Is the data collection period of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia representative of long-term climatology?

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[1] The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) sampled surface-atmosphere flux exchanges and related ecohydrometeorological processes at several flux tower sites in the Amazonian region between 1999 and 2006. This extensive database is now being analyzed to investigate, for example, the carbon balance of the Amazon basin and the effect of land use change in the basin on climate. It is therefore important to establish whether the period during which these data were collected is representative of the long-term climatology for the region. This study analyzed long-term climate station data for stations located nearby the LBA eddy flux tower sites. Measurements taken during the period of data collection were compared with the long-term station climatology using the Kolmogorov-Smirnov test and analysis of histogram from random samples from the long-term climatological record. In terms of precipitation, the LBA data collection period is statistically consistent with the climatology for all LBA study sites. In terms of temperature, the same result is true for most flux station sites; the main exception being the Bananal Island site where the temperature during the LBA period is significantly warmer by about 1°C. There were some short periods when temperature in the region of other LBA flux sites was also statistically different (higher) during the LBA data collection period and an average but not statistically significant tendency toward higher temperatures across the whole region during the LBA period relative to previous years. This is probably because there has been significant land cover change near some of the LBA study sites, but a contribution from climate warming cannot be ruled out.

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1. Introduction

[2] The Large-Scale Biosphere Atmosphere Experiment in Amazonia (LBA) is a major Brazilian-lead project involving many scientists from South America, North America, and Europe that investigate the climate, ecology, hydrology, and biogeochemistry of the Amazon River basin and surrounding areas at both the local and continental scale. It addresses fundamental questions of international importance including whether Amazonia is a source or sink of carbon and whether land use changes in the Amazonia are affecting local, and perhaps global, climate. To investigate such questions requires knowledge of the exchanges of energy, water, carbon dioxide, and other chemicals between the land surface and the atmosphere above and, consequently, the experiment established study areas which were located across the Amazon region [*Avissar et al.*, 2002; *Keller et al.*, 2004; *LBA Science Planning Group*, 1996] where surface exchange fluxes and other corollary data were gathered for an extended period between 1999 and 2006.

[3] These data have already contributed understanding of surface flux exchanges and other significant components of the ecohydrometeorological system [e.g., *Costa and Foley*, 2000; *Houghton et al.*, 2000; *Huete et al.*, 2006; *Nepstad et al.*, 2001; *Ometto et al.*, 2005; *Richey et al.*, 2002; *Saleska et al.*, 2003; *Silva Dias et al.*, 2004; *Soares-Filho et al.*, 2006] and are increasingly being used to calibrate and validate models which will be used to describe and predict local, regional, and global phenomena. It is therefore important to place the period during which data were collected in the LBA Experiment in its proper context climatologically, specifically to address the question: Is the data collection period of the Large-Scale Biosphere-Atmosphere (LBA) Experiment in Amazonia representative of long-term climatology? This study addresses this question by identifying climate stations in the region of the several LBA study sites where long-term data on precipitation, temperature, or both were available, and compares the

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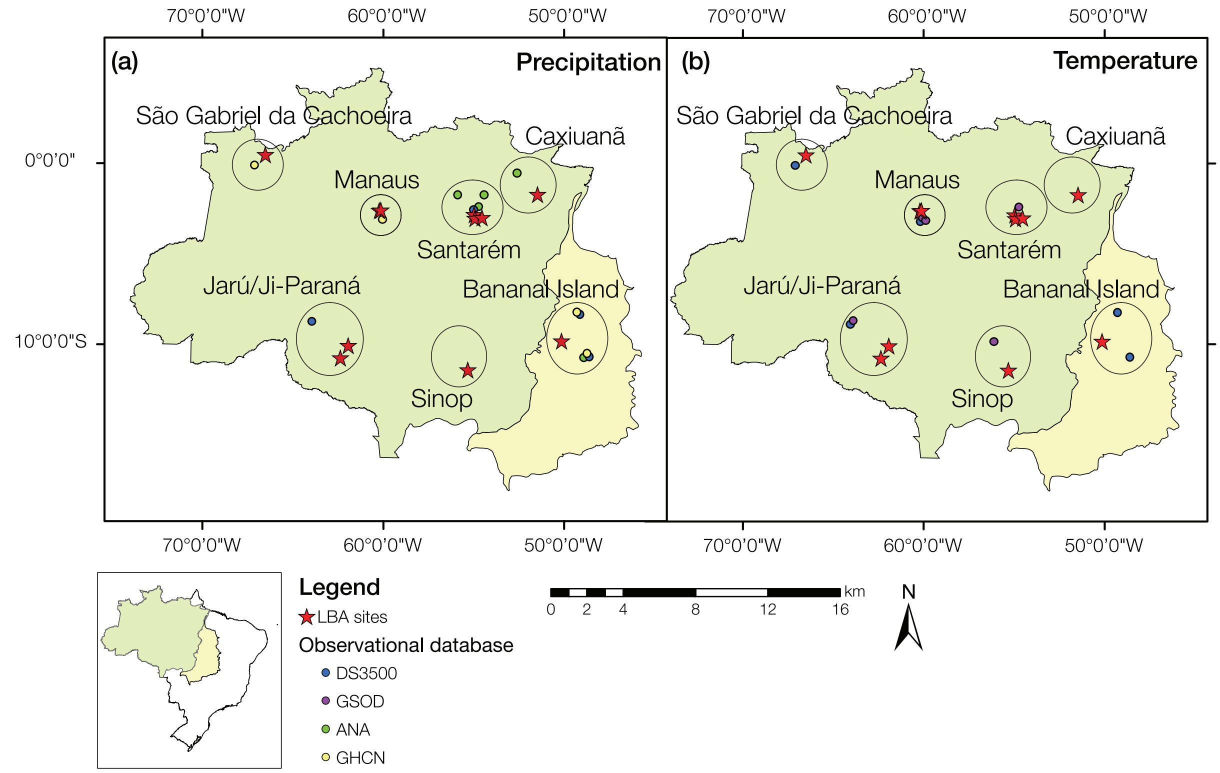

Figure 1. Location of the climate stations where data for (a) precipitation and (b) temperature were used in this study and their location relative to LBA study sites for which they are considered representative. LBA sites are shown as red stars surrounded by circles which represent one of the regions given in Table 1. Some regions (e.g., Manaus and Santarém) show overlapping site locations because of the resolution of the map. The two basin boundaries shown correspond to the Amazon basin where most of the regions are located and the Tocantins basin where the Bananal Island region is located. (Credits: D. de C. Victoria.)

measurements taken during the LBA study period at each site with the long-term climate record. In fact, the role of decadal (or multidecadal) variability is a significant issue in the context of the regional climate of Amazonia but this has been well documented by *Zhou and Lau* [2001] and *Marengo* [2004]. Consequently, it is not the purpose of the present paper to investigate the possible added value of including the additional years of LBA data at some sites to see if they have impact on this regional issue. The focus of this study is very strongly on analyzing representativeness that is tightly linked to the location of the LBA sites individually. The paper is divided into three sections: section 2 describes the data and the analysis methods used, section 3 reports the results obtained, and section 4 gives the overall conclusions of the study.

