús respectively. These data provide evidence for a greater retention of energy in the form of sensible heat during the night, possibly due to a more difficult energy exchange between the surface and the atmosphere.

Key words - Climatic changes. Global warming. Air temperature.

Resumo - Apesar das incertezas sobre as verdadeiras causas, há uma grande quantidade de evidências de mudanças climáticas na Terra. Com o objetivo de investigar as mudanças em temperaturas extremas do ar, bem como os efeitos locais das mudanças, oito conjuntos de dados coletados ao longo do Estado do Ceará, Brasil, foram analisados. Quatro série de dados foram obtidas a partir da região semi-árida, três da zona costeira e uma de uma região montanhosa. Para quantificar as mudanças que ocorreram durante o período do estudo, as variações nas temperaturas máximas e mínimas foram calculadas em relação à média de cada série. As taxas anuais de aumento de temperatura foram estimadas pelos coeficientes angulares das linhas de melhor ajuste. Os resultados mostraram que, embora haja diferenças nas tendências entre as estações, ocorreu um aumento sistemático da temperatura máxima e mínima, que foi especialmente evidente na década seguinte, dos anos 90. As maiores taxas de crescimento foram registradas para as temperaturas mínimas (de 9,0 a 8,3 °C por século) para as estações de Guaramiranga e Crateús, respectivamente. Estes dados fornecem evidências para a maior retenção de energia na forma de calor sensível durante a noite possivelmente devido a uma troca de energia mais difícil, entre a superfície e a atmosfera.

Palavras-chave - Mudanças climáticas. Aquecimento global. Temperatura atmosférica.

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Introduction

Since the start of the second half of the 20th century, meteorological observations have been registering systematic increases in the air temperatures, both at the global and regional scales (SILVA, 2004). Research studies conducted in different parts of the world (LEBASSI *et al.*, 2009; LINKOSALO *et al.*, 2009; WALTERS *et al.*, 2007) have identified that the increases in the minimum air temperatures are more significant than increases in the maximum air temperatures. The increases of air temperature occur in an asymmetric form, representing the effects of different global and regional agents (PITMAN; PERKINS, 2009) on the air temperature changes. The asymmetries of these changes have had significant impacts in many regions of the globe, while in other places no significant changes have been observed (BONSAL *et al.*, 2001; PRIETO *et al.*, 2004).

Anthropogenic action is being considered as the main reason for these changes (IPCC, 2007), both at the global (BALLESTER *et al.*, 2010; VOSE *et al.*, 2005) and regional (BROHAN *et al.*, 2006; LOBELL; BONFILS, 2008) scales. The best example of an anthropogenic effect on the local air temperature is the urban heat island effect, which has been investigated in different cities (KOLOKOTRONI; GIRIDHARAN, 2008; LOPES *et al.*, 2008; PEREIRA; MORAIS, 2007). Unfortunately, many uncertainties still exist regarding the real cause responsible for generating these climatic changes that have been registered in the last two decades (SPENCER, 2010).

The projections of these changes indicate that the increase in air temperatures will promote climate changes that could affect the planet significantly, especially in regions of extreme temperatures, with a greater impact on the tropical regions and the less developed countries (IPCC, 2007). These changes in temperatures will promote alterations in the distribution of precipitation (MARENGO *et al.*, 2009) and on the water availability (MARENGO; VALVERDE, 2007), which will have serious impacts for natural systems and human life (HOMAR *et al.*, 2010; PETERSON, 2003).

As an example, the document "Climate Change 2007: The Physical Science Basis" (IPCC, 2007) suggested that the semiarid regions of the globe could undergo desertification, thereby becoming unsuitable for human life. Researchers such as Marengo (2008) have commented that maximum air temperatures in the northeast region of Brazil have increased between 1.5 and 2.0 °C in the last 40 years. Just like all the tropical arid and semiarid regions of the globe, the Brazilian northeast naturally presents a high potential for evaporation due to the high solar energy availability. This natural condition, associated with the increase in sensible heat (air temperature) due to global warming, will result in a higher rate of lake evaporation as well as a higher

demand for water by the vegetation (increase in the evapotranspiration rates). In this scenario of extremely limited water resources, the sustainability of the regional development could be compromised unless, due to global warming, the depth of rainfall also increases. Based on these questions, this study focused on the investigation of the tendency of extreme air temperature changes (maximums and minimums) in three different climate areas of Ceará State, Brazil.

Material and methods

Region description

The studied area corresponds to the Ceará State (FIG. 1) in the semiarid region of the northeastern part of Brazil, which is characterized by a unimodal rainfall distribution with a high spatial and temporal variability. It exhibits an average potential evaporation rate of 2,527.6 mm year⁻¹ with an insolation of 2,776.4 hours year⁻¹ and an average global radiation of 23 MJ m⁻² day⁻¹.

