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ON THE DIURNAL VARIABILITY OF RAINFALL IN EASTERN AMAZONIA ALONG ATLANTIC COAST DURING RAINY SEASON

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ABSTRACT Five years (2001-2005) of continuous rainfall data collected *in situ* by LBA station in Bragança-PA are used to describe the diurnal pluviometric variation in a point located in the core of the eastern Amazon off Atlantic coast, during rainy season (January to May). The 5-yr average of accumulation of rainfall in each 6 hours (06:00, 12:00, 18:00 and 24:00 LST) evidenced maximum peaks during the morning and dawn periods and a sharp minimum in the afternoon. A significant diurnal cycle of the cloudiness band related to the Intertropical Convergence Zone over equatorial Atlantic is pointed out as the main mechanism regulator of diurnal pluviometric variability in coastal region along the Pará and Amapá states. The highest frequency of rainy days occurs in March following sequentially by April, February, January and May. Rainfall events with values lower than 10 mm $6h^{-1}$ explain the largest proportional contribution of the total rainfall observed during all rainy season months. Such events result from contribution of the weak and continuous stratiform-like rainfall persisting for more than 3-4 hours along the day.

1. INTRODUCTION

The diurnal variability of rainfall over the Amazon basin (hereafter referred to as Amazonia) has been previously documented using high temporal resolution data collected in field experiments. Five years (1990-1994) of observations obtained from ABRACOS (Anglo Brazilian Climate Observation Study; Gash and Nobre, 1997) evidenced rainfall maxima in southwest and central Amazonia (Ji-Paraná-RO and Manaus-AM) in the afternoon, while in the eastern Amazonia (Marabá-PA) there is a maximum in the morning (Ferreira da Costa *et al*., 1998; Liebmann *et al*., 1998). The LBA (Large-scale Biosphere-Atmosphere Experiment in Amazonia) provided support for accomplishment of intensive campaign called LBA-TRMM (Silva Dias *et al*., 2002), which was held during January-February 1999 wet season in southwestern Amazonia (Rondônia state). Tota *et al*. (2000) and Marengo *et al*. (2004) described details of diurnal variability of rainfall observed in these region and they found a late afternoon maximum (early morning minimum) associated with the westerly (easterly) regime. These results are consistent with analyses based on satellite data that also reported a late afternoon peak of rainfall in southern Amazonia (Negri *et al*., 2000). On the other hand, there have been few investigations on the diurnal variability of rainfall over eastern Amazonia in particular along the Atlantic coastal region. Fortunately, the MilênioUFPa project (Cohen *et al*., 2001) has implemented sites in different ecosystems typical of eastern Amazonia along Atlantic coast of Pará state, where meteorological measurements have been recorded continuously. MilênioLBA, a sub-project of the LBA, completed five years (August 2000 to present day) of continuous measurements to yield a comprehensive meteorological database available to study regional climatological aspects throughout eastern Amazonia.

In the present study, we utilize five years (2001-2005) of continuous rainfall data collected by LBA station in Bragança-PA (a point located in the core of eastern edge of the Amazonia off Atlantic coast), in order to describe the mean characteristics of diurnal pluviometric variation as well as its frequency distribution considering different intensity ranges for each month and period of diurnal cycle. Furthermore, based on high spatial resolution rainfall estimates derived from satellite microwave observations (Joyce *et al*., 2004), we have identified the main dynamical mechanism regulator of the diurnal pluviometric variability in the region studied. This diagnostic analysis focus on January through May (JFMAM) months, when rainy season prevails in the mouth of Amazonia (Marengo *et al*., 2001) and the distinctive cloudiness band of the Intertropical Convergence Zone (ITCZ) reaches its southernmost climatological location in the equatorial south Atlantic (Souza *et al*., 2004), leading to maximum yearly precipitation commonly observed in these regions (Souza and Ambrizzi, 2003).

