The South American Water Balance: The Influence of Low-Level Jets

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(Manuscript received 20 January 2015, in final form 14 October 2015)

ABSTRACT

To study the climatology of the water balance over South America and analyze the influence of low-level jets (LLJs), a climate study of the water balance and its main components was performed, specifically in the Amazon and La Plata basin (LPB) region, from 1979 to 2008. The results showed that on average for the analysis period, the Amazon basin and LPB performed as a sink of moisture (ET $< P$) and as a moisture convergence for the regions, which accounted for approximately 62% and 43% of the precipitation, respectively. During the study period, 884 days with an occurrence of LLJs were observed, occurring most frequently during the winter and around 0000 and 0600 UTC. When considering the water balance for the days with LLJs, it was observed that the Amazon acts as a source of moisture, especially in the dry season, and that the LPB behaves as a sink during all months. The influence of the LLJ as a modulator for precipitation on the LPB is clear, as the precipitation is 32% higher during the LLJ events compared with days without LLJs. This main pattern shows that the moisture convergence trough of the LLJs is crucial for the water balance on the LPB, whereas evapotranspiration is a more important variable of the water balance on the Amazon basin with or without the LLJs.

1. Introduction

South America has two important drainage basins: the Amazon basin, which is the largest in the world, and the La Plata basin (LPB), which is formed by the junction of three subbasins (Paraná, Paraguay, and Uruguay) and is the second-largest water basin in South America. The role played by the Amazon basin, which is one of the world's largest hydrographical systems, is recognized as important for moisture transport from the basin to extratropical latitudes.

Several researchers, including Herdies et al. (2002), Marengo et al. (2004), Nascimento (2008), and Arraut et al. (2012), have shown that much of the moisture available in southern and southeastern Brazil and in the LPB is transported from the Amazon by low-level jets (LLJs). In a conceptual model of the LLJs in South America, Marengo et al. (2004) showed that moisture transport, which is driven by the trade winds that change direction when they meet the Andes, begins in the Amazon region and the North Atlantic region. Then, the moisture transport shifts to the south of Brazil and the north of Argentina in the exit region. Berbery and Barros (2002) showed that the LLJ east of the Andes provides moisture from the tropical region of South America throughout the year. According to Dirmeyer et al. (2009), the moisture observed in the LPB has its origin in the Amazon, but some researchers, including van der Ent et al. (2010), Keys et al. (2012), and Martinez and Dominguez (2014), have shown that there is a large contribution from local terrestrial sources (local recycling) on the observed precipitation over the LPB.

According to Martinez and Dominguez (2014), the link between atmospheric circulation patterns and moisture transport over the LPB is a field that requires

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DOI: 10.1175/JCLI-D-15-0065.1

more study. This lack of knowledge is the motivation behind this study regarding the important role played by the LLJs on the water balance and its components, such as precipitation, evapotranspiration, and moisture convergence, for a large portion of the Amazon region and over the LPB.

Studies have been conducted on the water balance in the Amazon region since the 1970s. Molion (1975, 1993), Salati and Marques (1984), and Salati (1987) attempted to quantify the components of the water balance and moisture recycling using observations, some radiosonde data in the Brazilian Amazon, and moisture budget models. Subsequent studies used a variety of observational datasets, including radiosonde data, global reanalysis, a combination of the two, or climate models, to estimate the hydrological cycle, its variability during various time scales, and the impacts of local or remote atmospheric patterns on the variability of water balance components and the water balance for the entire Amazon (Matsuyama 1992; Eltahir and Bras 1994; Marengo et al. 1994; Vörösmarty et al. 1996; Rao et al. 1996; Costa and Foley 1999; Curtis and Hastenrath 1999; Zeng 1999; Labraga et al. 2000; Leopoldo 2000; Rocha 2001; Roads et al. 2002; Marengo 2004, 2005; Karam and Bras 2008; Satyamurty et al. 2013).

The absence of continuous precipitation and evaporation measurements throughout the Amazon basin and the lack of drainage measurements from the Amazon River and its tributaries have forced many scientists to use indirect methods to assess the water balance in the region. Estimates of its components have been made from moisture and wind grid point data obtained from global reanalysis from international meteorological centers, such as the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF).

In this study, reanalysis data from the Climate Forecast System Reanalysis (CFSR) at the NCEP is used for the 30-yr period from 1979 to 2008 to examine the behavior of the water balance components for the majority of South America, specifically for the Amazon and LPB regions, in order to identify their behavior as a source or sink of moisture for the atmosphere. Furthermore, considering the contribution made by the LLJ in the transport of moisture between the tropics and extratropics, their influence on the main water balance components in these same locations, the Amazon and LPB regions, is identified and quantified.

