

Analysis of the breeze circulations in Eastern Amazon: an observational study

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Abstract

An observational analysis was conducted in five different cities in Eastern Amazonia, in order to detect the breeze circulations in the region. The frequency of wind direction, wind speed, and precipitation was analyzed along with estimated spatio-temporal rainfall through the Climate Prediction Center Morphing Technique (CMORPH). The results show different types of breezes that occur in these cities, with regular time from 0900–2100 UTC for SB (sea breeze), 0000–0900 UTC for LB (land breeze), and 1200–0000 UTC for RB (river breeze). The SB has been shown to be more frequent from September to November (SON), while the LB is more prominent from March to May (MAM). However, the RB highlights throughout the whole year in Belém. The hour of occurrence of the SB circulation and the precipitation along the coast has shown a relationship.

Keywords: sea breeze; river breeze; land breeze; local circulation; Amazon rainforest; Climate Prediction Center Morphing Technique

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1. Introduction

The Eastern Amazon (Figure 1 for the geographical location of the target area in this study) observes a variety of mesoscale convective systems, among which we can highlight mesoscale convective complex (CCMs) and squall lines (SLs) (Kousky, 1980; Maddox, 1980; Cohen *et al.*, 1995; Vitorino *et al.*, 1997; Silva Dias *et al.*, 2004; Lu *et al.*, 2005; Fitzjarrald *et al.*, 2008; Ramos da Silva *et al.*, 2011; Cohen *et al.*, 2014; Matos and Cohen, 2015).

The SLs that form along the Amazon Atlantic coast has its genesis associated with the sea breeze (SB) circulation (Kousky, 1980). This convective system is responsible for 45% of the precipitation in Eastern Pará (Figure 1) and in the Amazon central region during the rainy season (Greco *et al.*, 1990; Garstang *et al.*, 1994; Cohen *et al.*, 1995). The diurnal cycle of rainfall is highly influenced by the breeze circulations, having its maximum pronounced when these circulations occur (Kousky, 1980; Janowiak *et al.*, 2005).

The river breeze (RB) circulation, as well as the SB and the land breeze (LB), is the result from the difference of the heat capacity of the continent and water. During the day, the temperature in the continent is greater than on the water, while at night we observe the opposite. On the hot side has a low pressure with the air flow coming from the relatively cooler side; this air coming to the hot side goes up and returns to the cooler side, thus generating a local circulation.

According to Kousky (1980), the diurnal variation of the rainfall in the neighborhood of the coastal area of Eastern Amazon experience a maximum rainfall at night until the early due to the low level convergence associated to the mean flow coming from the ocean and the continental flow directed toward the ocean (LB).

About 700 km inland from the Amazon Atlantic coast, there is the confluence of the Amazon and Tapajós rivers, where the diurnal variability of the rainfall was analyzed according to the distance of the river. Near the Amazon bigger rivers, the precipitation is predominantly nocturnal, while on the continent it takes place both at night, associated with the passage of the SLs, as in the afternoon due to the RB (Fitzjarrald *et al.*, 2008; Cohen *et al.*, 2014).

Although the breeze circulations are well known, there are few studies that define the average patterns of these circulations observationally. In that sense, this study aims to investigate the mesoscale atmospheric circulation, associated with the breeze circulations and its contribution in the diurnal cycle of precipitation.

2. Data and methodology

The study was conducted in Northeastern Pará region located in Northern Brazil using data from automatic weather stations installed in five different cities: Belém, Pará's state capital, located in (−1.4103°; −48.4383°); Soure, located in the Marajó's island