2. DATA AND METHODS

The precipitation data collected *in situ* by the automatic meteorological station installed in a 27m tower is used in this work. This LBA station is located in Bragança (00º50'S, 46º38'W), a city whose mangroves ecosystem is typical of Atlantic coast along the state of Pará in the eastern Amazonia. The original precipitation data in Bragança were recorded every 30 minutes. Additionally, we use daily mean (24 h accumulation) precipitation data collected by INMET conventional meteorological station in Tracuateua (01º05'S, 46º56'W) also located in the eastern Pará. Figure 1 shows the locations of these two stations situated in regions with altitude near the sea level. For both stations we utilize the continuous rainfall data collected during the rainy season (January to May) for the last five years (2001-2005).

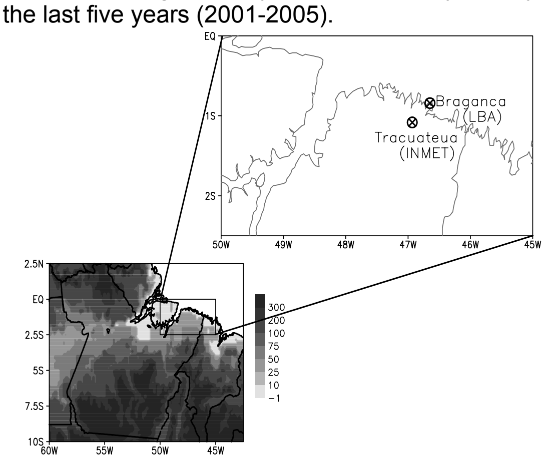

Figure 1: Location of Bragança (LBA) and Tracuateua (INMET) stations in the eastern Amazon. Shaded areas are topography (m).

To characterize the dynamical mechanism related to the diurnal variability, we use the product named as CMORPH (CPC MORPHing technique), a precipitation analysis at very high spatial and temporal resolution. CMORPH combines the superior quality of the passive microwave precipitation estimates with the excellent sampling characteristics. This technique uses precipitation estimates that have been derived from low orbiter satellite microwave observations exclusively, and whose features are transported via spatial propagation information that is obtained entirely from geostationary satellite infrared data. Here, we use 3-hourly CMORPH rainfall estimates available on a grid with a spacing of 0.25 degree in latitude and longitude since December 2002 to present days. The detailed description of CMORPH is documented in Joyce *et al*. (2004). In addition, zonal (u) and meridional (v) components of the wind and specific humidity (q) data produced by the National Centers for Environmental Predictions/National Center for Atmospheric Research reanalysis project (Kalnay *et al*., 1996) for the same period are used.

In the present work we used the accumulation of rainfall in each 6 hours of day, i.e., at 06:00, 12:00, 18:00 and 24:00 local time (LST), which represents rainfall accumulation during the dawn, morning, afternoon and night period, respectively. We consider a rainfall *event*, when it is observed values different from zero and greater than 0.3 mm $6h^{-1}$. The frequency distribution of rainfall events in each period of the diurnal cycle is calculated for six different intensity ranges (< 10, 10.1 to 25, 25.1 to 50, 50.1 to 75, 75.1 to 100 and > 100.1 mm $6h^{-1}$) by using the expression $F_r = \frac{F_{6h}}{F_t} \times 100$. F_r is the relative frequency, F_{6h} is the number of events observed in given range and F_t is the total number of events for this range in each month (January to May) and period of diurnal cycle during 2001 to 2005.

3. RESULTS

3.1. Monthly rainfall variations

Although the location of Bragança is near the Tracuateua station (distance of approximately 90 Km), a exact correspondence between rainfall values is not waited due the large spatial variability observed into deep tropics. This characteristic is verified in Figure 2 that shows monthly rainfall accumulation for both stations during each 2001 to 2005 rainy season. The peak of the rainy season for both stations occurs in March in most of the five years analysed, when is observed highest rainfall values varying between 400 and 800 mm. Since Bragança rainfall data are not enough to produce a long-term mean, we use the INMET 30-yr climatology (1961-1990) of Tracuateua, in order to take a general characterization of the rainy season as a whole in the eastern Pará during the last five years. By comparing the monthly values with 30-yr climatology, one can verify a predominance of above normal rainy season during 2003 and 2004, around normal during 2001 and 2002 and below normal during 2005. In general, the rainfall observed off Atlantic coast (Bragança) presents monthly accumulation slightly higher than more inside continent (Tracuateua).

