NOTES AND CORRESPONDENCE

Surface Air Temperature Variations in the Amazon Region and Its Borders during This Century

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20 February 1996 and 11 July 1997

ABSTRACT

Monthly average surface air temperature records from 17 stations in the Brazilian Amazon from 1913 to 1995 were used to compute annual air temperature means. The data were converted into temperature anomalies, as the differences between annual mean temperatures and the mean temperature of a reference period (1958–85). By averaging the anomalies, an increasing trend of 0.56°C century^{-1} was observed, which is similar to the trend found for the Southern Hemisphere of 0.57°C century^{-1}. The results of two nonparametrical statistical tests showed that the trend became significant in the late 1960s to early 1970s.

1. Introduction

Present estimates of rising temperature from enhancement of the greenhouse effect suggest a global increase of approximately 0.5°C century^{-1} (Jones et al. 1986a; Jones et al. 1986b; Folland et al. 1990; Wigley and Barnett 1992; Jones 1994). According to some authors, natural processes alone, such as solar variability or volcanic eruptions cannot explain this increase (Wigley and Barnett 1992; Hulme and Jones 1994). Changes in land cover and land use may also lead to changes in the surface energy balance and, consequently, in air temperature. Using global circulation models, several simulations of deforestation in the Amazon Basin calculated potential increases in the air temperature ranging from 0.6° to 3.8°C, with an average of nine simulations of 1.7° ± 1.2°C (e.g., Lean and Warrilow 1989; Nobre et al. 1991). Therefore, while natural variability may show cycles of increasing trends, greenhouse gases and especially deforestation could also lead to an increase of the air temperature over the Amazon Basin.

Because the functioning of tropical ecosystems is sensitive to temperature variations, such temperature increases could have significant ecological consequences. Towsend et al. (1992) suggest that small changes in temperature may increase the already high rates of soil respiration found in the Tropics. Increases in the already rapid turnover rates of soil organic matter in tropical forest (Trumbore et al. 1995) could increase the CO_2 flux to the atmosphere, consequently forcing a positive feedback to the greenhouse effect. Grace et al. (1995) have recently shown that a patch of undisturbed rain forest located in Rondônia, in southwestern Amazonia, currently acts as a net absorber of carbon dioxide, but in modeling carbon accumulation over an entire year they showed a high sensitivity to changes in air temperature. Therefore, temperature changes may induce major changes in the regional carbon balance over a long-term period.

In this paper we analyze the surface air temperature data from 17 stations distributed over the Amazon re-

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gion and bordering areas. Trends in surface temperature records on a regional scale are useful for detecting differences and similarities in relation to larger-scale estimates, such as those made for the hemispheres (Jones et al. 1986a; Jones et al. 1986b; Hansen and Lebedeff 1987). These trends also provide evidence for spatial discontinuity in relation to global-scale estimates.

2. Database

One of the major difficulties in determining temperature variability over a large area is simply the lack of appropriate coverage by measuring stations (Jones et al. 1986a; Hansen and Lebedeff 1987). This is especially true in Brazil. In a comprehensive study on air temperature variations in the Northern and Southern Hemispheres, Jones et al. (1986a) and Jones et al. (1986b) were able to find only seven stations with suitable data for the entire country. More recently, Jones (1994) added several other stations in Brazil to update the estimates from the earlier works.

In this study three databases were used in order to achieve the best possible spatial coverage of the region: the National Institute of Meteorology of Brazil (INMET), the National Oceanic and Atmospheric Administration baseline quality controlled climatological datasets (BQCC), and the Global Historical Climatology Network Version 2 (GHCN) databases. Details about the GHCN and the BQCC datasets are available at the following Internet URLs: http://cdiac.esd.ornl.gov/ftp/ndp020rl/ and http://www.ncdc.noaa.gov/onlineprod/ghcmcdwmonth/form.html, respectively.

Monthly mean temperatures were used to derive annual mean temperatures. Annual means were not computed when there was more than 1 month missing in each year. Only stations with 20 yr or more of data and with no more than one interruption were included. Using these criteria 13 stations were discarded from the original INMET dataset, 24 stations from the BQCC, and 4 stations from the GHCN. To verify station homogeneity we used historical information about each station to check for possible changes and compared two to three neighboring stations using the method proposed by Jones et al. (1986a). Although Jones et al. (1986a) proposed that neighboring stations used to check for homogeneity should fall inside an area varying from 10^3 to 10^5 km^2, in our case the best possible grouping of stations was 1) São Gabriel da Cachoeira, Manaus, and Taperinha; 2) Taperinha, Belém, and São Luís; 3) Cruzeiro do Sul, Manaus, and São Gabriel da Cachoeira; 4) Cáceres, Góias, and Catalão; (5) Brasília, Cuiabá, and Cáceres e Catalão, and 6) Saint George, Saint Laurent, Nickerie, Belém, and Taperinha.