The dominant climate of the region, which comprises 80% of the State's area, according to Koppen's classification is semiarid - BSw'h'; the remaining 20% is almost entirely classified as sub-humid climate (Aw') (coastal region). There are also small mountain regions where the climate is classified as Am (mountain climate) (TAB. 1).

Among the meteorological stations considered in this study, one is located in the city of Fortaleza, which has a population of 2.4 million people, and the other 7 stations are distributed in urban centers with populations of less than 40 thousand people. Although it is a metropolis, the city of Fortaleza was included in the study due to the fact that the station is situated in the Campus of the Universidade Federal do Ceará (area of 100 ha) in a place that has a great vegetated area without drastic alterations in its vicinities.

Data set

In order to identify changes in extreme air temperature monthly datasets (1961/2008) including absolute maximum and minimum temperatures measured two meters above the ground in eight meteorological stations throughout the Ceará State were employed. The data was provided by the 3rd INMET district and by the Universidade Federal do Ceará. The first part of the study was to investigate whether there were any missing data in the monthly time series. Any missing data in the data were filled by the value of the mode of the respective month. To investigate whether the extreme temperatures registered in the meteorological stations in the Ceará State are undergoing successive increases, as well as to quantify these increases, the annual increment of the maximum and minimum temperatures was determined in relation to the

Figure 1 - Studied area location

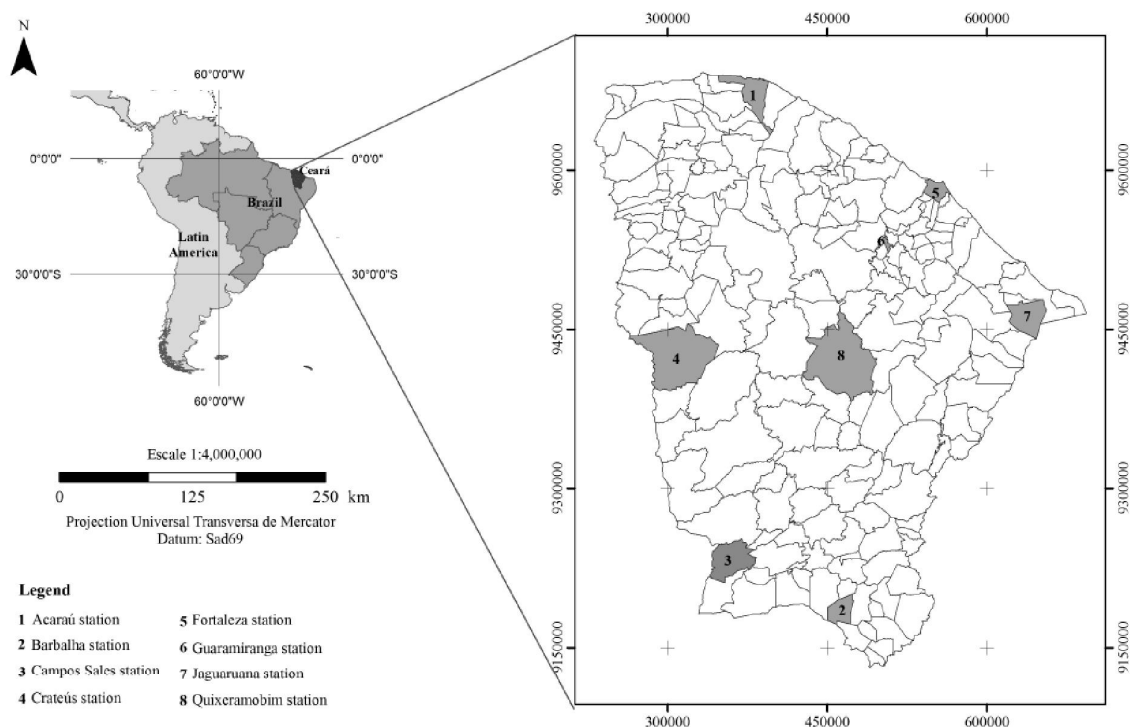


Table 1 - Identification of the meteorological stations

Stations	Regions	Latitude	Longitude	Altitude (m)	Climate
Cratêus	Arid land	05°10' S	40°40' W	297.00	BSw'h'
Quixeramobim	Arid land	05°10' S	39°17' W	179.50	BSw'h'
Barbalha	Arid land	07°19' S	39°18' W	409.00	BSw'h'
Campos Sales	Arid land	07°00' S	40°23' W	583.50	BSw'h'
Acaraú	Coastal	02°53' S	40°08' W	16.50	Aw'
Fortaleza	Coastal	03°45' S	38°33' W	19.53	Aw'
Jaguaruana	Coastal	04°47' S	37°46' W	11.70	Aw'
Guaramiranga	Mountain	04°17' S	39°00' W	871.00	Am