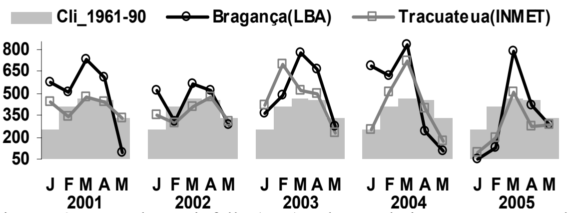

Figure 2: Monthy rainfall (mm) observed in Bragança and Tracuateua for January to May during 2001 to 2005. Light grey bars show INMET 30-yr climatology (1961-1990) for Tracuateua.

3.2. Diurnal variation of rainfall

The diurnal variation of rainfall in Bragança observed at 06:00, 12:00, 18:00 and 24:00 LST corresponding to the 5-yr average (2001-2005) for every month of the rainy season is shown in Figure 3a. The maximum peak of rainfall occurs during the morning (accumulation at 12 LST) in January, February and April, while it is verified during the dawn (accumulation at 06 LST) in March (but very close to the morning peak) and during the night (accumulation at 24 LST) in May. On the other hand, the minimum peak is established during the afternoon (accumulation at 18 LST) in January, March, April and May, while in February it is observed during the night. They both diurnal amplitude and intensity are somewhat larger (lower) in March and January (May) than other months. Concerning diurnal variation related to the rainy season as a whole, i.e., 5-yr JFMAM average, Figure 3a reveals clearly the establishment of maximum peak of rainfall around 9.9 and 9.7 mm $6h^{-1}$ during the morning and dawn respectively, and the minimum peak around 4.9 mm $6h^{-1}$ during the afternoon. Still considering the 5-yr average but for the 24h accumulation, Figure 3b reveals that the highest frequency of rainy days occurs in March (18.5 days with rainfall events and mean rainfall around 10 mm) following by April (15.9 days and 7.3 mm), February (13.7 days and 7.3 mm), January (11.4 days and 9.5 mm) and May (11 days and 5.1 mm). Note that although the number of rainfall events in January is lower than April and February, the former presents rainfall intensity higher than these latter months.

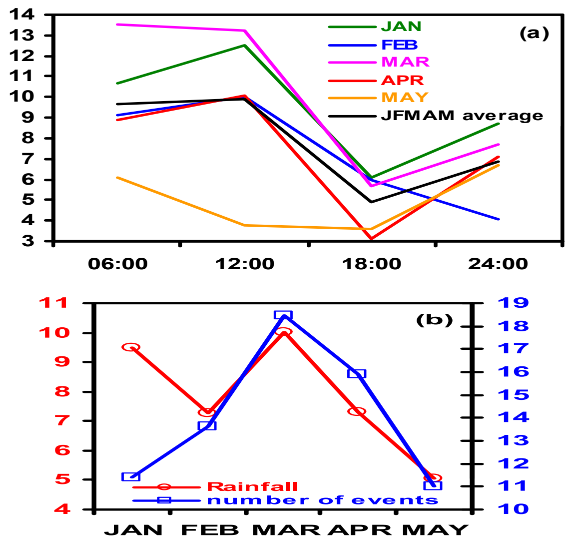

Figure 3: (a) Accumulation of rainfall (mm 6 h^{-1}) observed in Bragança at 06:00, 12:00, 18:00 and 24:00 LST. (b) Rainfall (mm) and number of rainfall events for the rainy season months. All values represent a 5-yr average (2001-2005).

Coherent results are found when frequency distribution of rainfall events is analyzed taking into account different intensity ranges observed. Here, it was investigated six ranges: < 10, 10.1 to 25, 25.1 to 50, 50.1 to 75, 75.1 to 100 and > 100.1 mm $6h^{-1}$. Figure 4 displays frequency distribution of rainfall during each month of rainy season (January to May) corresponding to the average 4-times a day (i.e. 06, 12, 18 and 24 LST). Likewise, Figure 5 shows frequency distribution of rainfall for JFMAM average at 06:00, 12:00, 18:00 and 24:00 LST. Both Figures represent diurnal variations considering 5-yr rainfall (2001-2005) average. The joint analysis of these two figures allows to evidence important distinctions related to the diurnal variation of rainfall during the dawn, morning, afternoon and night periods within the rainy season in the Bragança station, as detailed below.