2. Data and methodology

Reanalysis data from CFSR at the NCEP (Saha et al. 2010) were used to conduct a climatological study of the water balance and classify the days with occurrences of LLJs. The CFSR data were developed to produce a high-resolution simulation of a surface–atmosphere–ocean system. The global atmospheric model has a resolution of approximately 38 km (T382), with 64 vertical levels, available every 6 h, but daily averages were generated in this study. According to Quadro et al. (2013), the CFSR reanalysis has a good correlation with observed precipitation data, especially over the South Atlantic convergence zone (SACZ) region and LPB, indicating that this was a good dataset for studying the water balance over South America.

This study conducted a climatological study of the water balance components over 30 years (1979–2008) for four preestablished regions: the first two regions are in the west (box 1.1, 15°S–5°N, 75°–60°W) and in the east (box 1.2, 15°S–5°N, 60°–45°W) of the Amazon, and the second two regions are based on the research performed by Lee and Berbery (2012). These regions are in the north (box 2.1, 28°–15°S, 66°–46°W) and south (box 2.2, 37°–28°S, 65°–51°W) of the LPB, as shown in Fig. 1. The division into different regions facilitates the analysis of the water balance, indicating its behavior as a source or sink of moisture for other regions. There is a great contribution of moisture from the tropical Atlantic Ocean to the moisture flux over the Amazon basin, and this occurs mostly in the eastern portion of the basin. Thus, the division into two boxes improves the analysis of this feature.

Considering that the precipitation from the CFSR dataset is a modeling product and not a direct measurement, we performed a comparison with the monthly mean precipitation dataset from Matsuura and Willmott (2012) (see Table 1 herein). This dataset has a spatial resolution of 0.5° and is interpolated for the global domain. For all of the study areas (boxes), there is a correlation of 0.95 in which the CFSR dataset overestimates the precipitation by approximately 15% compared with the dataset from Matsuura and Willmott. Considering that this observational dataset shows precipitation values only for the monthly averages, its use for the proposed study is not feasible because daily information is necessary to study of the influence of the LLJ on the study area.

Therefore, the methodology adopted to calculate the water balance is based on the method presented by Marengo (2005), as follows:

$$\frac{dW}{dt} = -P + C + \mathrm{ET}, \tag{1}$$

where dW/dt represents the water stock change period, P is the precipitation, ET is the evapotranspiration, and C is the vertically integrated moisture convergence. Thus,