median in each series, as well as to the five-year moving average. To investigate the tendency of the extreme values and the year when they occurred, the five highest values (95th percentile) and the five lowest values (5th percentile) were considered for the three hottest months and the three coldest months recorded at each station. To quantify the increase in the rate of the extreme temperatures, of the best fit lines for the annual data were adjusted and parameter coefficients were tested at a 5% significant level.

Results and discussion

Table 2 shows some descriptive statistics for the maximum and minimum air temperature in the eight meteorological stations. Table 2 reflects a low variability (standard deviation and coefficient of variation) for all stations. The highest registered variability was for station Barbalha with coefficient of variation values above 10%, followed by Cratêus, Quixeramobim and Campos Sales stations, all located in the semiarid region.

Table 2 - Maximum, minimum, mean, SD (standard deviation) and CV (coefficient of variation) for the air temperature monthly datasets (1961/2008)

Stations	Maximum Air Temperature					Minimum Air Temperature				
	Max	Min	Mean	SD	CV	Max	Min	Mean	SD	CV
Cratéus	39.80	30.80	35.35	1.93	5.46	23.50	12.00	19.63	1.94	9.90
Quixeramobim	39.60	29.90	34.81	1.95	5.59	24.00	13.70	20.80	1.52	7.31
Barbalha	39.90	29.80	34.08	2.22	6.50	22.00	10.40	17.81	2.04	11.48
Campos Sales	39.90	28.50	33.37	1.99	5.97	21.40	10.80	17.73	1.78	10.04
Acaraú	37.10	30.20	33.51	1.19	3.57	23.00	15.10	20.71	1.22	5.55
Fortaleza	34.20	23.60	31.77	0.85	2.67	26.60	16.60	22.03	1.22	5.91
Jaguaruana	41.00	30.80	35.25	1.54	4.37	23.80	14.50	20.80	1.47	7.07
Guaramiranga	35.60	23.40	27.15	1.74	6.41	19.20	10.00	16.61	1.34	8.07

Fortaleza station showed the lowest variability among studied stations, and that fact can be explained by the place where the station is sited (Campus of the Universidade Federal do Ceará). In the Campus, there are a great vegetated area (> 100 ha) without drastic alterations.

Maximum air temperatures

The registered temperatures in the eight studied stations clearly indicate an increase in the maximum temperatures, regardless of the geographical position (coastal, semiarid land or mountain). After the year 1996, the maximum temperatures were all above the median dataset temperatures for almost stations, and the increments were positively increasing (FIG. 2). Although the city of Fortaleza has a population of 2.4 million that is 60 times larger than the populations of the other urban centers, the temperature trends is similar to the other stations.

The urban heat island effect, defended by Peterson (2003), with respect to the temperatures in large urban centers (populations greater than 100,000), was not observed at the station in the city of Fortaleza city. This result can be explained by the location of the aforementioned station, which is installed at the Campus of the Universidade Federal do Ceará, where there is a considerable amount of vegetated area and an absence of nearby buildings. The absence of the urban island effect at the CCA/UFC meteorological station was also identified by Lopes *et al.* (2008), when a comparative study between the temperatures of two meteorological stations in two different places of the city was conducted.

In the studied period, the extremes in the annual averages of the maximums air temperatures were registered in 1998 and in 2007 (FIG. 2), with the four highest increments occurring during the last ten years. The highest increases occurred in the Cratéus, Quixeramobim

and Campos Sales stations located in the BSw'h' climate region. The lowest increases were observed in the city of Guaramiranga, which is located in a region with a climate classified as Am. As for the stations located in Fortaleza, Acaraú and Jaguaruana, which are in the coastal region (sub-humid climate), the station in Acaraú registered the largest increases in temperature during the last decade.