Extreme events with precipitation above 100 mm $6h^{-1}$ are observed during January (0.7%) and March (0.2%) and such events are only verified during the morning (0.8%) period (Figures 4 and 5). Others extreme events related to the rainfall accumulation between 75.1 and 100 mm $6h^{-1}$ tend to occur mainly in March (1%), April (0.5%) and January (0.5%). The occurrence of these events is distributed during the night (0.6%), dawn (0.6%) and morning (0.4%) periods. Therefore, none extreme episode with rainfall greater than 75 mm was observed during the afternoon period, at least for the last 5 years.

Events with rainfall accumulation between 50.1 and 75 mm $6h^{-1}$ happen during all rainy season months with highest frequency in March (3.1%) and January (2.9%) during the morning (2.8%) and dawn (2.3%), following by February (1.7%), April (1.2%) and May (0.6%) during the night (1.7%) and afternoon (0.9%). On the other hand, it is noticed a distribution slightly regular along the rainy season of the events containing rainfall accumulation for 25.1 to 50 and 10.1 to 25 mm $6h^{-1}$. The frequency of rainfall events between 25.1 and 50 mm reaches 6.5% in March, 5.3% in January, 5% in April, 4.5% in February and 2.1% in May. Such events are distributed during the dawn (6.3%), morning (6%), night (3.8%) and afternoon (2.7%). Concerning episodes with occurrence of rainfall between 10.1 and 25 mm, the highest frequencies are observed in January (17.2%), February (16.4%) and March (16.1%) during the dawn (20.8%) and morning (18.8%), following by April (15.7%) and May (13.9%) during the night (14.3%) and afternoon (9.7%) periods.

An outstanding result evidenced in Figures 4 and 5 is the frequency distribution of events with rainfall lower than 10 mm $6h^{-1}$. These events explain the largest proportional contribution of the total rainfall observed during all rainy season months, which reaches 83.3% in May, 77.5% in April, 74.3% in February, 73.3% in January and 72.9% in March. These episodes have preferential occurrence period during the afternoon (84.2%) and night (79.7%) and they are relatively less frequent during the morning (71.2%) and dawn (70%). An analysis of the hourly rainfall time series indicated that such events are associated with the occurrence of weak and continuous precipitation persisting for more than 3/4 hours. Therefore, this evidence suggests that most of the pluviometric total observed mainly in the end of the rainy season (April and May) results from contribution of the stratiform-like rainfall (i.e., weak and continuous precipitation) along the day.

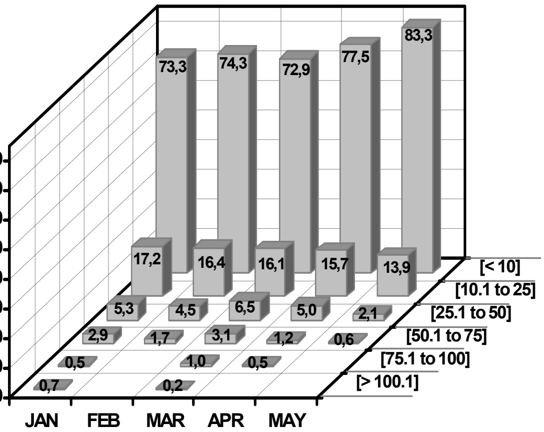

Figure 4: Frequency distribution (%) of the 5-yr rainfall average (2001-2005) observed in Bragança according to the six intensity ranges (< 10, 10.1 to 25, 25.1 to 50, 50.1 to 75, 75.1 to 100 and > 100.1 mm $6h^{-1}$) during each month of the rainy season.