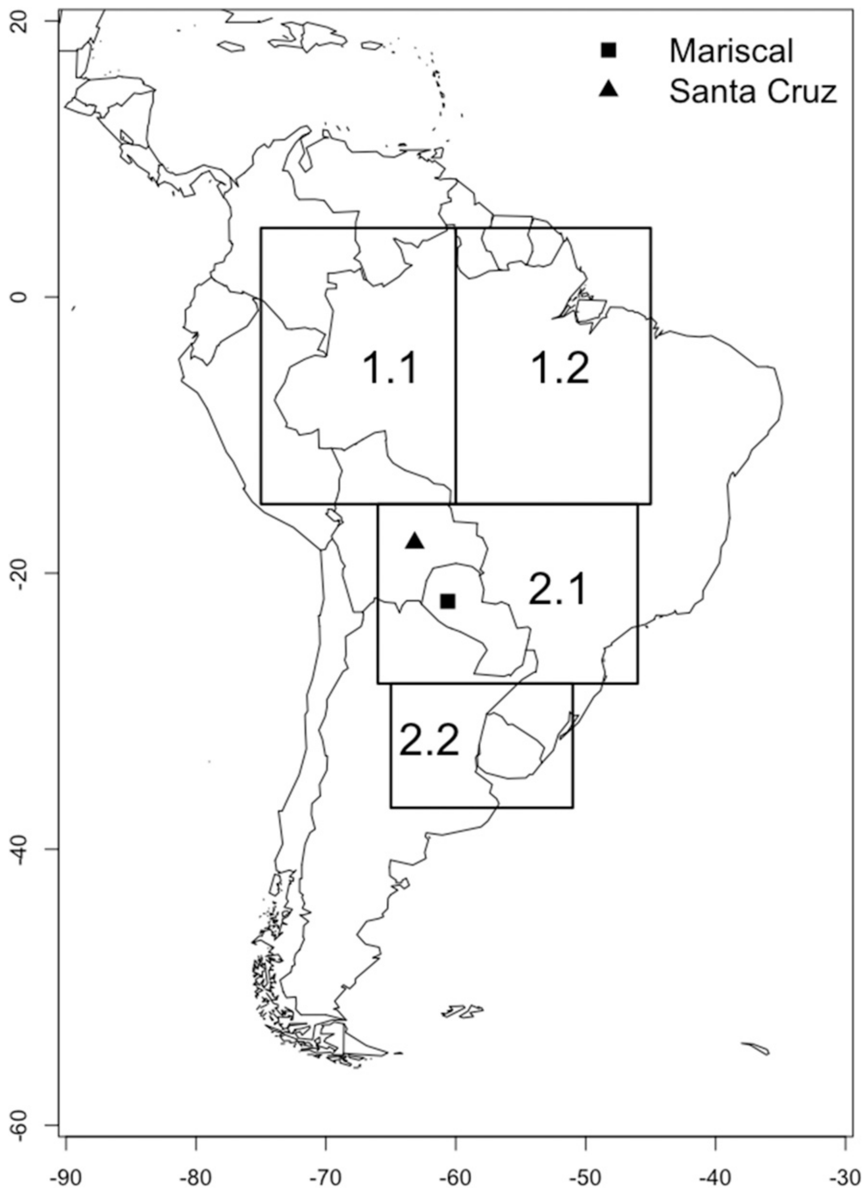

FIG. 1. Illustration of the study area with the predefined regions that were used to calculate the water balance. The cities of Mariscal and Santa Cruz de la Sierra are highlighted.

$$C = -\nabla \cdot Q, \quad (2)$$

where Q is the moisture flux. According to Zeng (1999), dW/dt may be ignored for a period that is greater than or equal to one month because changes in the atmospheric precipitable water is very small during seasonal times. The equation to calculate the water balance is thus written as follows:

$$P - \mathrm{ET} - C = 0. \quad (3)$$

The moisture convergence was vertically integrated between 925 and 100 hPa, and the moisture flow is shown for the layer between 925 and 700 hPa because it is in this layer that the transport related to the LLJ is concentrated. Thus, the role played by the LLJ in the moisture transport between the tropicsss and extratropics will be identified.

This study also classified the LLJ days from 1979 to 2008 using Bonner criterion 1 (Bonner 1968), which was adapted for South America. This criterion specifies that the magnitude of the wind at 850 hPa must be greater than or equal to 12 m s^{-1}, that the vertical wind shear must be at least 6 m s^{-1} between 850 and 700 hPa, and that the meridional component of the wind must be

TABLE 1. Water balance variables for the preestablished regions (mm month^{-1}) for the period between 1979 and 2008 [P: precipitation, ET: evapotranspiration, C: moisture convergence]. The CFSR caption refers to the CFSR data, and the WM caption refers to the Willmott–Matsuura data.

	B 1.1	B 1.2	Amazon	B 2.1	B 2.2	La Plata
P (CFSR)	169.30	150.55	159.92	88.81	75.38	82.10
P (WM)	195.76	163.90	179.83	107.44	93.27	100.35
ET	107.88	112.47	110.17	76.99	66.39	71.69
C	90.06	49.30	69.68	18.51	30.96	24.74
$P - \text{ET} - C$ (CFSR)	−28.64	−11.22	−19.93	−6.69	−21.97	−14.33

negative and greater in module than the zonal component. Therefore, an LLJ day was registered when the criterion was simultaneously satisfied in the cities of Santa Cruz de la Sierra, Bolivia, and Mariscal Estigarribia, Paraguay, for at least one of the four times (0000, 0600, 1200, and 1800 UTC). These two cities were chosen because they sit along the LLJ flow, as described by Marengo et al. (2004). Previous studies, such as those by Douglas et al. (1999), Saulo et al. (2000), and Marengo et al. (2002), also focused their analyses on Santa Cruz de la Sierra because it is representative of the central jet area.

3. Water balance

The average of the water balance variables (Table 1), including the precipitation (P), evapotranspiration (ET), moisture convergence, and ratio between the precipitation and evapotranspiration (ET/P), are shown for the entire Amazon region (Fig. 2a) and for the west (box 1.1) and east (box 2.1) regions (Figs. 3a,b) between 1979 and 2008.