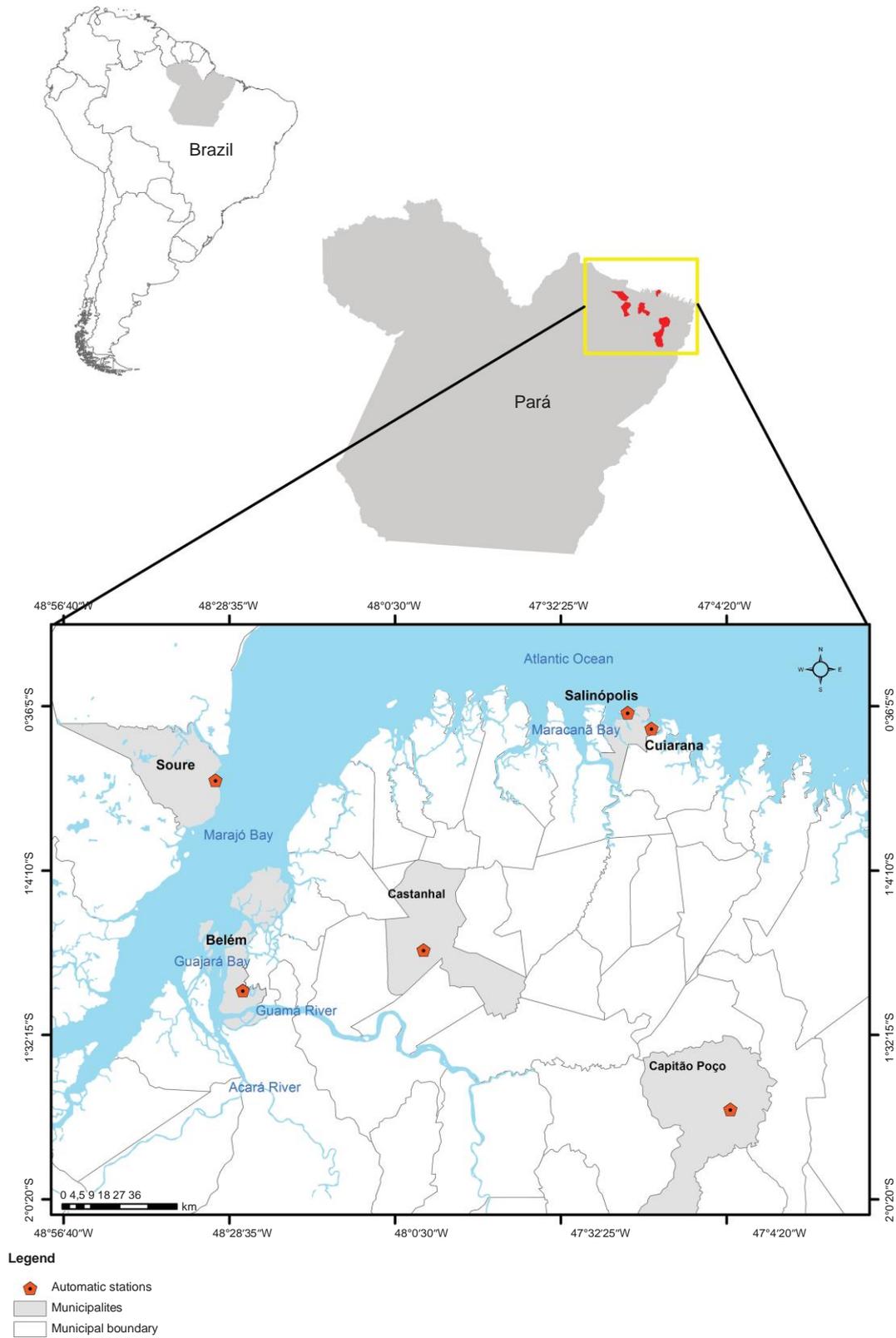


Figure 1. Map of the study area showing the location of the automatic weather stations.

(-0.8112° ; -48.5158°); Salinópolis (-0.61868° ; -47.3511°); Cuiarana (-0.6636° ; -47.2842°); Castanhal (-1.2952° ; -47.9281°), and Capitão Poço (-1.7489° ; -47.0614°) as shown in Figure 1. It is worth emphasizing that each location has different surface characteristics, Belém (population: 1 0393 399)

is an urban metropolis; Soure (population: 23 001) is located on the western bank of the Marajó Bay – a large estuary of the Amazon and Tocantins rivers; Cuiarana and Salinópolis, both part of the same municipality (population: 37 421), are located on the coastline near the Atlantic Ocean; Castanhal (population: 173 149);

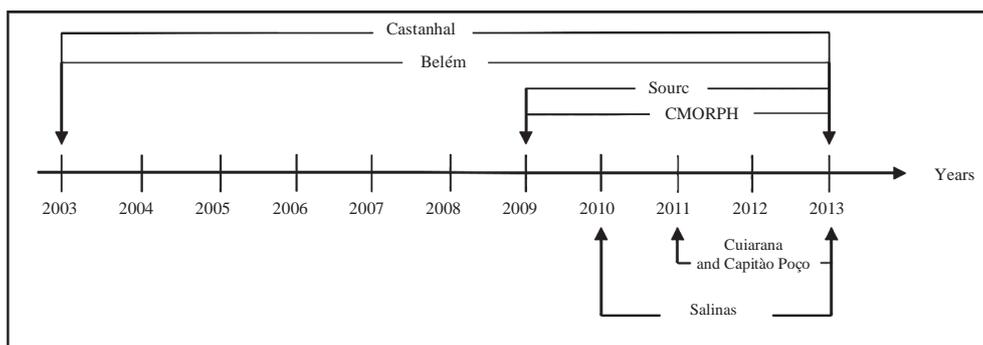


Figure 2. Description of the time series data for each location.

and Capitão Poço (population: 51 893) are located a little further inland.