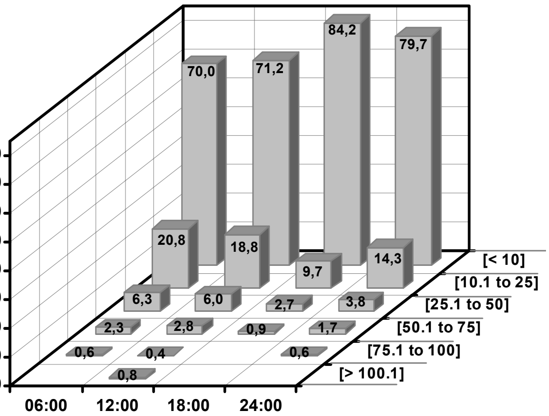

Figure 5: Frequency distribution (%) of the 5-yr rainfall average (2001-2005) observed in Bragança according to the six intensity ranges (< 10, 10.1 to 25, 25.1 to 50, 50.1 to 75, 75.1 to 100 and > 100.1 mm $6h^{-1}$) corresponding to the JFMAM average at 06:00, 12:00, 18:00 and 24:00 LST.

3.3. Dynamical mechanisms

The diurnal variation obtained from CMORPH-based rainfall estimates and vertically integrated moisture flux corresponding to the 3-yr average (2003-2005) in the eastern Amazonia and adjacent equatorial Atlantic are shown in Figures 6 and 7, respectively. In fact, these figures provided comprehensive evidences of a significant diurnal cycle of the ITCZ as the main rainfall-producing mechanism in the equatorial Atlantic including continental areas of the eastern Amazonia. During the dawn period (accumulation at 06 LST in Figure 7), there is an area containing stronger rainfall between 7 and 11 mm $6h^{-1}$ stretching zonally along the equator and affecting Marajó island and coastal region of Pará near Bragança. Subsequently, a southward expansion with intensification up to 15 mm of the rainiest area is observed, which leads to the maximum peak of rainfall during the morning (accumulation at 12 LST in Figure 6) covering most of Atlantic coast of Pará state (Bragança region). Other important characteristic noticed in this period is the establishment of the double band of ITCZ whose north side also induces rainfall over eastern and southern Amapá state. These features are supported by strong northeasterly flow from equatorial Atlantic whose configuration supplies moisture into zonally oriented ITCZ convective band. During the dawn there is significant moisture convergence along the coastline of the Amazonia with maximum center located around 2ºN, which progressively increases, expands equatorward affecting eastern Amazonia as a whole during the morning period (Figure 7). In the afternoon period (accumulation at 12 LST), the ITCZ-related convective band (Figure 6) and its maximum center of low-level moisture convergence (Figure 8) shift northward, yielding intensified rainfall to the north of Pará and most of Amapá. Consequently, the regions located below of equator to the east of 50ºW present significant pluviometric reduction, determining the minimum peak over these areas. These configurations are similar during the night (accumulation at 24 LST) but with a small increase of magnitude of rainfall in the regions analyzed. Importantly, it is the close correspondence between spatial configuration and intensity of CMORPH-based rainfall (Figure 6) and the diurnal variation of the rainfall in Bragança station (Figure 3a), which both present maxima peaks during the dawn and morning periods and a sharp minimum peak during the afternoon and night periods.

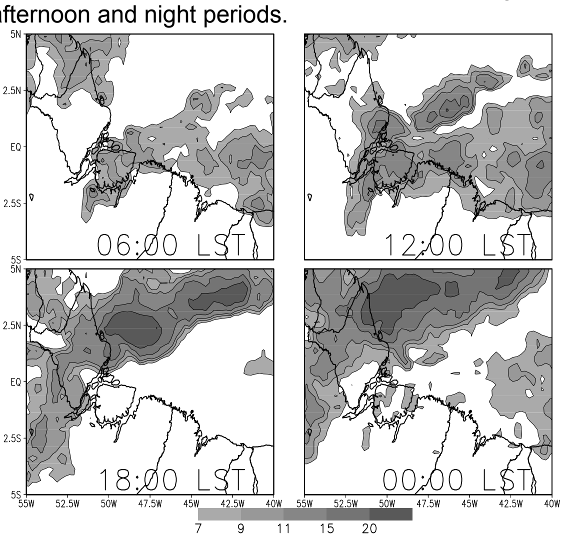

Figure 6: 6/6 h accumulation of the CMORPH rainfall estimates (mm 6 h^{-1}) at 06:00, 12:00, 18:00 and 24:00 LST corresponding to the 3-yr average (2003-2005) for rainy season as a whole (JFMAM). Only values greater than 7 are plotted (see legend).