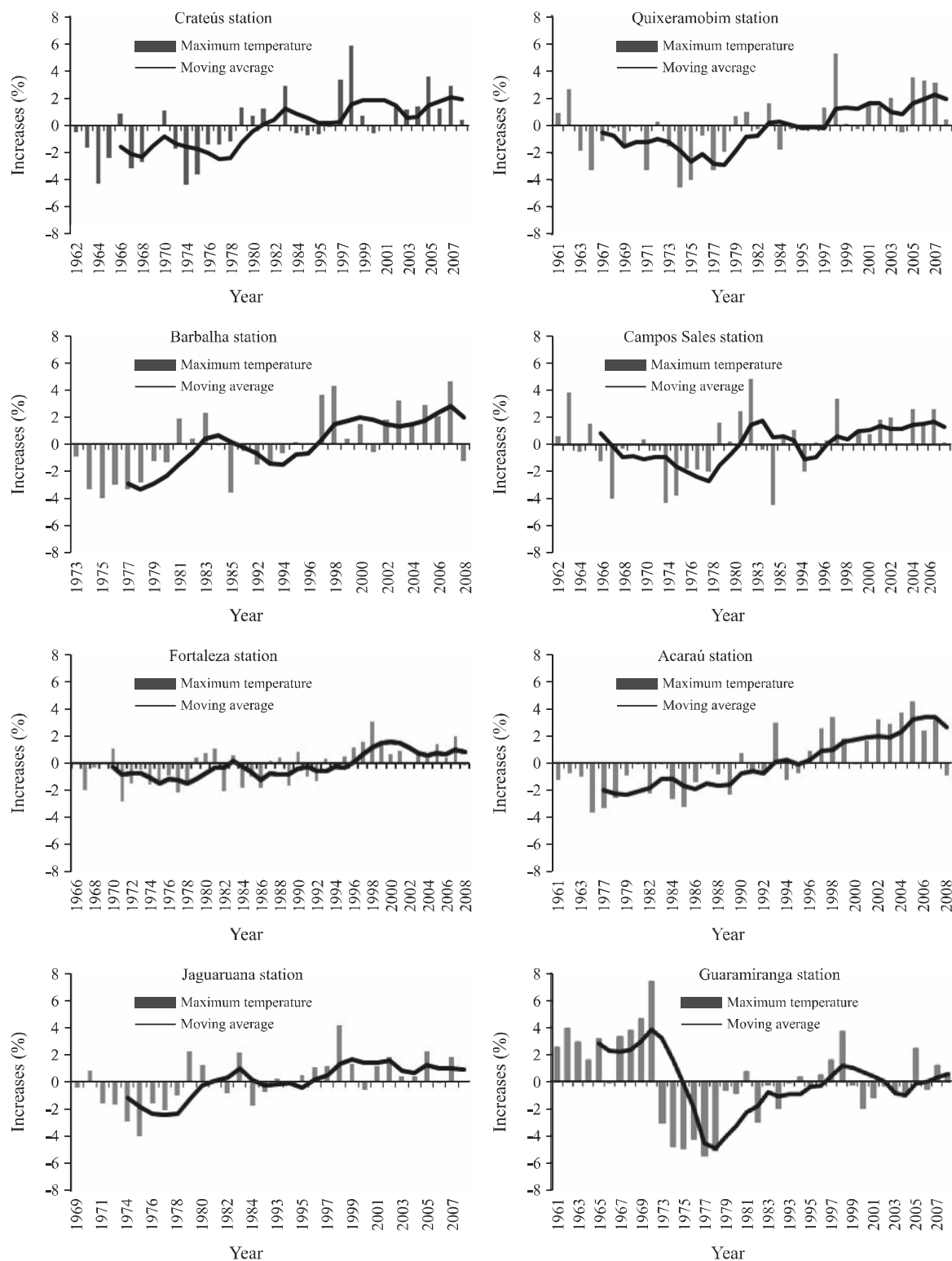
The tendency towards an increase in temperature, as well as the smaller variability of the increments, can be observed in the five-year moving average. A systematic increase in temperature was observed in all eight studied stations, representing a tendency of the climatic changes in the region. In studies regarding the maximum and minimum temperatures in southern Brazil for the period of 1961 to 2002, Marengo and Valverde (2007) also identified tendencies for the increases of these temperatures, illustrating a continued heating of the south region of Brazil.

The Acaraú station (coastal region) exhibited the highest tendency for a systematic increase in the annual average of the maximum temperatures (FIG. 2), while the highest variability for the tendency of increase was verified for the stations in Campos Sales (semiarid climate) and Guaramiranga (mountain climate). This fact express that temperature changes are independent of the climatic classification. Also, it was observed that all stations exhibited a tendency toward an increase in temperature after the decade of the 90s. This is in accordance with the IPCC (2007), which commented that the increase of 0.65 °C in the average temperature of the globe was more evident after the start of that decade.