2. Data and Methods

[4] The data used in this study region were taken from climate station records that included measurements of precipitation and temperature or both over an extended period that overlapped with the LBA data collection period. Available long-term climate station data are very limited in the Amazon region but relevant data are available from four databases, specifically those provided by the (1) Agência Nacional de Águas (ANA) (daily precipitation), (2) NCDC/NOAA Global Summary of the Day (GSOD) (daily temperature), (3) NCDC/NOAA Data Set 3500 (DS3500) (monthly precipitation and temperature), and (4) NCDC/NOAA Global Historical Climatology Network Version 2 (GHCN v2) (monthly precipitation).

[5] Because the objective of the study is to investigate the extent to which the prevailing regional climate during LBA data collection is representative of long-term climatology, the climate stations used were selected to be reasonably close to one of the LBA flux tower sites. Figure 1 shows the location of the climate stations used in this study and the LBA flux sites to which they relate. For each climate station selected, Table 1 gives the source database and the site specification within that database, the location of the climate station, the period for which data are available for the station, the distance of the climate station from the LBA study site for which it is assumed to be representative, and the availability or otherwise of precipitation and temperature data at the climate station. The daily values of precipitation and temperature available from the ANA and GSOD databases were first converted to monthly average values (monthly totals, in case of precipitation) subject to the requirement that daily values were available for at least half the days in each month, otherwise the monthly average/total value was subsequently ignored in the analysis.

[6] For the climate station selected as representative of the Caxiuanã LBA study site only precipitation date were available, while for the climate station selected as represen-

Table 1. Data Source, Coverage Period, and Available Measurements for All the Weather Stations Individually Associated With LBA Study Sites

LBA Site	LBA Site Data Collection Period	Station Code	Source Database	Station Location	Climate Station Data Collection Period	Distance From LBA Site (km)	Precipitation Availability[a]	Temperature Availability[a]
São Gabriel da	2005–2006	30382106000	GHCN v2	0.13°S/67.08°W	1922–2006	93	X	
Cachoeira		821060	DS3500	0.13°S/67.08°W	1987–2005	93		X
Manaus[b]	1999–2006	30382331000	GHCN v2	3.13°S/60.02°W	1872–2006	61	X	
		823310	DS3500	3.13°S/60.01°W	1987–2005	61		X
		821110	GSOD	3.03°W/60.05°W	1977–2006	49		X
		823320	GSOD	3.15°S/59.98°W	1973–2006	64		X
Santarém[c]	2000–2006	00154000	ANA	1.77°S/54.40°W	1972–2005	142	X	
		00155000	ANA	1.76°S/55.86°W	1968–2004	178	X	
		00254000	ANA	2.43°S/54.69°W	1968–2005	65	X	
		822440	GSOD	2.43°S/54.71°W	1973–2006	65		X
Caxiuanã[d]	1999–2004	00052000	ANA	0.57°S/52.58°W	1968–2004	178	X	
Jarú/Ji-Paraná[e]	1999–2003	828250	DS3500	8.76°S/63.91°W	1986–2005	270	X	X
		828240	GSOD	8.76°S/63.91°W	1982–2006	270		X
Sinop[f]	1999–2002	829650	GSOD	9.86°S/56.10°W	1988–2004	212		X
Bananal[g]	2004–2006	01048000	ANA	10.76°S/48.90°W	1971–2004	172	X	
		30382861000	GHCN v2	8.25°S/49.28°W	1915–2006	198	X	
		30383064000	GHCN v2	10.52°S/48.72°W	1915–2006	175	X	
		828610	DS3500	8.25°S/49.28°W	1987–2005	198	X	X
		830640	DS3500	10.71°S/48.58°W	1987–2005	198	X	X

[a]Here the X indicates that it is available.
[b]*Araújo et al.* [2002] and *Malhi et al.* [1998].
[c]*Goulden et al.* [2004], *da Rocha et al.* [2004], *Saleska et al.* [2003], *Sakai et al.* [2004], *Miller et al.* [2004], and *Miller et al.* [2007].
[d]*Carswell et al.* [2002].
[e]*von Randow et al.* [2004].
[f]*Priante-Filho et al.* [2004] and *Vourlitis et al.* [2004].
[g]*Tannus* [2004].

tative of the Sinop LBA study site only temperature data were available. At the other four LBA study sites at least two climate stations were available and the long-term average climatology of measurements made at these different stations was compared. In all cases the standard deviation in the mean monthly cumulative precipitation and temperature measured at the individual stations associated with specific LBA study sites was broadly comparable but, in some cases, there were systematic differences in the long-term average yearly cycle of these variables. In the case of precipitation, the systematic difference tended to be in the amplitude of the average yearly cycle while, in the case of temperature, systematic differences tended to be in the form of an offset in the average yearly cycle. In most cases these systematic differences in amplitude and offset were less than the standard deviation in the monthly averaged values. Only in one case (temperature records from the DS3500 station near Santarém) was the behavior of a specific climate station considered suspect and the station excluded from the analysis. In this region, hydrometeorological variables including temperature and precipitation may be affected by the effect of the river breeze from the Tapajós river [*Silva Dias et al.*, 2004] and the confluence of the Tapajós and Amazonas rivers [*Fitzjarrald et al.*, 2008]. In fact the mean monthly cumulative precipitation at the three stations in the Santarém region (not shown), which are derived from the same database and which are available for similar periods (∼34–37 years), are similar. However, the mean monthly temperature derived from the DS3500 data set were systematically lower by about 2°C than those from the GSOD and were only available for about half the period of the GSOD records (not shown). The DS3500 data are for locations very close to the east bank of the Tapajós river and the GSOD data are likely more credible as an inland climatological record. For these reasons, rather than creating a single average data set for the Santarém site which included a second set of data for the last 18 years of the record with distinct behavior arguably due to river breeze influences, the authors preferred to use the 34-yearlong continuous climatological data available from the GSOD data set (Table 1) for the Santarém region. In all other cases, the observed systematic differences were considered real, and the climate station data therefore included in the analysis as a legitimate spatial sample of the climatology for the region of the LBA study site with which the climate station is associated.