The annual average rainfall over the Amazon region for the study period was 159.92 mm month^{-1} with the highest values (221.1 mm month^{-1}) occurring during the rainy months (November–May) and the lowest values (74.26 mm month^{-1}) occurring during the dry months (June–October) (Fig. 2a). This finding is in agreement with the definition of the dry and rainy seasons by Silva Dias et al. (2002) and Marengo (2005). According to Marengo (2005), a region acts as a source (sink) of moisture to the atmosphere when the evaporation is larger (smaller) than the precipitation. Another definition of moisture source and sink was given by Satyamurty et al. (2013), in which the authors explain that when there is divergence (or convergence) of moisture in a certain region, it behaves as a source (or sink) of moisture to the neighboring regions.

By analyzing the evapotranspiration, which is another important component of the water balance, we observed that there were no pronounced differences over the months, but in the Amazon region the evapotranspiration was also higher during the rainy period and lower during the dry season (Fig. 2a), corresponding to 68% of the total precipitation for the entire period. These maximum values are directly related to the volume of precipitation and the quantity of water available at the surface for the evaporation process. An analysis of the ratio between the evapotranspiration and precipitation indicated that between the months of July and October (dry season), the Amazon behaves as a source of moisture to the atmosphere, with an availability of water to the atmosphere that is 36% higher than the observed precipitation. Evapotranspiration plays a key role in the water balance over the region during the dry season. This seasonality in the ET/P ratio of the water balance by Marengo is also discussed and highlighted in the review (2006).

According to Marengo (2006), the ET/P ratio is the recycling rate, which indicates how evapotranspiration contributes to the average rainfall in a given area, and it can serve as a tool for diagnosing the interactions between the surface and regional climate.

A large portion of the regional precipitation over the Amazon is due to the moisture convergence from the Atlantic Ocean during the rainy season, and the remaining moisture comes from evapotranspiration in the forest (Salati et al. 1979; Satyamurty et al. 2010, 2013). The largest values for moisture convergence coincide with the rainiest period over the region; thus, they directly contribute to the largest rainfall indices, which occur mainly during the summer and fall (Fig. 2a). During July, August, and September, there was a moisture divergence with the lowest rainfall and highest ratio between the ET and P. Thus, during these months, the region behaved more as a source of moisture. As shown in Table 1, the average moisture convergence observed in this study is consistent with the results obtained by Marengo (2005).

The observed ET/P ratio for November to May corresponds to 56% of the total precipitation over the Amazon. From the water balance equation, using the variables generated from the reanalysis data, it can be estimated that, on average, the moisture convergence