Minimum air temperatures

Except for the temperatures registered in Fortaleza, the highest values for the minimum temperatures occurred in 1998 (FIG. 3), which characterizes that year as the

Figure 2 - Percentage of increase in the maximum temperatures in relation to the average and the five-year moving average for the temperatures of the studied stations



hottest year during the studied period. The same situation was observed for the maximum temperatures. Just as it did for the absolute maximums, the 90s decade exhibited absolute minimums above the normal average, and this tendency was confirmed in the 2000-2010 decade.

Among the four stations that represent the semiarid climate (Crateús, Quixeramobim, Campos Sales and Barbalha), the highest variations were observed for the station at Barbalha. Although the temperatures registered in the four stations may exhibit the same tendency, specific behaviors to each of them were observed. For example, there is a higher similarity among the registered temperatures in Quixeramobim and Campos Sales stations. The smallest variations in the annual average temperature ($< 5\%$) were identified in the station of Jaguaruana, while the station of Guaramiranga exhibited the most number of years (22 in total) with annual averages above the median of dataset. In the last two decades, many researchers (LEBASSI *et al.*, 2009; LOBELL; BONFILS, 2008; MARENGO; VALVERDE, 2007) have studied and discussed the influence of land use in the variations of air temperature.

With the exception of temperatures registered in the Fortaleza city, it was verified that after the year 1995, the annual minimum temperature averages were all above the average. This fact confirms what has been observed by other researchers in different parts of the globe (FERRON *et al.*, 2001; HOMAR *et al.*, 2010; KOLOKOTRONI; GIRIDHARAN, 2008).

The tendency toward systematic increases in the minimum temperatures can be confirmed by the five-year moving average (FIG. 3). In the last two decades, the moving average, with the exception of the minimum temperatures of Fortaleza, has been greater than the normal average for the minimum temperatures. The minimum temperatures of the Fortaleza station, although the population of the city is greater than 2.4 million people, do not point towards the urban heat island effect because there is no tendency towards a systematic increase in the minimum temperatures.

According to researchers such as Lebassi *et al.* (2009), Pereira and Moraes (2007) and Walters *et al.* (2007), the increase in the minimum temperatures of the great urban centers that generate the urban heat island effect is a result of the greater retention of heat during the night due to a higher difficulty in the exchange of this heat. It is believed that this effect still does not exist at the Fortaleza station due to its location, the Universidade Federal do Ceará Campus, where there is an organized occupation of the space near the station.

Air temperature change

The best fit lines for each station (FIG. 4) reveal a tendency towards an increase in the maximum and minimum temperatures at rates varying from 0.0005

to $0.0568\text{ }^{\circ}\text{C year}^{-1}$ for the maximums and from 0.018 to $0.0903\text{ }^{\circ}\text{C year}^{-1}$ for the minimums. Except to maximum temperatures registered in the Fortaleza station, all temperature rates were statically significant at a level of 5%.

Analysis of the three stations (Fortaleza, Acaraú, and Jaguaruana) representative of the coastal area revealed that the highest angular coefficients for maximum air temperatures were obtained for the station in Acaraú. The station in Fortaleza registered the lowest values (0.0005 and $0.0181\text{ }^{\circ}\text{C year}^{-1}$) of maximum and minimum temperatures rate increases, respectively. As for the stations located in the semiarid lands, the smallest rates of increase (0.0163 and $0.0604\text{ }^{\circ}\text{C year}^{-1}$) for the maximum and minimum air temperatures were registered in Campos Sales, respectively. The highest rates ($0.0813\text{ }^{\circ}\text{C year}^{-1}$) of maximum air temperature were obtained for the station in Crateús while the highest rates for minimum were identified in Barbalha station. These values confirm the high regional variability of the temperatures already observed in many different parts of the globe (HERTIG; JACOBET, 2008; HOMAR *et al.*, 2010; LEBASSI *et al.*, 2009).

In addition, it was found that the station representative of the mountain region (Guaramiranga) registered an increased rate in the absolute minimum temperature of $0.0903\text{ }^{\circ}\text{C year}^{-1}$, which corresponds to an increase of $9.0\text{ }^{\circ}\text{C}$ per century. Data such as these reveal an increase in the minimum temperatures that is greater than the increase in the maximum temperatures. Similar results were also observed by other researchers (JUNG *et al.*, 2002; LADOCHY *et al.*, 2007; VOSE *et al.*, 2005), showing that although there is a high regional variability in the increase of temperature, the same tendency of an increase is evident in different parts of the globe.

Another indicator of the detected increase in temperature is the fact that approximately 73% of the extreme observations (values greater than the 95th percentile) of the maximum temperatures were observed in the last two decades, with 50% of these occurring in the period of 2000-2008 (TAB. 3). It is also observable that 85% of the lowest values in the maximum temperatures were registered in the 1960s and 70s, revealing a gradual increase in the diurnal temperatures. The variation of air temperature is attributable to the expression of energy in the form of sensible heat present in the air.