The data that we have used in this study were precipitation (mm), wind speed ($m s^{-1}$), and direction (degrees). The data were retrieved from automatic weather stations located in each city. In Cuiarana, these data were collected and stored every 10 min in the period from 2011 to 2013. On the other hand, the data collected in Belém, Castanhal, Capitão Poço, Soure, and Salinópolis were collected every hour, for different periods (Figure 2): Belém and Castanhal (2003 – 2012); Soure (2009 – 2012); Cuiarana and Capitão Poço (2011 – 2013), and Salinópolis (2010 – 2013). After retrieving the data, hourly averages were computed. The hourly averages were determined for each city considered in this study. The months with more than 15 days missing were not computed and the days with no information were considered as NA (not available).

To calculate the hourly frequency of wind speed and direction, and precipitation we used the Metvurst package – Meteorological visualization utilities using R for science and teaching (Appelhans *et al.*, 2013). To obtain the average variability of the circulation and precipitation we applied the calculation of the hourly frequency. After that, the data were divided into seasonal series.

In order to evaluate the diurnal cycle of precipitation associated to the breezes circulations with high spatio-temporal ($0.25^{\circ}lat/long - 3/3 h$), we used the data from the Climate Prediction Center Morphing Technique (CMORPH), according to Joyce *et al.* (2004). The intervals considered in this study for the definition of the breeze circulations were: SB 0900–2100 UTC, LB 2100–0900 UTC, and RB 1200 – 0000 UTC. These criteria were defined from the observation of the average standards of breezes circulations, as shown in several studies (Haurwitz, 1947; Fitzjarrald *et al.*, 2008; Teixeira, 2008).

3. Results and discussion

3.1. Average patterns of the local circulations

In general, the wind direction diurnal cycle presents a Northeastern (NE) main maximum for most of the locations, featuring the occurrence of the SB on the

same direction of the trade winds. The SB is most frequent during the period from 1200 to 2100 UTC as shown in Figure 3(a). These local winds are associated with the mean flow of the trade winds that through displacement of the subtropical ridges can change the intensity of local circulation (Cavalcanti, 1982; Uvo, 1989, Baptista, 2003). In that sense, it is observed that the SB for Salinópolis and Cuiarana is much more pronounced when compared to other localities, due to its proximity to the Atlantic Ocean. We also notice that the wind speed (Figure 3(c)) generally increases with the occurrence of the SB. This is due to the fact that the SB is in the same quadrant of the mean flow – vectorially the SB is in the same quadrant as the mean flow, thereby increasing its intensity (Frizola and Fisher, 1963; Atkinson, 1981; Costa and Lyra, 2012; Santos *et al.*, 2013). In Castanhal and Capitão Poço, we observed an eastern pattern on the wind direction, having its most pronounced frequency during the hours from 1200 to 1800 UTC along with an increase in the wind speed, again due to the penetration of the SB.

The increase in the wind speed (Figure 3(c)) is directly related to the time when the air-sea temperature contrast is higher, forcing the inland penetration of the SB. The penetration of the SB is clearly represented by a slight shift in the wind direction (Figure 3(a)) from NE to E in Capitão Poço, Castanhal, and Soure. Cuiarana and Salinas did not have an apparent wind direction shift, suggesting that the SB penetrates in the same direction as the mean flow, as discussed before. However, the wind speed increase in Cuiarana and Salinas is as noticeable as in the other cities. Pearce (1955) states that the SB is at first slow, becoming more rapid as the heating continues; the onset of the SB well inland does not occur until a few hours after heating commences. This air-sea temperature contrast determines whether we have the formation of the SB or not; therefore, when we have large-scale weather systems such as the Intertropical Convergence Zone (ITCZ) over the region this contrast becomes smaller, weakening, and sometimes not allowing the formation of the SB. A further analysis of this seasonal difference will be discussed in Section on Seasonal Analysis of the Breeze Circulations.