[7] Representative monthly total/average values of precipitation and temperature were then calculated for each LBA study site as the inverse distance squared weighted average of the values available from the climate stations considered to be representative of the site. The mean and standard deviation of these representative monthly average values of cumulative precipitation and temperature were then calculated for the whole period for which data were available and also for the period of LBA data collection. For the purpose of illustration, a "dry season" was defined for each LBA study site as the periods when the long-term mean monthly precipitation was less than 100 mm per month. In the case of Sinop region where no precipitation data were used, the definition of dry season was based on the 30-year precipitation record from Vera (Mato Grosso), located approximately 30 km southeast of Sinop [*Priante-*

Filho et al., 2004; *Vourlitis et al.*, 2002]. In fact there is some evidence [e.g., *Marengo et al.*, 2001; *Zhou and Lau*, 1998] that the definition of the dry season has regional dependency. However, the primary results of this study are not sensitive to the detailed criterion selected to define the dry season, and selection of 100 mm month^{-1} to separate dry and wet seasons within the LBA data set is common practice among LBA flux data users [see, e.g, *Saleska et al.*, 2003; *Vourlitis et al.*, 2004]. Fortunately, a seasonal specification based on this simple criterion matches almost perfectly the digital maps provided by *Sombroek* [2001].

[8] The Kolmogorov-Smirnov test (K-S test) was used to define whether the inverse distance squared weighted average of cumulative precipitation and temperature for selected nearby climate stations during the LBA data collection period was representative of that in the long-term climatology. For additional information about the K-S test, see for instance Numerical Recipes in FORTRAN, chapter 14 (available at http://www.nrbook.com/a/bookfpdf.php). If the samples are known to follow a given distribution a priori, other methods may be more sensitive. However, the advantage of the K-S test is that it can determine whether or not a sample distribution is significantly different from a second distribution without making any prior assumption regarding the nature of the sample distribution. The two-sample K-S test is implemented by first calculating the cumulative distribution functions (CDFs) of the two samples and is widely employed because it is sensitive to differences both in the location and shape of the empirical cumulative distribution functions of the two samples, and the size of the samples to be compared does not need be the same. To test the null hypothesis that the two samples are drawn from the same underlying population using the K-S test for a given the level of confidence (5% in this study), the maximum distance between the two CDFs is computed and the null hypothesis that they are drawn from the same population can be rejected when the computed "p-level" is lower than 5%. In this study, the K-S test was used to compare average monthly values during the LBA data collection period with long-term climatology for individual months, and for the dry and wet seasons as a whole, and also to compare monthly average/total values in a single year with long-term climatology for individual months.

[9] The Kolmogorov-Smirnov test assumes that data in the samples compared are serially independent. This assumption may well hold when analyzing mean values for each month separately, i.e., when comparing January or February (and so on) separately during the LBA period with January or February in the climatology. However, correlation between adjacent months is possible; therefore the test may suggest similar results in consecutive months. One way to test for the representativeness of a given sample with respect to a larger one that may avoid this serial correlation and also provide an alternative to applying the Kolmogorov-Smirnov test is to make a histogram analysis during the LBA period for each region, and to compare this with that for samples randomly chosen from the entire climatological period with the same period length as the LBA period (Table 1). To avoid oversampling in the present analysis the number of samples taken was approximately 30% of the maximum number of possible samples for each region, and sometimes differed according to the length of the sampling period for precipitation and temperature even in the same region (Table 1).

3. Results

3.1. Precipitation

[10] Figure 2a shows the comparison between the measured annual variations in precipitation during the periods when LBA data were collected relative to long-term climatology for the six LBA study sites where precipitation was measured at nearby climate stations. The component graphs in Figure 2a are arranged to broadly follow the geographical position of the several sites, with São Gabriel da Cachoeira at the top left and Bananal at the bottom right, for example. The mean monthly cumulative precipitation for climate stations are shown in solid red line with standard deviation when evaluated for the relevant LBA data collection period (given the second column of Table 1), and in solid black line with the gray area indicating one standard deviation when over the period which long-term climate data are available (given in the fifth column of Table 1). The white bars show the difference between the mean calculated during the LBA data collection period relative to the mean over the period for which long-term climate data are available. The yellow rectangles indicate periods when the monthly total precipitation was less than 100 mm, designated the dry season in this study. At São Gabriel da Cachoeira, the data collection period during LBA is just 2 years and the year-to-year variability of these monthly means is consequently greater. Notice that the criterion we have adopted to define a dry season in this study (i.e., months with less than 100 mm) implies there is no dry season at the São Gabriel da Cachoeira study site.

[11] In all six cases, the K-S test indicated that there is no significant difference between the annual average behavior during the two sample periods, although there are some minor differences in the mean values. In Manaus, for example, the rainfall toward the end of the wet season in April and May is greater than the climatological average by about 129 mm or 23%. *Araújo et al.* [2002] observed similar monthly patterns of precipitation, with annual rainfall reaching approximately 2200 mm, and July–August and March–April being the driest and wettest months, respectively, similar to these observations. Similar results were also found by *Malhi et al.* [1998]. The Santarém and Caxiuanã sites both enter the dry to wet season transition (November–December) with a rainfall deficit which is approximately 66 mm (32%) for Santarém and 79 mm (38%) for Caxiuanã, but in both cases the net rainfall during the wet season is very similar to the long-term average. The duration of the dry and wet seasons and the distribution of monthly precipitation are consistent with early studies [*Carswell et al.*, 2002; *da Rocha et al.*, 2004; *Saleska et al.*, 2003]. At the Jarú (Ji-Paraná) site, there is general consistency between the LBA data collection period and the long-term average, but about 100 mm or about 61%, more rain in May–June. During the period of LBA data collection, there was about 200 mm or 32% less than the climatological average rain during the early wet season (October–December) at the Bananal site, but 88 mm or 32% more later in the season in March. The annual rainfall at the Bananal site observed during the LBA period (1667 mm) is