The increase in the diurnal temperatures may indicate a change in the land use, where surfaces of higher albedo or lower emissivity are replaced by others that despite its higher capacities for absorption and emission, replace the latent heat flux by sensible heat flux. Another use of land that can also promote increases in air temperature is the removal or reduction of the vegetated

Figure 3 - Percentage of increase in the minimum temperatures in relation to the average and the five-year moving average of the temperatures in the studied stations

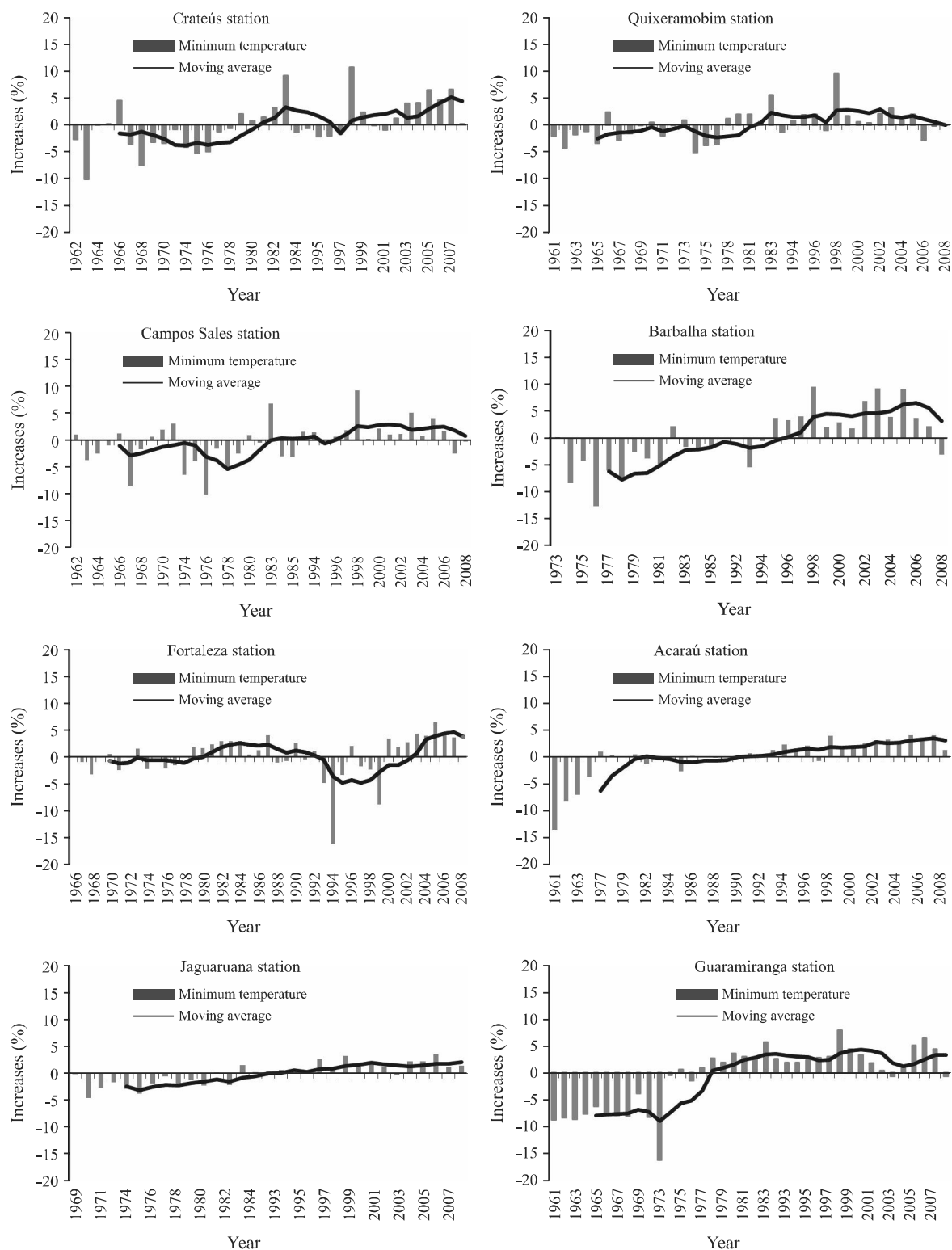


Figure 4 - Annual rates of maximum and minimum temperature increases for the investigated stations. * - statically significant at level of 5%