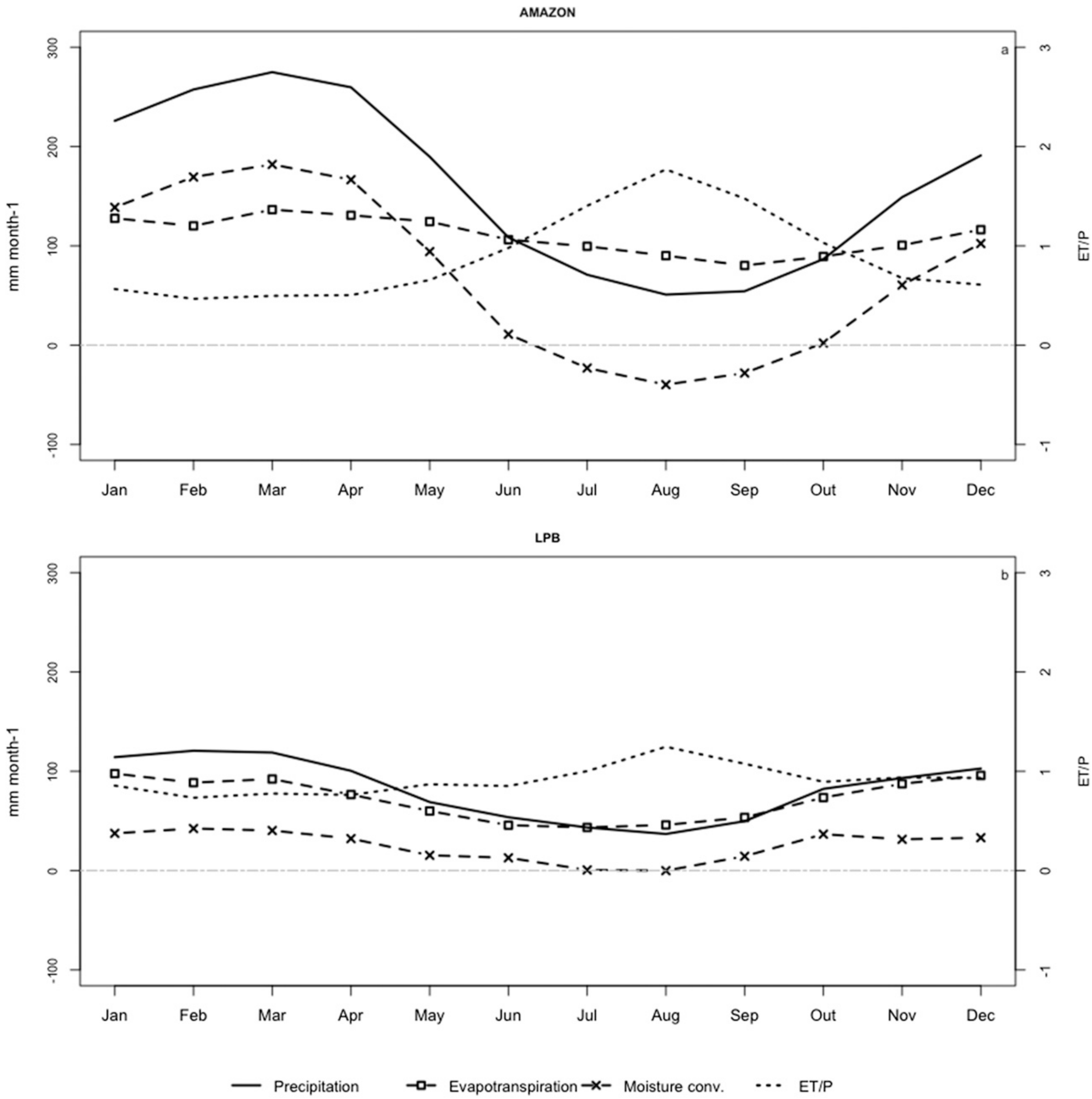

FIG. 2. Water balance variables (mm $month^{-1}$) over the Amazon and LPB regions from 1979 to 2008. Primary axis: precipitation, evapotranspiration, and moisture convergence. Secondary axis: ET/P ratio.

corresponds to 44% of the Amazon precipitation for the entire period, indicating that local evapotranspiration is critical for precipitation. These results are different from those of Satyamurty et al. (2013), who found that the moisture convergence corresponds to 75% of the precipitation over the region. Additionally, when the region behaves as a source of moisture (ET $>$ P), there is a reduction in the moisture convergence. Thus, the Amazon behaves, on average, as a sink of moisture (ET $<$ P) for the entire period. However, between the months of July and October, this region behaves as a source of moisture (ET $>$ P), as observed by Marengo (2005).

Regarding the water balance (Table 1) to the west and east (Figs. 3a,b) of the Amazon region, we observed the same pattern; both regions behaved as a sink of moisture, especially during the wet months. Additionally, during nearly all months except July, August, and September, the Amazon west sector (box 1.1) (Fig. 3a) behaved as a source of moisture to the atmosphere, similar to the eastern portion (box 1.2) (Fig. 3b), except from in