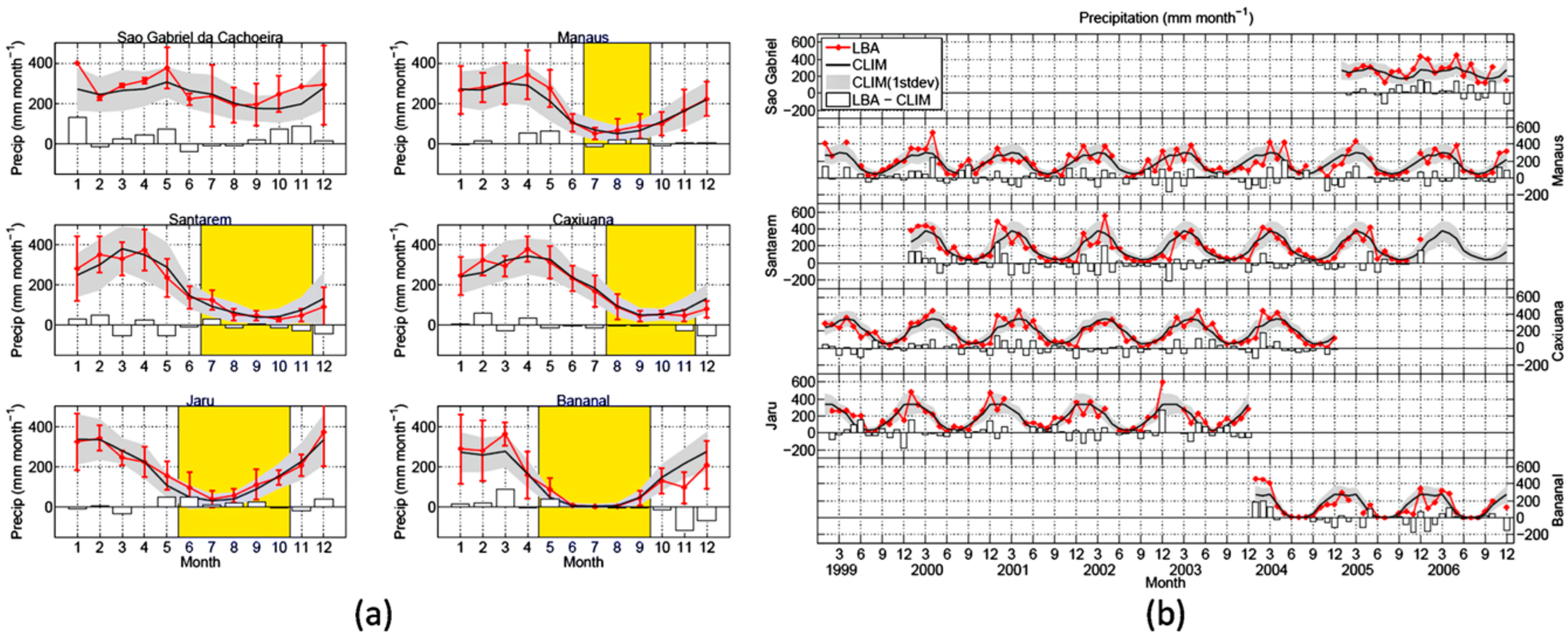

Figure 2. (a) Annual variation of the mean monthly station-averaged cumulative precipitation for the climate stations relevant to regions of the São Gabriel da Cachoeira, Manaus, Santarém, Caxiuanã, Jarú (Ji-Paraná), and Bananal LBA study sites evaluated for the relevant LBA data collection period (solid red line) compared to the period for which long-term climate data are available (solid black line and gray-shaded area). The white bars show the difference between the mean calculated during the LBA data collection period relative to the mean for the period for which long-term climate data are available, while the yellow rectangles indicate periods when the monthly total precipitation was less than 100 mm, designated the dry season in this study. (b) Monthly cumulative precipitation from 1999 to 2006 for the relevant LBA data collection period (solid red line) and the period for which long-term climate data are available (solid black line and gray-shaded area). The white bars show the difference between the value during the LBA data collection period relative to the long-term monthly average value.

reasonably close to the value found by *Tannus* [2004], i.e., 1690 mm.

[12] Figure 2b shows the individual month-to-month difference in rainfall with respect to the long-term average for the six LBA study sites where precipitation was measured at nearby climate stations and for the site specific period when data collection occurred at these sites. The solid black line and gray shading (repeated annually) show the mean and its standard deviation of the cumulative monthly precipitation calculated from long-term climatology, while the red line shows the value for each month during the period when data was collected at the corresponding LBA study site. As such, Figure 2b provides a point of reference from which the studies made by field observers during specific periods at specific sites can judge the extent to which the precipitation during their observations is representative of the long-term mean behavior.

3.2. Temperature

[13] Figure 3a shows the comparison between the measured annual variations in temperature during the periods when LBA data were collected relative to long-term climatology for the six LBA study sites where temperature was measured at nearby climate stations. The annual variation of the monthly average station-averaged temperature for the climate stations are shown as a solid red line with standard deviation when evaluated for the relevant LBA data collection period (given in the second column of Table 1), and as a solid black line with gray area indicating one standard deviation when evaluated over the period for which long-term climate data are available (given in the fifth column of Table 1). The white bars show the difference between the mean calculated during the LBA data collection period relative to the mean for the period for which long-term climate data are available. The yellow rectangles indicate periods when the monthly total precipitation was less than 100 mm, designated the dry season in this study. In the case of the São Gabriel da Cachoeira site, data were only collected for less than 1 year and there is therefore greater uncertainty when assessing how representative the climate was at this site relative to the long-term average. Nonetheless, during the year when data was collected at this site the monthly variations do seem to match the long-term climatology quite well, as do the monthly average temperatures over the period of LBA data collection at the Manaus, Santarém, and Jarú (Ji-Paraná) sites. It is interesting to note that at the Jarú (Ji-Paraná) site, the average yearly variation in temperature decreases in the early dry season when precipitation is less than 100 mm per month both during the LBA data collection period and as a long-term average. This is contrary to the behavior observed at all the other regions LBA study sites and reflects the effect of cold surge events (also known as "friagem" events) which involve strong cold advection from the south, some of which reach the southernmost part of the Amazon basin, including the Jarú (Ji-Paraná) region [*Marengo et al.*, 1997; *von Randow et al.*, 2004].