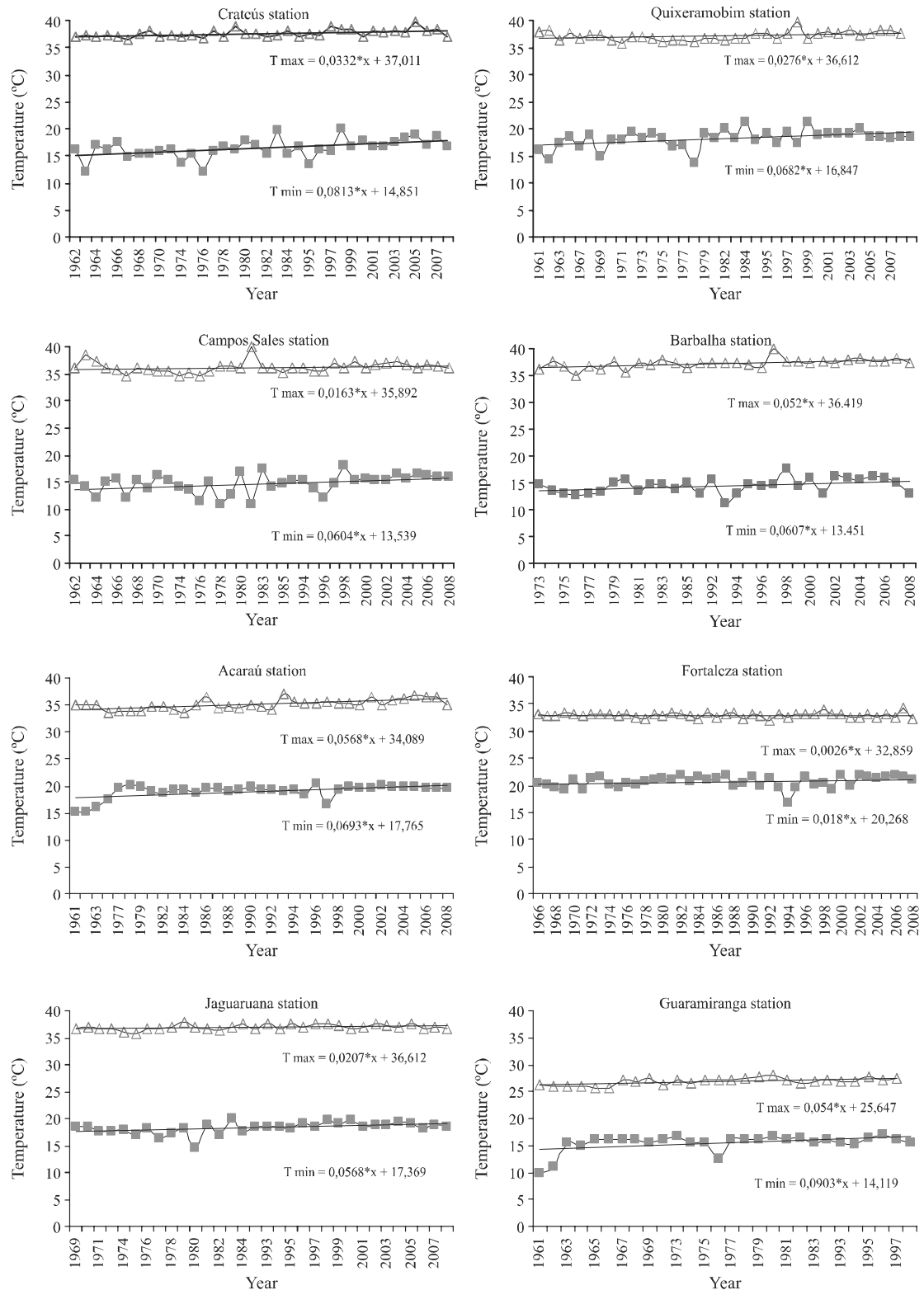


Table 3 - Register of the five biggest events present in the historical series of each investigated station with the respective year of occurrence