The stations of Conceição do Araguaia, Iquitos, Porto Velho, Pucalpa, Tafelberg, Tarapoto, Tumeremo, and Turiaçu were discarded due to uncorrectable inhomogeneities in the data (Jones et al. 1986c). The stations of Cuiabá, Góias, and São Luís showed major inhomogeneities that were corrected by applying the method proposed by Jones et al. (1986a). Effects of urbanization on the temperature data might be a problem in major cities such as Manaus, Belém, and São Luís. Indeed, Maitelli and Wright (1996), using 14 months of hourly data between 1991 and 1992, detected that air temperature measured in Manaus was higher than air temperature measured at a forest station located 60 km north from the city. However, when compared to neighboring stations located in much smaller towns (Taperinha and São Gabriel da Cachoeira), no signs of warming in the historical records, or inhomogeneities, were detected in the databases of these major cities.

At the end of this selection process, 12 stations from the INMET and 8 stations from BQCC and GHCN databases were considered suitable for further statistical analysis (Table 1, Fig. 1). All stations selected from BQCC were also present in INMET. However, records from INMET were longer and more complete than BQCC. The same was true for the three stations selected from GHCN that were also present in INMET. Therefore, a total of five new stations from GHCN were added to the 12 INMET stations to compose the data used in this study (Table 1). Strictly speaking, the stations of Brasília, Cáceres, Catalão, Cuiabá, Góias, Goiânia, and Santa Cruz de la Sierra are not in the Amazon region but rather on the border of the region and the Brazilian Central Plateau. Their inclusion in the estimates was based on this proximity. For the sake of simplicity, they were also referred to as being part of the Amazon region.

Most of the selected stations are situated in Brazil. For these stations, daily mean temperature records produced by INMET were used to calculate monthly mean temperatures and these averages were used to compose annual mean temperatures. Daily mean temperatures up to 1937 were calculated as

$$T = \frac{T_7 + T_{14} + 2T_{21}}{4}, \tag{1}$$

where T_7, T_{14}, and T_{21} are surface air temperatures measured at 0700, 1400, and 2100 local time, respectively. From 1938 on, the daily mean temperatures were estimated according to the following equation:

$$T = \frac{T_{12} + 2T_{24} + T_{\max} + T_{\min}}{5}, \tag{2}$$

where T_{12} and T_{24} are surface air temperatures measured at 1200 and 2400 UTC, respectively; and $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum temperatures. The daily average temperatures for the five stations selected from the GHCN database were calculated as the sum of the maximum and minimum temperatures divided by 2.

It is well known that mean daily temperature varies according to the time of observation (Baker 1975; Blackburn 1983; Karl et al. 1986); this can be a potential source of error in air temperature trends (Jones et al. 1986a). It is also important to recognize that, according

TABLE 1. Stations, location, and period covered by the dataset and interruptions in the records of air surface temperature measuring stations.

Station	Latitude	Longitude	BQCC	GHCN	INEMET	Interrup.
Belém[a]	01°27′S	48°29′W	1961–91	1949–91	1923–95*	No
Brasília[a]	15°47′S	47°55′W	1963–88	1963–87	1963–95*	No
Cáceres[a]	16°04′S	57°41′W			1913–95*	1966–69
Catalão[a]	18°10′S	47°57′W			1913–95*	1921
Cruzeiro do Sul[a]	07°38′S	72°36′W			1933–95*	1963–69
Cuiabá[a]	15°35′S	56°05′W	1910–91		1910–95*	No
Góias[a]	15°56′S	50°08′W			1913–85*	1937–46
Goiânia[a]	16°40′S	49°16′W	1961–86		1961–95*	No
Manaus[a]	03°08′S	60°01′W	1931–88		1918–95*	No
S. G. da Cachoeira[a]	00°08′S	67°05′W	1931–81	1931–79	1922–95*	No
São Luís[a]	02°31′S	44°16′W	1914–70		1911–95*	1959–69
Taperinha[a]	02°42′S	54°70′W	1975–92		1914–86*	No
St. George[b]	03°54′N	51°48′W		1961–80*		No
St. Laurent[b]	05°30′N	54°02′W		1961–80*		No
Nickerie[c]	05°38′N	57°03′W		1931–91*		1981
S. Fernando[d]	07°54′N	67°28′W		1951–76*		1973
Sta. Cruz de la Sierra[e]	17°48′S	63°10		1943–87*		1975–76

[a] Brazil; [b] French Guyana; [c] Suriname; [d] Venezuela; [e] Bolivia.