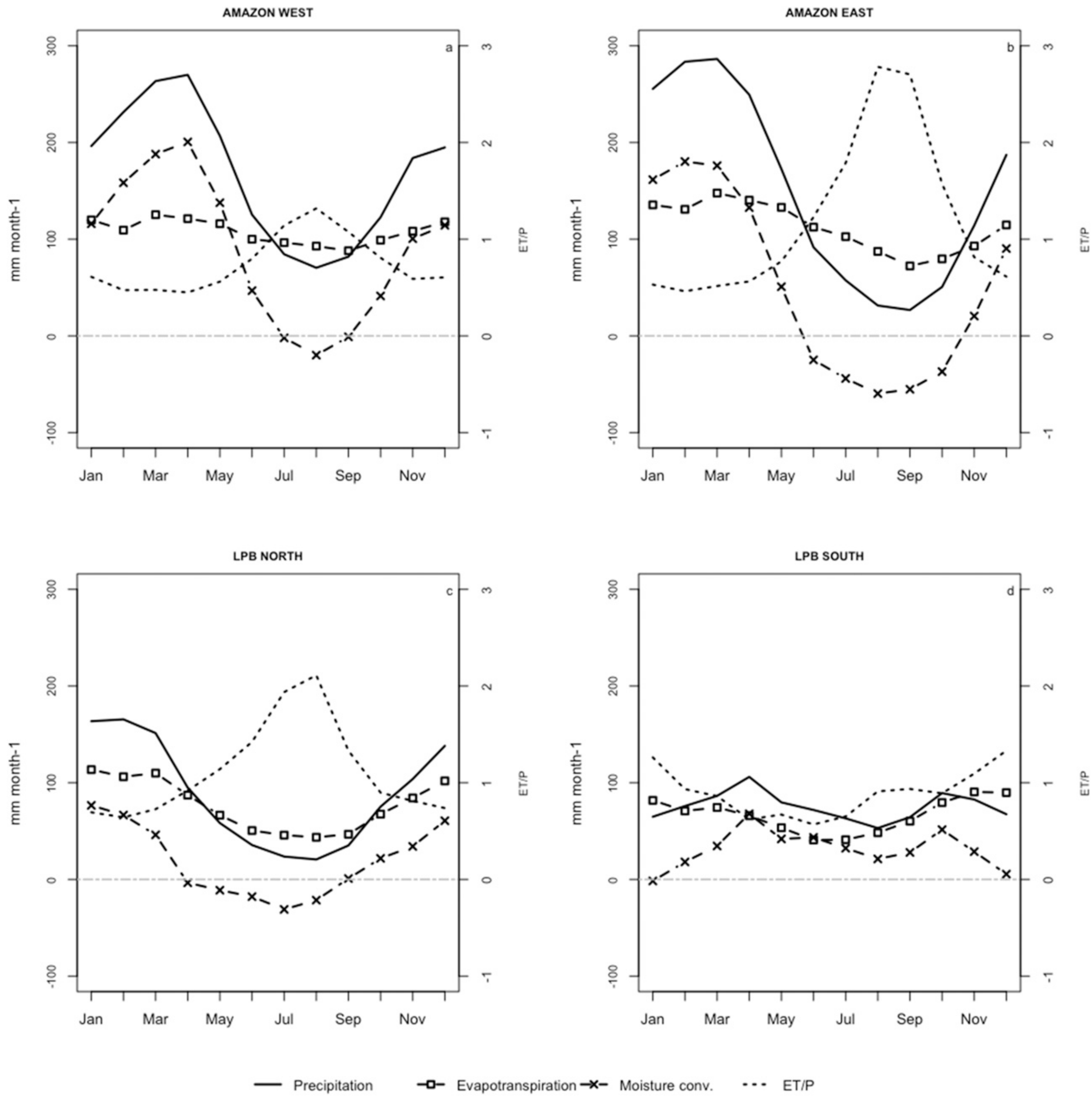

FIG. 3. Water balance variables (mm $month^{-1}$) from 1979 to 2008 over the regions (a) Amazon west, (b) Amazon east, (c) LPB north, and (d) LPB south. Primary axis: precipitation, evapotranspiration, and moisture convergence. Secondary axis: ET/P ratio.

June to October. For the period from June to October in the east sector, there was an increase in the divergence of moisture that became higher than the precipitation, thus providing moisture to other regions, as observed by Satyamurty et al. (2013).

Regarding evapotranspiration (Table 1) in the Amazon region as a whole, no major differences were observed between the months when the west and east portions were analyzed separately (Figs. 3a,b), but there was an increase in evapotranspiration during the rainy months. During the dry months, the evapotranspiration decreased, but the ratio between these two variables again demonstrate the key role of evapotranspiration during the dry season for the modulation of precipitation in both regions, similar to the results obtained by Satyamurty et al. (2013). Furthermore, the highest values of moisture convergence coincided with the rainiest months to both the west and east of the Amazon, corresponding to 53% of the rainfall in the west and 32% of the rainfall in the east. In the case of the east