Stations	Maximum Temperatures				Minimum Temperatures			
	> Percentile 95%		< Percentile 5%		> Percentile 95%		< Percentile 5%	
Fortaleza	Year	Temp.	Year	Temp.	Year	Temp.	Year	Temp.
1	2007	34.2	1986	31.0	2005	23.9	1994	16.6
2	1985	33.4	1976	31.0	2005	23.0	1994	16.8
3	1976	33.2	1975	31.2	1983	22.8	1994	17.6
4	2003	33.0	1971	31.2	2004	22.8	1971	19.3
5	2004	33.0	1967	31.3	1983	22.7	1999	19.4
Acarauí								
1	2001	36.6	1976	32.3	1998	22.0	1963	17.7
2	2007	36.0	1976	32.6	2002	21.2	1995	18.4
3	2001	35.8	2008	32.7	1998	21.2	1985	18.6
4	2004	35.7	2000	32.7	2007	21.2	1982	18.8
5	2004	35.7	1991	32.7	1993	21.0	1988	18.9
Barbalha								
1	1997	38.5	1976	33.1	1998	19.6	1976	12.6
2	2004	38.1	1976	33.3	2000	19.1	1976	12.7
3	2007	38.1	1978	34.0	1997	18.7	2001	13.0
4	2003	38.0	1980	34.3	2003	18.7	2008	13.0
5	2001	37.7	1974	34.3	1995	18.3	1994	13.0
Campos Sales								
1	1963	38.4	1985	32.8	1998	18.8	1982	10.8
2	1963	38.0	1976	33.3	1998	18.6	1967	11.9
3	1963	37.4	1978	33.4	2003	18.4	1967	12.1
4	1999	37.2	1979	33.8	1964	18.1	1967	13.1
5	2003	37.2	1976	33.8	1964	18.0	1975	13.5
Cratéus								
1	2005	39.8	1970	35.2	1983	21.3	1995	13.5
2	1997	39.0	1974	35.3	1998	21.1	1974	13.8
3	1997	38.5	1963	35.7	1998	20.6	1967	14.8
4	1999	38.3	1976	35.9	2007	20.5	1967	14.9
5	2006	38.2	1967	35.9	1983	20.2	1975	15.3
Guaramiranga								
1	1963	31.2	1974	26.3	1998	17.4	1973	10.0
2	1963	31.0	1974	26.4	2006	17.3	1974	10.9
3	1993	31.0	1978	26.4	1998	17.2	1973	12.2
4	1968	30.6	1975	26.6	2006	17.1	1994	12.4
5	1969	30.5	1976	26.8	2006	17.1	1970	13.0
Jaguaruana								
1	1993	37.6	1969	34.7	1998	21.9	1974	10.9
2	2002	37.6	1974	34.8	2004	20.8	1962	11.2
3	1979	37.5	1974	34.9	2006	20.8	1973	12.2

Continuação Tabela 3

4	1997	37.5	1974	34.9	1995	20.7	1970	13.0
5	2003	37.4	1976	35.1	1983	20.5	1968	13.2
Quixeramobim								
1	1998	39.6	1969	35.3	1998	22.8	1977	13.7
2	2003	38.1	1963	35.3	1983	22.0	1961	16.2
3	2006	38.1	1974	35.3	1983	21.5	1974	16.6
4	1961	37.9	1978	35.4	1998	21.5	1965	16.8
5	2001	37.8	1971	35.4	2004	21.5	1975	17.0
Occurrence after 1990	73%				78%			
Occurrence after 2000	50%				40%			
Occurrence before 1980			85%				65%	

area, resulting in a decrease of the quantity of energy used as latent heat of evapotranspiration.

Similar tendencies have been observed in different parts of the globe (BONSAL *et al.*, 2001; LINKOSALO *et al.*, 2009; PITMAN; PERKINS, 2009). This change in the land use is pointed out by the document “Climate Change 2007: The Physical Science Basis” (IPCC, 2007) as the main reason for the increase in air temperature. As for the minimum air temperatures, approximately 78% of the values greater than the 95th percentile occurred in the last two decades, and around 38% of these were registered in the period of 2000-2008 (TAB. 3).

The investigation also showed that 65% of the minimum temperatures less than the value equivalent to the 5th percentile occurred in the 1960s and 70s. Because the minimum air temperatures occur due to the energy in transit from surface of the earth to the atmosphere in the form of sensible heat, the results point toward a reduction in these exchanges, consequently increasing the number of “hot” nights. Such a fact supports the notion that records of extreme air temperatures were initially for the minimums. The increase in the minimum temperatures on both global (BALLESTER *et al.*, 2010; VOSE *et al.*, 2005) and regional (BROHAN *et al.*, 2006; PRIETO *et al.*, 2004) scales has already been detected by several researchers.

Conclusions

1. The highest values for the maximum and minimum air temperatures for the studied area have been registered in the last 12 years. For the studied period, independent of the regional variations in temperatures, eight stations presented a common tendency in relation to annual rates of increase in the extreme temperatures. In other words, the

stations revealed an annual rate of increase in the minimum temperatures that is superior to that of the maximums, representing a higher retention of heat during the night;

2. The highest rates of increase per century were registered for the minimum temperatures, for the stations of Guaramiranga and Crateús.

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