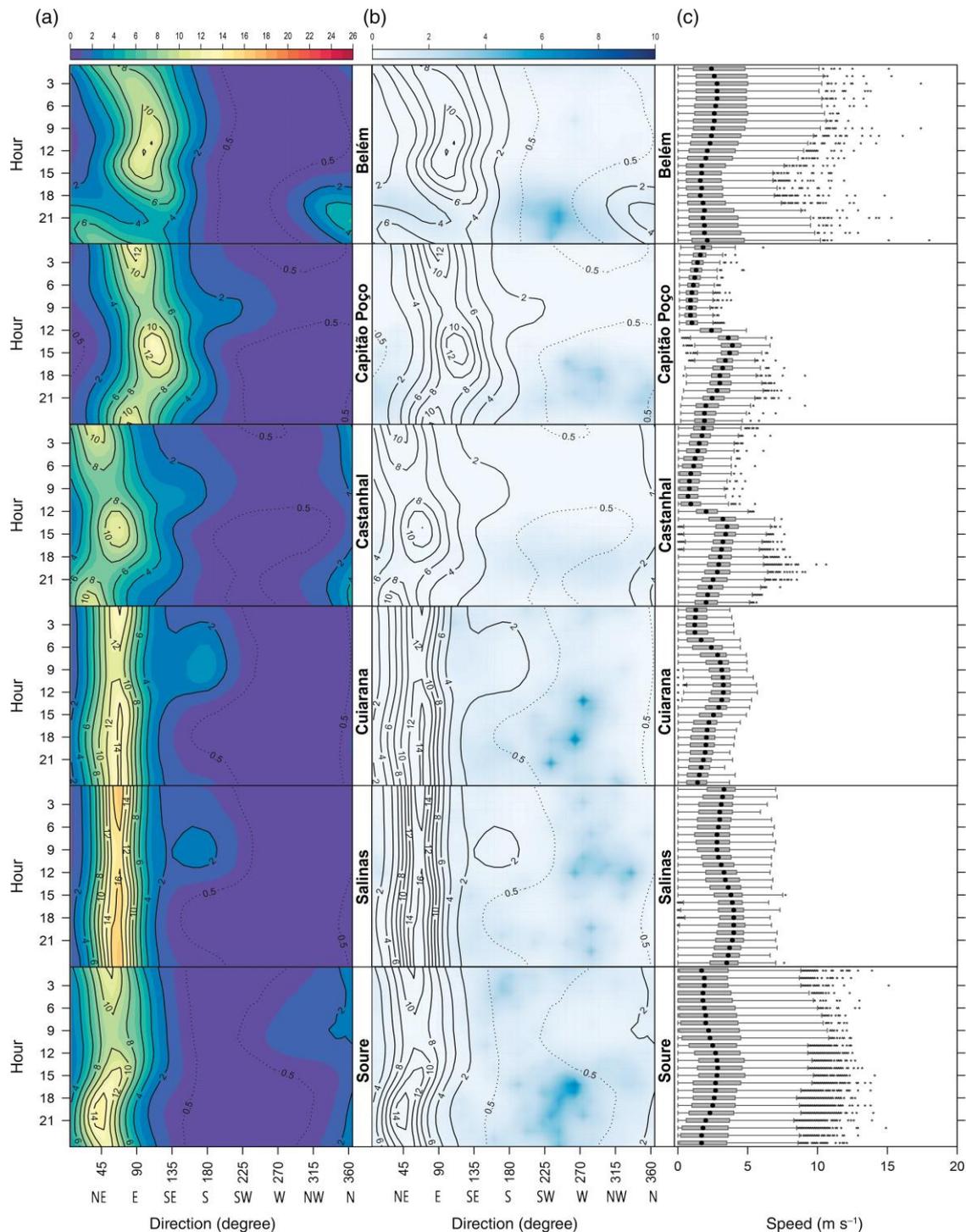


Figure 3. Hourly frequency: (a) wind direction (line, %), (b) wind direction (line, %) and precipitation (shaded, mm), and (c) the median for the wind speed (black points, m s^{-1}), with its respective quartiles (shaded gray bar, m s^{-1}); the outside bars represent the upper and lower whiskers and outliers are represented by asterisks outside of the plot.

The LB was identified from a secondary maximum in the wind direction from Southeast (SE)/South (S) in Salinópolis, Cuiarana, Castanhal, Capitão Poço, and Soure. We also notice that the most frequent hour of this circulation is from 0300 to 0900 UTC. Although we also observed the LB in Soure, the direction of this circulation is different due to its geographical position. The LB in Soure is in a different direction in relation

to other cities; in this case, the LB is from Northwest (NW)/West (W), but at the same time, as in the other cities. In general, we observe the lowest wind speed values (Figure 3(c)) at the same time when the LB is present. Therefore, the LB circulation is less intense when compared to the SB, since it is opposed to the direction of the mean flow (Atkinson, 1981; Teixeira, 2008).