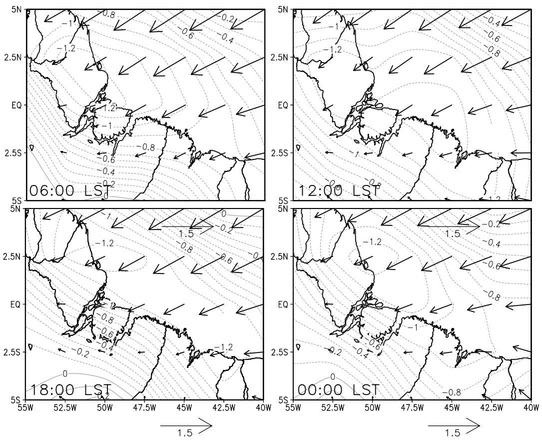

Figure 7: As in Fig. 6, but for the vertically integrated moisture flux (vectors) and its divergence field (contours). The reference vector is 1.5 Kg m^{-1} s^{-1}.

4. CONCLUDING REMARKS

Five years (2001-2005) of continuous rainfall data collected *in situ* by LBA station in Bragança-PA are used to describe the observational characteristics of the diurnal pluviometric variation in a point located in the core of the eastern Amazonia off Atlantic coast, during rainy season (January to May). The 5-yr average of accumulation of rainfall in each 6 hours (06:00, 12:00, 18:00 and 24:00 LST) evidenced maximum peaks during the dawn to morning period and a sharp minimum during the afternoon. A significant diurnal cycle related to the ITCZ activity in the equatorial Atlantic is pointed out as the main mechanism regulator of diurnal variability of rainfall in the coastal region along the Pará and Amapá states. In average, the highest frequency of rainy days occurs in March following sequentially by April, February, January and May. Note that the overall characteristics of the diurnal cycle in Bragança were obtained considering rainfall events different from zero and greater than 0.3 mm 6h^{-1}. There have been relatively few studies that approached observational aspects related to the diurnal rainfall variations for others points located particularly in the oriental Amazonia. Based on INMET daily reports for the period 1961-70, Kousky (1980) presented a pioneering study in which most coastal areas of the northeastern Brazil (e.g., Macapá-AM, Soure-PA and São Luis-MA stations) are found to experience a nocturnal to early morning maximum in rainfall activity, during January to May. Using five years (1990-94) of measurements from ABRACOS, Liebmann *et al*. (1998) reported that in Marabá-PA, near the eastern edge of the Amazonia, there is a broad maximum during the dawn and morning (02:00 to 10:00 LST) and a minimum during the afternoon between 12:00 and 17:00 LST. Nechet (2002) demonstrated that in Macapá-AP the peak of the daily precipitation events during March and April occurs usually in the early morning (08:00 to 09:00 LST). Therefore, the evidences reported in the present paper for the Bragança-PA station are consistently similar to these previous analyses. Furthermore, the frequency distribution of rainfall events considering six different intensity ranges (< 10, 10.1 to 25, 25.1 to 50, 50.1 to 75, 75.1 to 100 and > 100.1 mm 6h^{-1}) is documented for each month and period of diurnal cycle. An outstanding result evidenced is the frequency distribution of events with rainfall lower than 10 mm $6h^{-1}$, which explain the largest proportional contribution of the total rainfall observed during all rainy season months. The hourly rainfall time series indicated that these events result from contribution of the stratiform-like rainfall, i.e., weak and continuous precipitation persisting for more than 3/4 hours along the day. It is important to mention that although the mean characteristics of the diurnal cycle of rainfall reported here, have been evidenced from satellite estimates and *in situ* data with a high temporal resolution for the last 5 years (2001-2005), the overall results should not be generalized as climatological patterns as well as for the whole eastern Amazonia.

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