[14] The monthly average temperature at the Sinop study site is systematically higher during the LBA data collection period than the long-term average in every month except January, most noticeably so during the May–September dry season. As an annual average, it is around 0.4°C higher. One possible explanation is that the LBA data collection period was drier than the long-term average. *Priante-Filho et al.* [2004] showed that 2002 had 18% less rainfall than in the previous 2 years and *Vourlitis et al.* [2004] showed the annual precipitation observed between August 1999 and July 2001 was 100 mm less than 30-yearlong-term climatology. A second (and arguably more compelling) explanation is that substantial land use change in Mato Grosso and expansion of soybean crops northward has had an impact on the hydrometeorology of this region [*Nepstad et al.*, 2002]. Recently, *Costa et al.* [2007] studied the changes in precipitation and surface heat fluxes associated with soybean crop expansion in the Amazon and found a significant reduction in rainfall relative to forest and pastureland, and a noticeable difference in the Bowen ratio as a function of albedo anomalies, with less latent heat flux and more sensible heat. If the expanded soybean cover around the Sinop site is behaving in this way, some increase in near surface air temperature is to be expected.

[15] The multiyear average temperature behavior at the Bananal site is unique in this study because not only is there a temperature increase during the LBA data collection period relative to the long-term average at this site (readily observed in Figure 3a), but it is the only site where the difference in annual average temperature is identified by the K-S test as being statistically significant, albeit this test is likely to be less robust at this site because LBA data were only collected for 2 years. The monthly average temperature during LBA data collection here is higher than the long-term average in all months and is 0.8°C higher as a yearly average, with the greatest difference (2°C higher) in November. The increase in temperature in the early wet season (October–December) may be associated with the negative anomaly in rainfall at this site shown in Figure 2a, but during the wet to dry transition, warmer temperatures occur even though there is a positive rainfall anomaly in precipitation at this time.

[16] The K-S test was also used on a within year basis at each site to investigate whether individual seasons during the LBA data collection period at a specific site was statistically inconsistent with the long-term climate average. No statistically significant periods were found in the case of precipitation but, in the case of temperature, a few periods were identified as being significantly different. In Figure 3b, which is analogous to Figure 2b but for temperature rather than precipitation, the periods when temperature differences are significant are identified by orange boxes. At the Manaus site, for example, the temperature is significantly higher than the long-term average during portions of the 2003 wet season, while at the both the Jarú (Ji-Paraná) and Sinop study sites the year 2002 was significantly warmer, the latter having a noticeable monthly difference of 3°C in August. Finally, as mentioned before, the Bananal study site has significant higher temperatures during the LBA period than the long-term average and toward the end of 2005, the temperature difference approached 2°C. An important point (already mentioned in section 2) is that the duration of the orange boxes could be extended by a correlation between values in successive months. The random sampling analysis described in section 3.3 is an alternative way to analyze these data that avoids the problem of serial correlation.

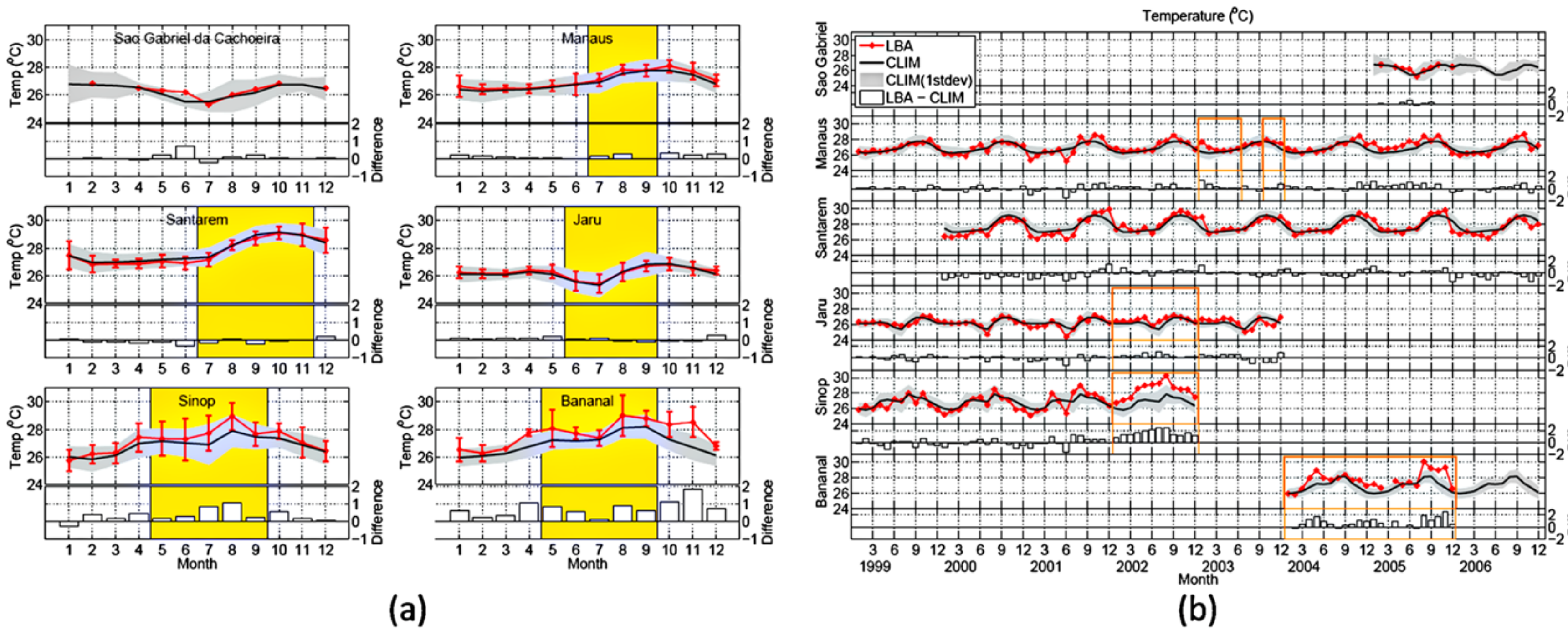

Figure 3. (a) Annual variation of the monthly average station-averaged temperature for the climate stations relevant to regions of the São Gabriel da Cachoeira, Manaus, Santarém, Jarú (Ji-Paraná), Sinop, and Bananal LBA study sites evaluated for the relevant LBA data collection period (solid red line) compared to the period for which long-term climate data are available (solid black line and gray-shaded area). The white bars show the difference between the mean calculated during the LBA data collection period relative to the mean for the period for which long-term climate data are available, while the yellow rectangles indicate periods when the monthly total precipitation was less than 100 mm, designated the dry season in this study. (b) Monthly average temperature from 1999 to 2006 for the relevant LBA data collection period (solid red line) and the period for which long-term climate data are available (solid black line and gray-shaded area). The white bars show the difference between the value during the LBA data collection period relative to the long-term monthly average value, and orange boxes indicate periods when the K-S test indicates a significant difference.