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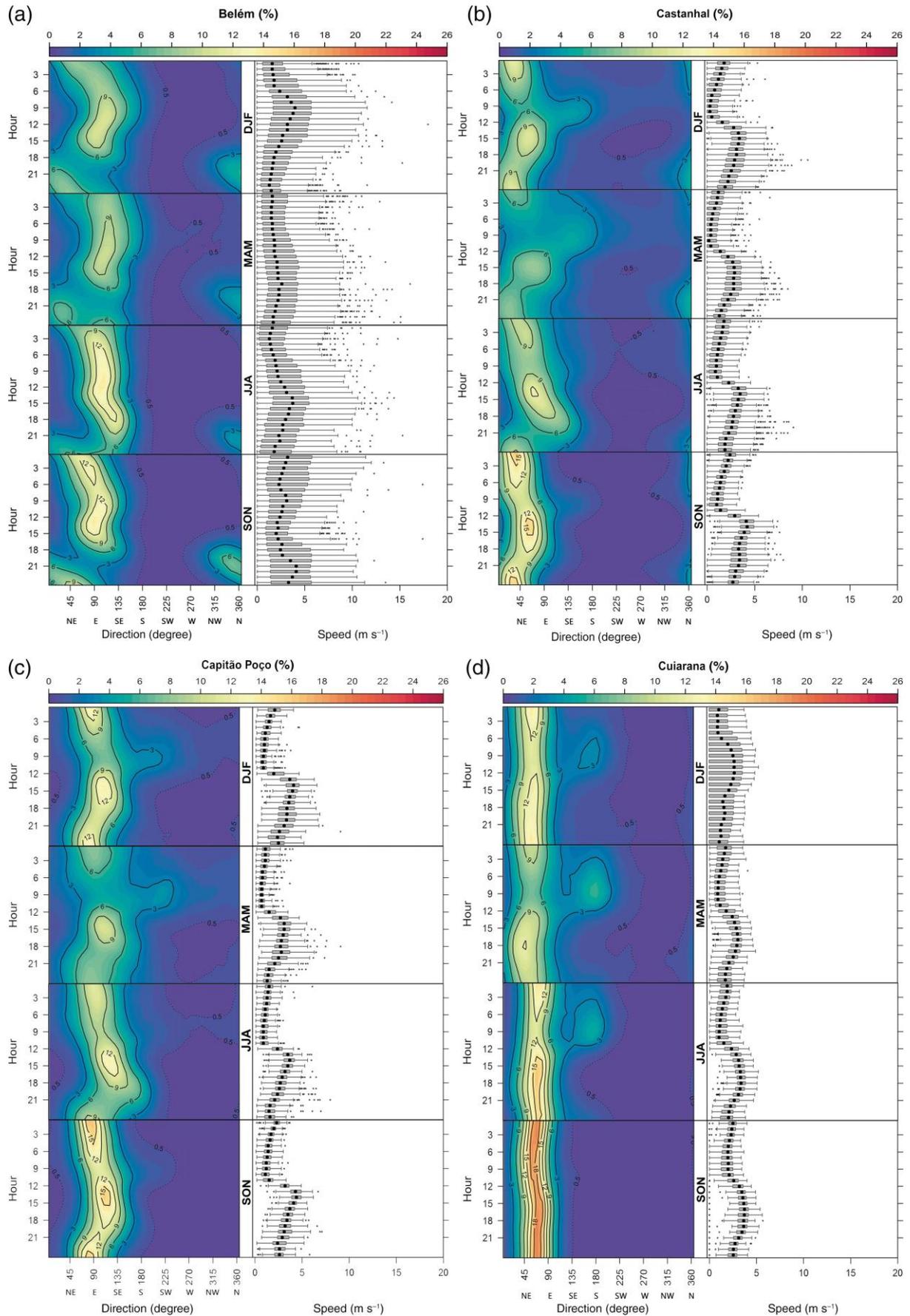


Figure 4. Seasonal hourly frequency of the wind direction (left panel) and speed (right panel) for Belém (a), Castanhal (b), Capitão Poço (c), Cuiarana (d), Salinópolis (e), and Soure (f).