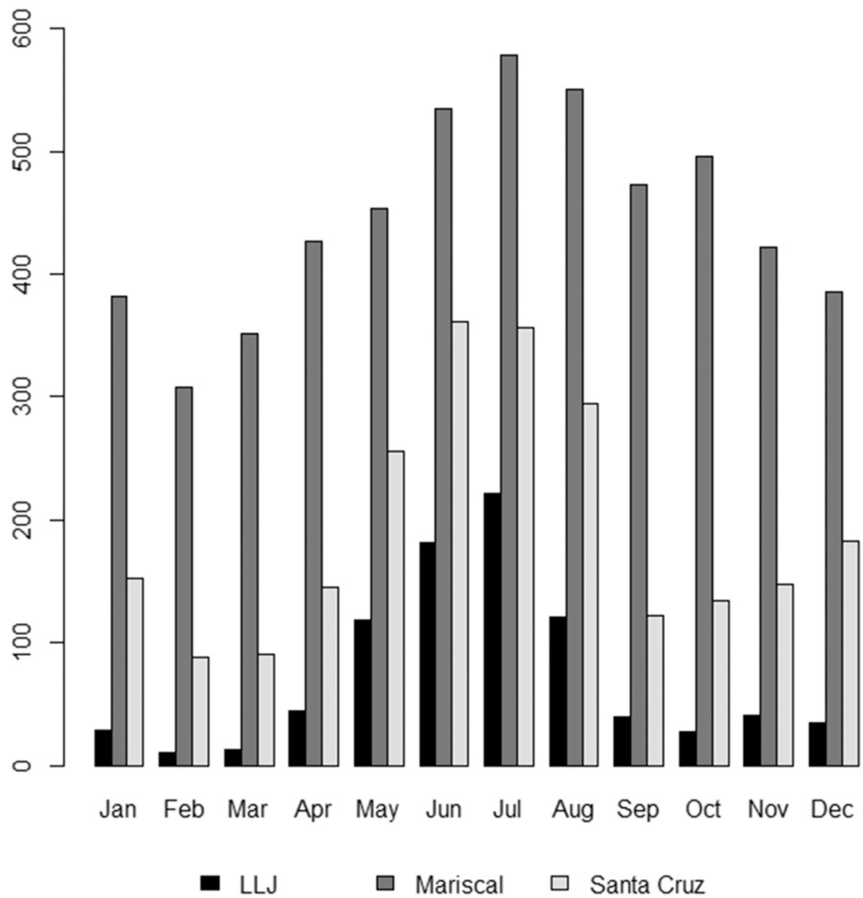

FIG. 4. Annual cycle of LLJs in Mariscal and Santa Cruz simultaneously (black), Mariscal Estigarribia (dark gray) only, and Santa Cruz (light gray) only from 1979 to 2008.

(box 1.2) (Fig. 3b), for the months in which the region acted as a source of moisture (June–October), there was moisture divergence or a decrease in the convergence, as in October, which indicates that during this period the region behaved as a source of moisture to the neighboring regions.

There was a different behavior between the higher and lowest precipitation values between the east and west regions of the Amazon. The largest volume was in the west, especially during autumn, whereas in the east the higher values occurred at the end of summer. An analysis of the ratio between the ET and *P* indicated that the contribution of the evapotranspiration to precipitation is higher in the east region, especially during the dry season.

The seasonality of the ITCZ (Uvo 1989) over the Amazon region is one of the main factors responsible for the modulation of the water balance and precipitation patterns. Penetration by the trade winds from the northeast, which occurs mainly during the Southern Hemisphere's summer months, is a fundamental factor that increases the moisture convergence over the region. The wind shift to the north during the winter months tends to reduce the convergence and increase the divergence over the Amazon, which is primarily caused by the action of the trade winds from the southeast. The ITCZ is more active in summer; thus, the formation of the Bolivian high (Silva Dias et al. 1983; Figueroa et al. 1995) creates a region of great divergence at high levels, which consequently increases in convergence over the Amazon region mainly on the west of the region. This fact explains the larger volumes of precipitation and the longer periods of moisture convergence.

Regarding the entire period throughout the Amazon region, the precipitation was, on average, greater than the evapotranspiration (Table 1), and considering the equation presented, the remaining residue has a value of 19 mm $month^{-1}$, which represents an error in the water balance by 12% of the total precipitation. This characteristic is in accordance with the results obtained by Marengo (2005) and Karam and Bras (2008), who suggested that these errors may be related to uncertainties in the reanalysis data.