FIG. 1. Map of South America showing the location of the meteorological stations used for measurement of surface air temperature. The shaded area shown on the map represents the Amazon region.

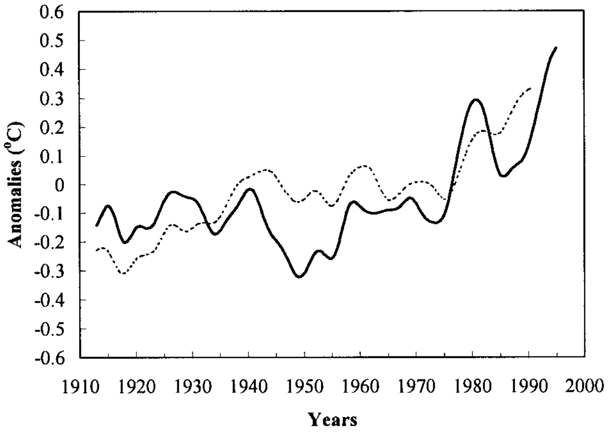

FIG. 2. Temporal trend in the air temperature anomalies. The solid line is a 10-term Gaussian filter of the temperature anomalies of the Amazon region. The dashed line is a 10-term Gaussian filter of the temperature anomalies of the Southern Hemisphere estimated by Jones et al. (1986b).

to Jones et al. (1986a), there are few countries in the world that have not changed their methods for calculating monthly mean temperatures, and the same authors concluded that it is virtually impossible to correct this problem. To estimate potential differences in the daily average temperatures calculated in Brazil by the two methods [Eqs. (1) and (2)], we tested the results of both equations for daily average temperatures using hourly temperature data from 1991 to 1993 obtained by the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS, Gash et al. 1996) in three different sites: Reserva Ducke (2°57′S; 59°57′W), located near the city of Manaus, Amazonas State; Fazenda Boa Sorte (5°45′S; 49°10′W), located near the city of Marabá, Pará State; and Reserva Jarú (10°05′S; 61°55′W), located in the Rondônia State.

Most of the time Eq. (2) yields daily average temperatures lower than the daily average temperatures estimated by Eq. (1). When Eq. (2) was used to obtain daily averages, the annual average temperatures were approximately 0.18°C lower. Therefore, since Eq. (2) produced cooler results than Eq. (1), the possibility of an artificial warming caused by changes in equations was eliminated. INMET stated that Eq. (2) was, among four others, the one that assured the best continuity in the temperature series (Serra 1960).

The results are presented as anomalies from a reference period (Jones et al. 1986a). The period from 1958 to 1985 was chosen because this period contains less missing data than the rest of the series (Jones and Hulme 1996). Average anomalies for the regions were obtained by interpolating annual temperature anomalies of each station using the Arc/Info Kriging method, which is a geostatistical procedure that generates an estimated surface from a scattered set of points based on the regionalized variable theory (Burrough 1986). The stations are clustered in two regions, 10 northern stations located at or near the equatorial zone and 7 southern stations located at subtropical latitudes (nonequatorial). The equatorial stations cover a larger area (approximately 2×10^6 km^2) than the nonequatorial stations (approximately 0.6×10^6 km^2) and between the two groups there is a void area. Interpolating both regions continuously would encompass this empty space, assuming it had the same trends in temperature anomalies as the monitored areas to the north (equatorial) and to the south (nonequatorial). To prevent this, annual temperature anomalies were considered as the area-weighted average between the annual anomalies of equatorial and nonequatorial regions, which were interpolated separately as suggested by Jones and Hulme (1996).

TABLE 2. Temperature anomalies trends (°C century^{-1}) for equatorial and nonequatorial stations using two different periods for regression analysis. Average is the arithmetical mean between equatorial and nonequatorial stations.

	1913–95	1937–95
Equatorial	+0.44°	+0.85°
Nonequatorial	+0.94°	+0.78°
Area-weighted average	+0.56°	+0.83°
Continuous interpolation	+0.49°	+0.71°

Two nonparametric statistical tests, the Mann–Kendall rank statistic (Sneyers 1975) and the Pettitt's change point test (Pettitt 1979), were used to detect the significance and to locate the approximate changing point of any potential trend in the anomalies. These tests have been widely used for this purpose (Goossens and Berger 1987; Sneyers et al. 1989; Demarée 1990; Demarée and Nicolis 1990; Cavadis 1992).