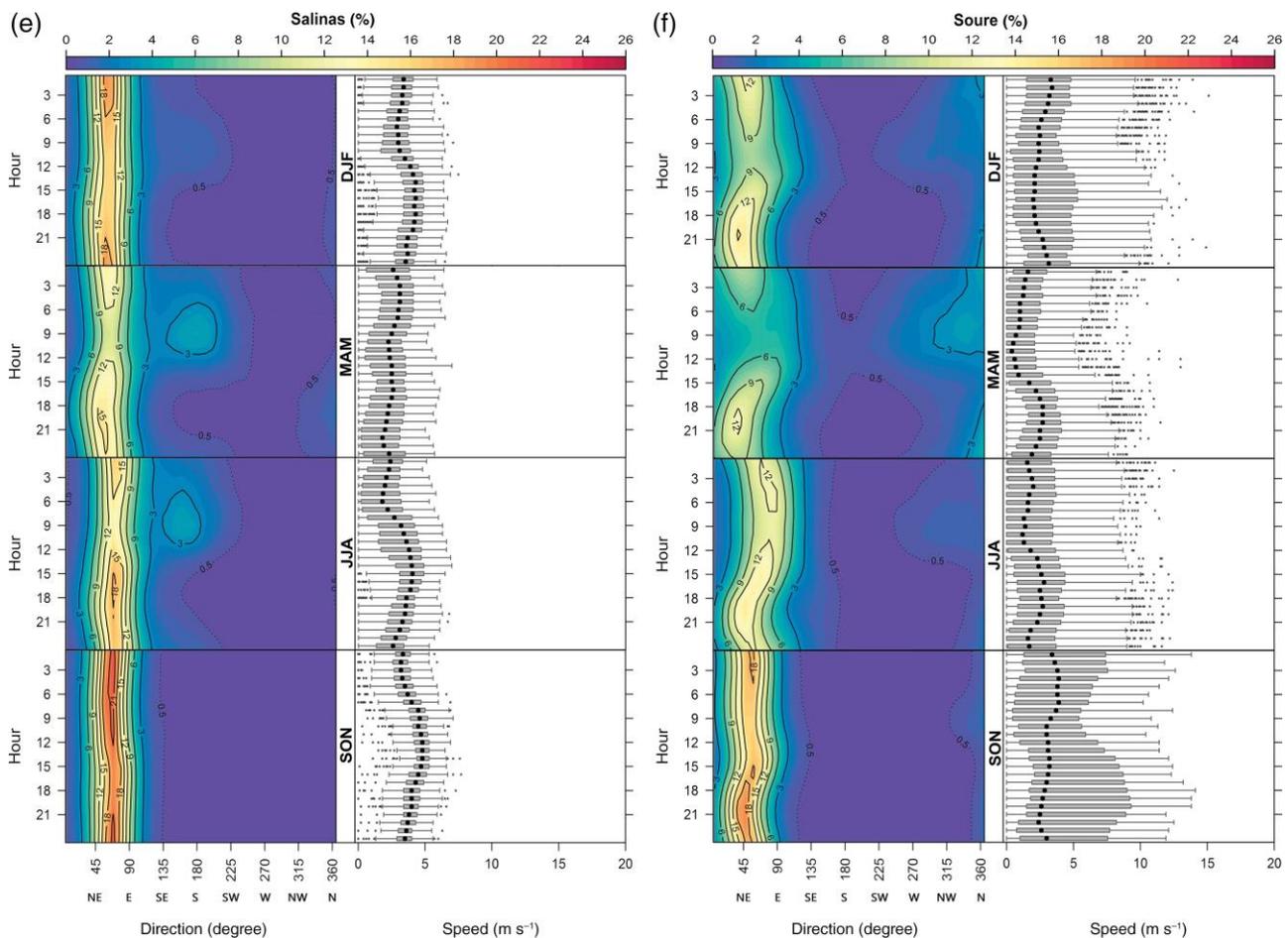


Figure 4. Continued.

In Belém, we cannot observe the LB signal, but we notice the presence of a secondary maximum in the wind direction from NW, with occurrence from 1500 to 0000 UTC, along with a decrease in the wind speed during the time of this secondary maximum. This may be associated with the presence of the RB due to the Marajó Bay proximity to the city. Therefore, this influence becomes much bigger than the oceanic effect on the SB. Other studies have shown the presence of the RB in Amazonian cities (Silva Dias *et al.*, 2004; Fitzjarrald *et al.*, 2008; Cohen *et al.*, 2014; Santos *et al.*, 2014; Matos and Cohen, 2015); generally this temperature contrast between the forest and the rivers can reach more than 6 °C (Greco *et al.*, 1992; Oliveira and Fitzjarrald, 1993).