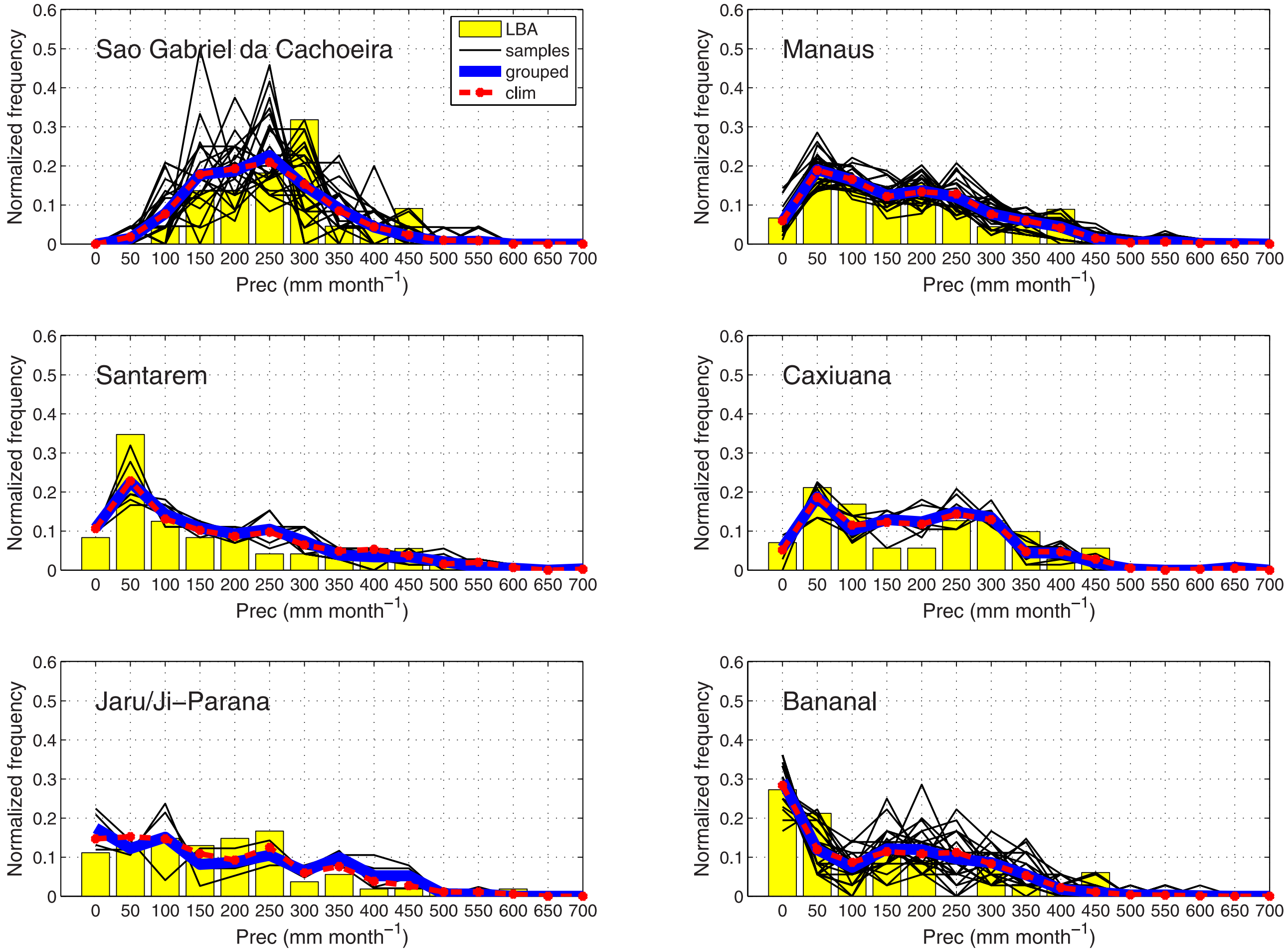

Figure 4. Precipitation (in mm month^{-1}) histogram analysis in which the LBA data collection period is compared with randomly selected samples from the entire long-term climatology. The LBA period distribution is represented by the yellow bars; individual and grouped random samples are shown as solid black and solid blue lines, respectively; and the dashed red line correspond to the distribution from the entire long-term climatological data.

3.3. Random Sampling Analysis

[17] The representativeness of the LBA period with respect to the long-term climatology was also tested by comparing histograms of randomly selected samples relative to the LBA period. The number of samples was defined individually for each region according to the maximum possible combinations feasible within the climatological record. This number is different from site to site, and in some cases also different when analyzing temperature as opposed to precipitation if there are different climatological records available for these two variables within the same region. So as to avoid simply reproducing the comparison against the long-term climatology previously carried out, it was decided to make comparison against only 30% of the maximum possible random samples that could be made with the same duration as the LBA period. The sample period corresponding to the LBA period are defined in Table 1.

[18] In general, comparison between the probability histogram for precipitation values during the LBA period and random samples of the same length from the climatological record supports and illustrates the results of the statistical test described above. In Figure 4, the yellow bars are the probability histogram associated with the LBA data collection period. The probability histograms for precipitation for each of the individual samples are depicted as solid, thin black lines, while the solid blue line corresponds to probability histogram in all of the random samples grouped together. The probability histogram for the entire climatology is also included as dashed red line, confirming that the seasonal variation similar between the LBA period and climatology (see, Figure 2). It is noticeable that the normalized frequency for the grouped random sample is similar to that for the whole climatology. The individual ranges of precipitation values that occur with finite probability are the same during the LBA period as for the grouped random sample. Overall, the probability histograms during LBA period are representative of long-term climatology and any individual differences for particular values during the LBA period are consistent with the random samples.