3. Results and discussion

The interpolation of annual temperature anomalies showed an increasing trend with time (Fig. 2).[1] A linear regression analysis from 1913 to 1995 yielded a trend of 0.56°C century^{-1} (Table 2). This trend is similar to the trend found by Jones (1994) for the entire Southern Hemisphere (0.57°C century^{-1}). As already mentioned, the 17 selected stations are spatially clustered into equatorial and nonequatorial stations. To check if the observed warming in the air temperature is spatially homogeneous, trends from 1913 to 1995 for each group were calculated separately. Overall, the equatorial stations had a lower trend than the nonequatorial stations (Table 2). This large difference between equatorial and nonequatorial trends may have a strong influence on the interpolation method to be used. In this study, following the recommendation of Jones and Hulmes (1996), annual temperature anomalies were considered as the area-weighted average between trends of the equatorial and

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[1] The dataset used in this study can be obtained upon request at the following e-mail address:zebu@cena.usp.br.

TABLE 3. Temperature anomalies trends (°C century^{-1}), years when the trends started to be significant (Mann–Kendall test), and years of changing points (Pettitt test) for different datasets. Period refers to the years used in the regression analysis in order to obtain the temperature trend.

Dataset	Period	Trend (°C century^{-1})	Significant (calendar year)	Changing point (calendar year)
INMET	1913–95	+0.56°	1976	1956
INMET	1937–95	+0.83°	1979	1968
BQCC	1937–91	+0.60°	1959	1956
GCHN	1943–91	+0.66°	1973	1964
Southern Hemisphere	1901–90	+0.57°	1932	1936

nonequatorial regions. Interpolating both regions continuously yields a trend of +0.49°C century^{-1}, which is approximately 13% smaller than averaging the two regions (Table 2).

To check for potential differences in the way daily average temperatures were calculated after 1937, which might induce an artificial average lowering of 0.18°C in the annual average, trends from 1937 to 1995 instead of 1918 to 1995 were also calculated (Table 2). The major difference was found for the equatorial stations, where the trend increased from 0.44°C century^{-1} for the 1913–95 regression analysis to 0.85°C century^{-1} for the regression analysis considering data after 1937. As the trends for equatorial and nonequatorial regions were similar, the two interpolation methods produced similar results. Averaging the equatorial and nonequatorial trends yielded a value of +0.83°C century^{-1}, while interpolating both regions continuously yielded a value of +0.71°C century^{-1}.

The dataset used in this study provides additional coverage to a relatively data-poor region of the world, by adding new records and by extending some series used previously. However, it is interesting to compare the trends found in this study with trends resulting from the exclusive use of the BQCC and GHCN databases. A total of eight suitable stations was found for each of these databases, with three coincident (Table 1). The trend for BQCC was estimated with data from 1937 to 1991, while the period from 1943 to 1991 was used for the GHCN dataset. The same reference period as that used for the INMET dataset was used (Table 3). Due to the small number of stations, it was not possible to split them into two groups, as done with the INMET dataset. The resulting trends for both datasets were similar but slightly higher than the one found with the INMET dataset using period from 1937 to 1995 in the regression analysis (Table 3).

The Mann–Kendall test showed that the trend for the INMET dataset becomes significant in the middle seventies. The Pettitt's test, on the other hand, points to a breaking point in 1956 (Table 3). The procedures of INMET were checked to ensure that no major modification in the measurements or stations was made in the 1950s that might have lead to an artificial inflection point in the temperature records. The only changes made were back in 1937, when the method to calculate daily average temperature was changed, as shown in Eqs. (1) and (2). To make sure that this did not induce an artificial increasing trend, the tests were applied on temperature anomalies after 1937. The results obtained were similar to those using the whole series, and the warming trend was confirmed. The same tests were applied for the BQCC and GHCN datasets. The warming trend was also confirmed in this case, although with variable significance (Table 3).

In conclusion, a warming trend was observed for the Amazon region. Although there is some variability in the data, it is reasonable to say that the change occurred in the middle of the 1960s and the warming trend started to be statistically significant in the 1970s. To compare the regional increasing trend in temperature anomalies with global-scale estimates, the same tests were applied for surface air temperature anomalies estimated for the entire Southern Hemisphere (Jones et al. 1986b). The Mann–Kendall test indicates a significant increasing trend in the early 1930s and Pettitt's test locates a change in 1936. Therefore, the warming of the South American hemisphere started to be significant three decades earlier than the warming of the Amazon (Table 3).

The major causes for increasing trends in surface air temperature are natural climate variability, enhancement of the greenhouse effect (Wigley and Raper 1990; Hulme and Jones 1994), and changes in land cover and use (Nobre et al. 1991). A conclusive relationship between warming trends and deforestation in Amazonia is difficult to establish with the data available. The period of temperature rise is, however, coincident with the beginning of major changes in land cover in the Brazilian Amazon (Skole and Tucker 1993).

Acknowledgments. We would like to thank P. D. Jones and two anonymous reviewers for comments and suggestions on the manuscript.

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