The precipitation (Figure 3(b)) occurs during the late afternoon and early evening, this result agrees with the results found by Kousky (1980), indicating that the largest rain volumes are in the afternoon, between 1700 and 2100 UTC, with the occurrence of rain also at night. The SB causes this nighttime maximum in local precipitation. According to Janowiak *et al.* (2005), with daytime heating the precipitation rapidly develops along the coast, having its most pronounced effects inland from the coast, producing a nocturnal maximum due to its propagation inland. The effects of the SB on the precipitation are more evident in locations that are farther

inland, such as Belém, Castanhal, Capitão Poço, and Soure, which all experience a higher frequency of nocturnal precipitation from 1500 to 2100 UTC, while Salinópolis and Cuiarana observe precipitation earlier in the day. These results indicate that the SB enters the coast, but its ascending branch which originates convection, is established within the continent. Furthermore, we can also observe the presence of a secondary maximum of precipitation in Soure and Salinópolis, during the early hours of the day from 0000 to 0300 UTC. These results converge again with Kousky (1980), who indicates that the rainfall peak at 0000 – 0300 UTC is associated to the passage of the SB front at Soure, when the convective cells are not totally developed.

3.2. Seasonal analysis of the breeze circulations

Figure 4 shows the seasonal variation of the wind direction for each city, which shows that the SB is more pronounced during the period of September – November (SON), while the LB is more pronounced during the period of March – May (MAM). These seasonal differences both in wind speed and direction in SON are directly connected with the intensification of the South Atlantic subtropical high pressure (Baptista, 2003), contributing to the inland penetration of the SB, which is perpendicular to the coast. According to Nobre and

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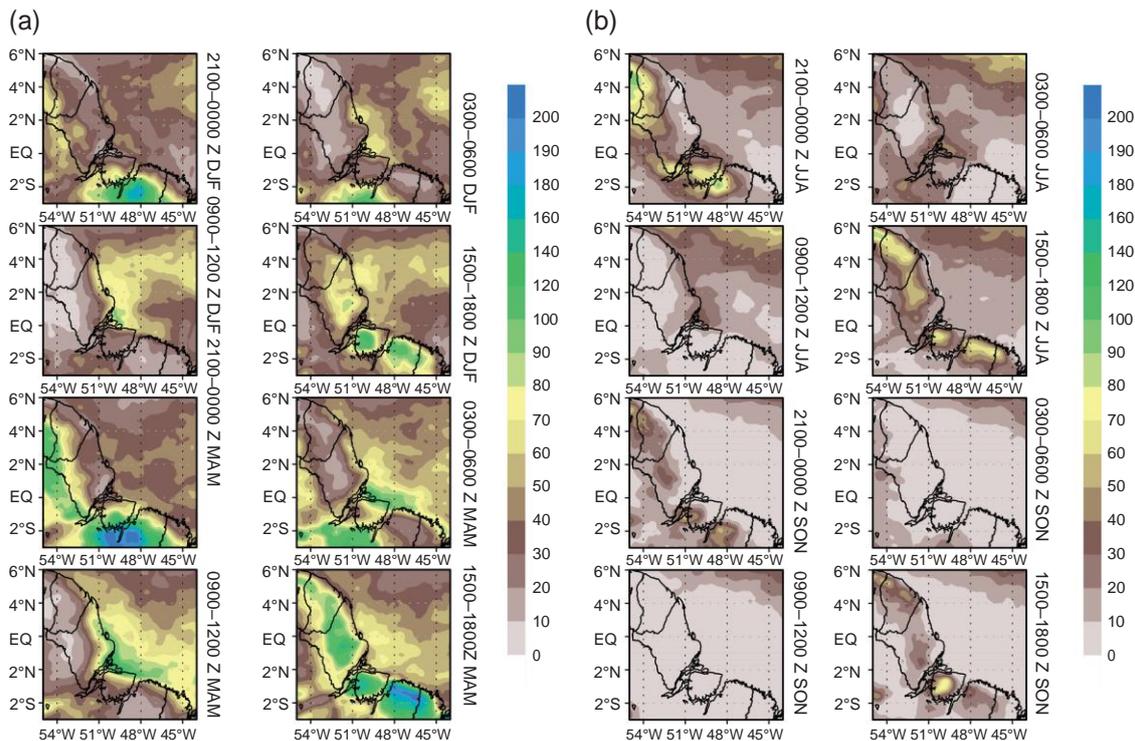


Figure 5. Precipitation patterns associated with the diurnal cycle in the intervals of 2100–0000 UTC, 0300–0600 UTC, 0900–1200 UTC, and 1500–1800 UTC for the seasonal periods of DJF, MAM, JJA, and SON, respectively in mm/3 h.