[19] Temperature records are fewer than precipitation records so the number of possible random samples that can be made for comparison with the LBA period is less. Nonetheless, histogram analysis shows that the LBA period also represents the long-term climatology for almost all

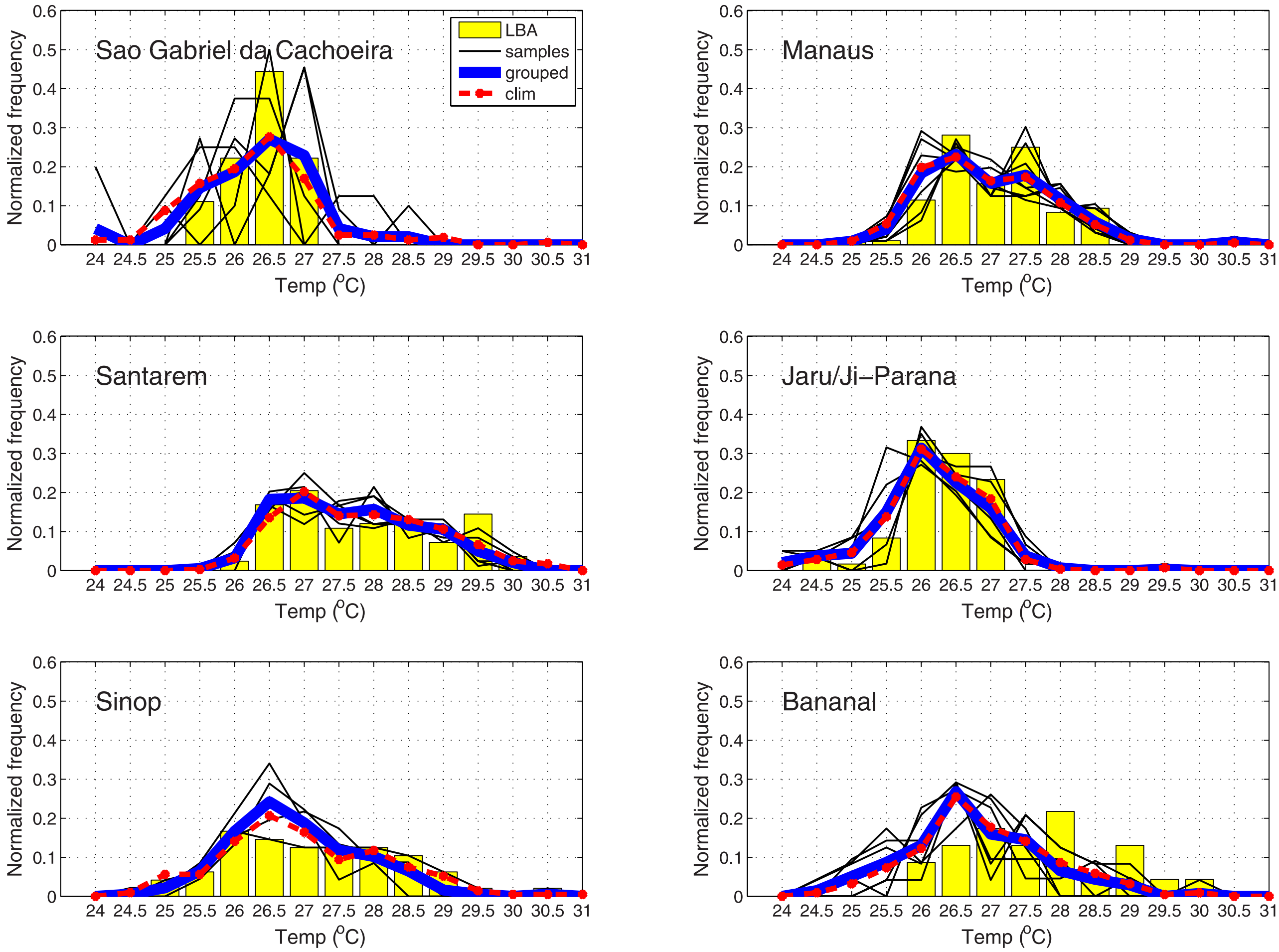

Figure 5. Temperature (in °C) histogram analysis of the LBA data collection period in comparison to randomly selected samples from entire long-term climatology. The LBA period distribution is represented by the yellow bars; individual and grouped random samples are shown as solid black and solid blue lines, respectively; and the dashed red line correspond to the distribution from the entire long-term climatological data.

regions (Figure 5), the exception being, once again, the Bananal Island region. Careful comparison shows that for all the other regions the ranges of temperature occurring with finite probability and the normalized frequency histograms for temperature agrees quite well with the grouped random samples. However, in the case of the São Gabriel da Cachoeira region, the agreement is less certain because there is less than 1-year data available during the LBA period. On the other hand, the Bananal Island results clearly illustrate a shift in the probability distribution toward warmer temperatures during the LBA period relative to both the grouped random samples and the entire climatology. The distribution seems to be approximately 1.5°C to 2°C warmer, supporting the statistical test described above. In summary, in terms of temperature the LBA data collection period agrees well with the long-term climatological data for all but the Bananal Island site, suggesting care should be taken when interpreting the data at this particular site.

3.4. Multisite Features

[20] The primary purpose of this study was to investigate the extent to which the climate at individual sites was representative of the long-term average at individual LBA study sites, but it is also of interest to consider the overall climate of the Amazon region as a whole, as sampled by the several sites where LBA data were taken. With this in mind, Figure 6 shows a comparison between the measured monthly average cumulative precipitation and temperature for all sites during all of the site-specific periods when LBA data were taken relative to the equivalent monthly average values derived for each site from the long-term climate data available. In this diagram, open and close symbols correspond to the dry and wet seasons at each site, respectively, but note that there is no dry season at São Gabriel da Cachoeira using the definition adopted to distinguish the dry season in this study. The linear regression line ($R^2 = 0.90$) shown in Figure 6a has a gradient and offset of 1.0376 ± 0.0007 and -0.70 ± 72.51, respectively; and that in Figure 6b has a gradient and offset of 1.0064 ± 0.0048 and 0.11 ± 0.67, respectively, with $R^2 = 0.82$. Figure 6a shows, and the linear regression confirms, that the precipitation pattern for all sites is well related to long-term climatology on average, consistent with the result found using the K-S test. However, the temperature comparison in Figure 6b shows, and the linear regression confirms, that there is a systematic