Shukla (1996), the ITCZ is most active over Northern and Northeastern Brazil during MAM. Due to the intense convection associated with the ITCZ during this period, the mean flow may suffer attenuation, reducing the intensity of the wind that enters the coast. Therefore, the LB shows greater intensity in this period due to the performance of large-scale weather systems such as the ITCZ.

It is observed that cities located closer to the coastline as Cuiarana and Salinópolis, has a predominance of winds from E/NE during most of the year, due to its geographical position, facilitating the SB initiation. The LB was more prominent in the period June– August (JJA) and MAM. On the other hand, in Soure it appears that an increased LB occurs during SON, whereas the LB becomes more evident during December – February (DJF) and MAM. As Belém, Castanhal, and Capitão Poço are located further inland, it is clear the SB is weaker than in the cities closer to the coastline. The LB in Castanhal and Capitão Poço are stronger during MAM, while we cannot identify the LB in Belém. In Belém, we also notice the occurrence of the RB during every month of the year, as well as the SB more intensely during JJA.

Figure 5(a) shows that the highest precipitation values are on the coast, in the period of 1500 – 1800 UTC. These maximums are related to the SB circulation. We can observe that during the hours of 0900 – 1200 UTC precipitation maximums are more localized on the ocean, inducing higher accumulates in located near the coastline as in Soure, Cuiarana, and Salinópolis. These results agree with Negri *et al.* (1994), who demonstrates

the interaction between the SB and LB causing maximum rainfall on the continent and ocean, respectively. During the months of MAM is more noticeable the influence of the LB in the rainfall over the ocean and the SB on the continent. As discussed previously, the LB is more frequent during the months of MAM, justifying the highest values found at the ocean in the period of 0900 – 2100 UTC. However, it should be noted that this pattern is repeated in the diurnal cycle in DJF when the ITCZ is located farther North. It is also possible to verify that the inland precipitation moves during the interval of 2100 – 0000 UTC, possibly associated with the displacement of the SB front and the squall lines (Kousky, 1980; Cohen *et al.*, 1995).

Figure 5(b) shows that the influence of the LB in the precipitation is not evident during the months of JJA and SON. However, we can still clearly see the influence of the SB during the period of 1500 – 1800 UTC both JJA as SON. In SON the maximum precipitation decrease, as these are the months dry period in the region, making it evident the effects of the SB in the precipitation since there are no large-scale weather systems in this period (Figuroa and Nobre, 1990; Rao *et al.*, 1996). It is noteworthy that the same propagation observed in Figure 5(a) is still observed in the months of SON and JJA. These results suggest that the SB circulation would be the main trigger in the formation of the Amazonian SLs, as hypothesized by Kousky (1980) and Cohen *et al.* (1995). However, it is known that the SBs usually occur every day, while the same does not occur with the SL, indicating that besides the SB there must be some other mechanism for the formation of the SLs.

4. Conclusion

The main goal of this study was to analyze the local circulations in Belém, Castanhal, Capitão Poço, Soure, Cuiarana, and Salinópolis and its influence on the diurnal cycle of precipitation. For this, we used rainfall data and horizontal wind (direction and speed) from the automatic stations located in these cities, as well as estimated rainfall through the CMORPH.

It was observed that the SB has a regular frequency in the NE/E quadrant. The LB was more intense in coastal regions during the hours of 0900–2100 UTC, moving in the same direction of the mean flow. On the other hand, the LB was observed only in Cuiarana, Salinópolis, Castanhal, and Capitão Poço in the quadrant SE/S, while in Soure, the LB was observed in the NW/N quadrant due to its geographical position. In general, the time of its performance takes place from 0000 to 0900 UTC. The SB was more intense during the SON, while the LB was observed more pronouncedly during MAM and JJA. The hourly rainfall was more related to the SB than the LB.

In contrast, Belém observed the presence of the RB in the NW/N quadrant, with time of occurrence from 1200 to 0000 UTC; this circulation has been regularly observed throughout the year. Although we can detect the signal of the SB in cities located farther inland, it is weaker compared to coastal regions.

The rainfall estimates through CMORPH confirm the influence of the SB circulation generating a cumulative rainfall during the period of 1500–1800 UTC on the coast and inland 2100–0000 UTC. Accumulated located more on the ocean due to the LB is also evidenced in the study, during 0900–1200 UTC.

Finally, despite the breezes are well studied, there are few studies that examined observationally the breezes circulations in the Amazon. Local circulations in the Amazon region contribute to the precipitation regime and are represented in the climatological normal, being relevant for the improvement of weather and climate models, and knowledge of the interactions between scales.

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