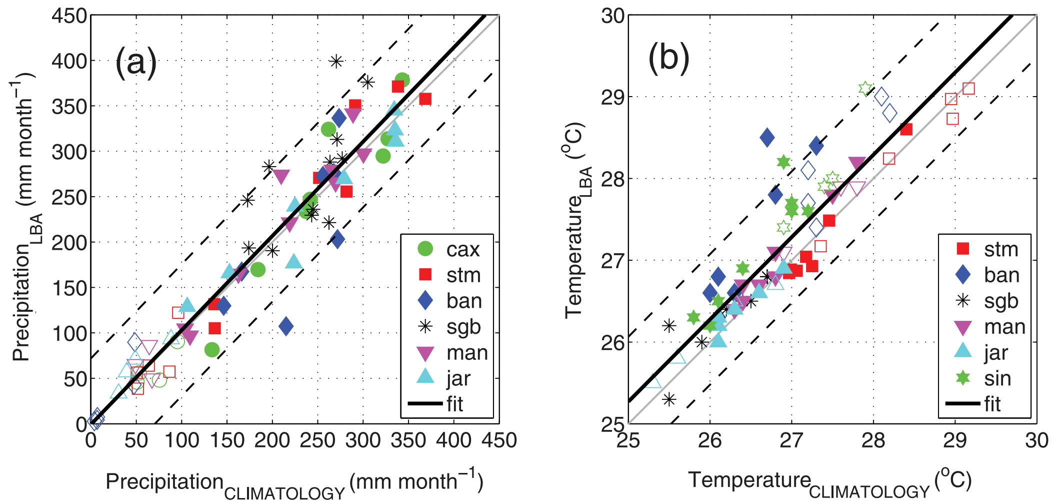

Figure 6. Comparison between (a) the monthly average cumulative precipitation and (b) the monthly average temperature calculated from the climate stations in the region of each LBA study site for all months when data were being taken at that LBA study site relative to the equivalent climate-averaged value for the same month calculated from the same climate stations. Open symbols correspond to values in the dry season and solid symbols correspond to values in the wet season. In both Figures 6a and 6b, the solid light gray line is the 1:1 line and the solid black line is the linear regression fit to the data. The dashed lines correspond to the 95% confidence interval around the linear regression. (Note the São Gabriel da Cachoeira study site does not have a dry season according to the definition used in this study.)

tendency toward higher temperatures for all the LBA study sites taken together, although the Santarém site uniquely has a tendency to be slightly cooler than climatology. Finally, as might be expected, the most significant elevated temperatures occur in the dry season and, as discussed above, the differences are most obvious at the Bananal sites (blue diamonds) and Sinop site (green stars) although there is also a less obvious bias toward higher temperatures at the Manaus site (purple triangles). This warming tendency can be considered a result of the regional land use/land cover changes occurred in these regions, especially in the surrounding areas of the Bananal Island site and the soybean crops expansion in the entire state of Mato Grosso which encompasses Sinop.

[21] The unique behavior observed at the Santarém site may be associated with either a river breeze phenomenon or thermally induced atmospheric circulations due to small-scale land use/land cover changes, a “vegetation breeze,” which has been observed at Amazon sites. Both mechanisms can support the enhancement of fair weather (shallow) cumulus clouds due to modified circulation and moisture convergence, which result in less radiation reaching the surface and a decrease in temperature. *Silva Dias et al.* [2004] observed a river breeze circulation associated with the Tapajós river during weak trade wind regimes which they consider to be thermally induced and due to temperature differences between the river and the adjacent land, and which results in enhanced cloud formation (mostly shallow cumulus clouds) on the east side of the Tapajós river especially during daytime [see, e.g., *Silva Dias et al.*, 2004, Figure 7]. *Fitzjarrald et al.* [2008] suggest that the Tapajós river breeze appears to extend a few kilometers inland. Both studies emphasize the importance of characterizing this circulation correctly in climatological analysis. *Lu et al.* [2005] suggest that the Tapajós river breeze is not present only in weak trade winds regimes but it is also induced mechanically throughout the year by the geometry and location of the river (approximately normal to the easterly flow) and contributes to the channeling effect observed at the Tapajós-Amazonas confluence, thus enhancing the convergence on the east side of the river [see, e.g., *Lu et al.*, 2005, Figures 9 and 13].

[22] A further possible explanation for the lower temperatures is that they may be associated with land cover changes in this region. Several studies in the Amazon suggest that small-scale deforestation may induce the formation of cumulus clouds (again mainly shallow cumulus) which then modifies the energy and water partition at the surface-atmosphere interface [*Cutrim et al.*, 1995; *Durieux et al.*, 2003; *Negri et al.*, 2004] and, in turn, the type and intensity of the rainfall in deforested regions, as discussed by *da Silva and Avissar* [2006]. Using a high-resolution deforestation scenario based mainly on road paving and law enforcement in the Santarém region (BR-163 highway), *Rosolem* [2005] showed the formation of a thermally induced circulation due to the geometry and location of the highway (approximately parallel to the Tapajós river) which induced cumulus cloud formation. The enhancement of cloud formation due to the vegetation breeze could also influence the results shown in Figure 6b for the Santarém site.

4. Conclusions

[23] As described in the introduction, this study of the short-term “climate” during the LBA period study was carried out to provide a context into which other LBA observation and modeling studies of the climate and surface exchanges that rely on LBA flux data can be placed. The analysis is restricted to the comparison of a small number of

weather stations which are nearby the LBA eddy flux towers that provided data for an extended period that also overlapped with LBA data collection period.

[24] Direct comparison of the data available and application of the Kolmogorov-Smirnov test shows that the LBA period is representative of the long-term climatology for all seven LBA study sites stations, the only exception being the temperature record associated with the Bananal Island LBA study site which was significantly warmer by 1°C, with individual monthly values up to 2°C warmer. These findings were supported by the results found when samples were randomly chosen from the climatological record and compared with the LBA data collection period. However, although the climate at most LBA study sites is not significantly difference from the long-term climate of the site, there are a few periods when the monthly average temperature in particular year can be considered to be significantly different at the Manaus, Jarú, Sinop and, especially, Bananal Island study sites. Also, when the data from all the sites are taken together as spatially distributed overall measure of the climate of the region, there is again no evidence of a difference in precipitation climate during the LBA study period but the regional temperature is higher by about 0.3°C, the only exception being the Santarém site where a tendency for colder temperature is found during the LBA period. This unique behavior of the Santarém site is probably associated with enhancement of shallow cumulus cloud formation on the east bank of the river as a result of the river breeze circulation over the Tapajós river but may be due to a vegetation breeze circulation due to small-scale deforestation, these being associated with the geometry and location of the river and deforested area, respectively. Speculatively, the increase in temperature at some of the other study sites is because there has been significant regional land cover change and the nearby climate has been modified as a result, but some contribution to the overall increase in the recent record of temperatures from climate warming cannot be ruled out.

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