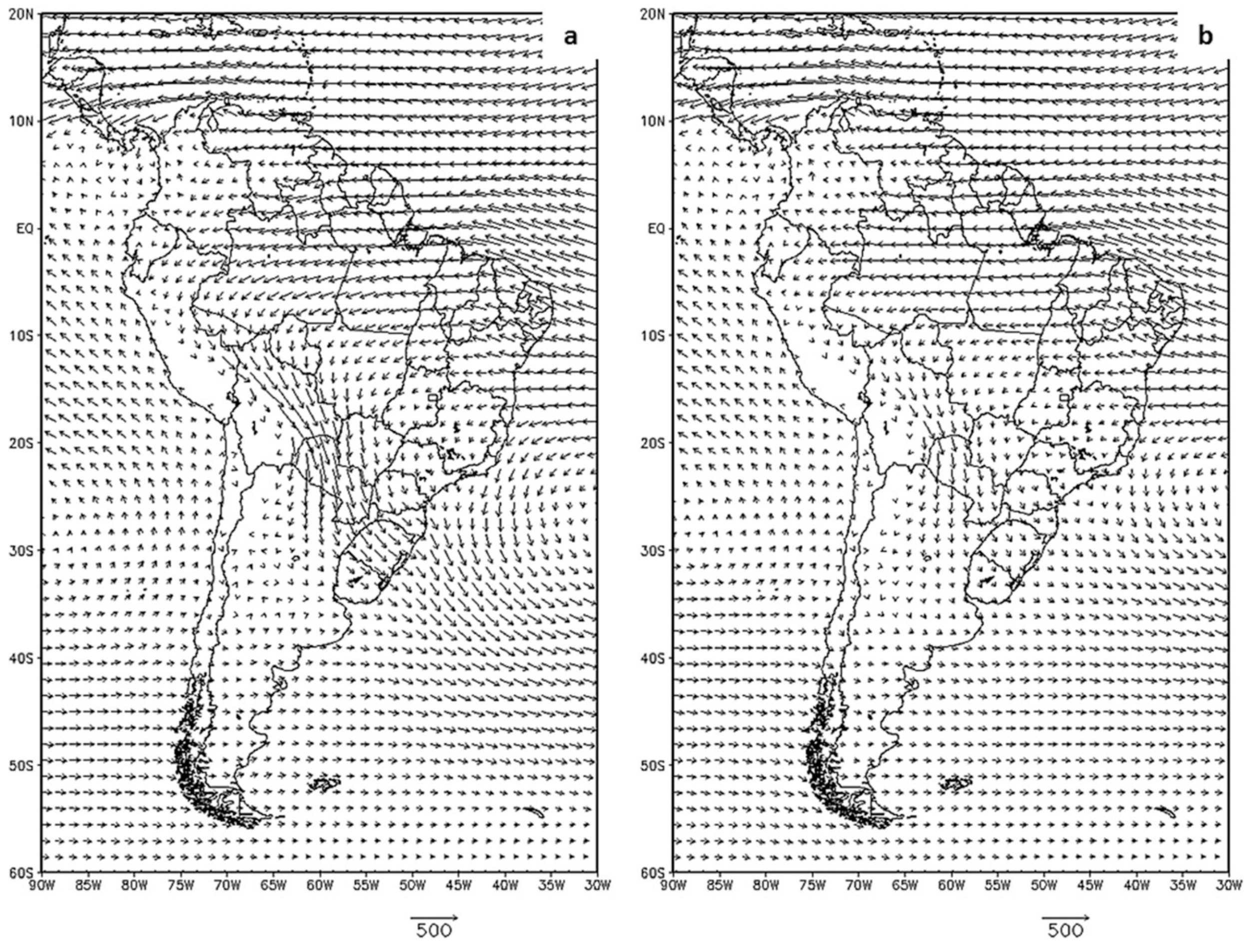

FIG. 5. Moisture flux (kg m s^{-1})that was vertically integrated between 925 and 700 hPa from 1979 to 2008 for days (a) with and (b) without LLJ events.

Similar charts to those produced for the Amazon region, showing the water balance and the ratio between precipitation and evapotranspiration (ET/P) from 1979 to 2008 were also produced for the LPB (Fig. 2b), and the north (box 2.1) and south (box 2.2) of the basin (Figs. 3c,d).

The average monthly rainfall over the LPB is 82 mm month^{-1}, with a well-defined rainy season between the months of November to April (108 mm month^{-1}) and a dry season between the remaining months (55.8 mm month^{-1}) (Fig. 2b). Berbery and Barros (2002) found a monthly maximum rainfall of approximately 165 mm month^{-1} for the entire analysis period and a maximum rainfall of 270 mm month^{-1} during the summer. During these warmer months (October to April), the mesoscale convective complexes are frequent and represent a large portion of the total precipitation (Velasco and Fritsch 1987; Laing and Fritsch 2000). Conversely, in the colder months, transient systems are chiefly responsible for the accumulated precipitation (Vera et al. 2002). When compared with the Amazon region (Fig. 2a), these average precipitation volumes are significantly lower in the LPB (Fig. 2b).

The evapotranspiration curve is directly related to the precipitation curve, and the maximum values are related to the maximum precipitation volumes and the quantity of water available on the surface for evaporation (Fig. 2b). An analysis of the ET/P ratio indicated that on the LPB, for the entire period, evapotranspiration is the main determinant of precipitation, corresponding to 87% of the total observed precipitation. As observed over the Amazon region, the LPB acts as a source of moisture (ET $> P$) for the atmosphere during the dry season between the months of July to September. During the other seasons and during all analysis periods, the region acts as a moisture sink, with a moisture deficit of approximately 17% for the total precipitation.

The moisture flux convergence curve is not as pronounced, but the highest values are in agreement with the largest precipitation and evapotranspiration values (Fig. 2b). For the LPB, the moisture convergence was

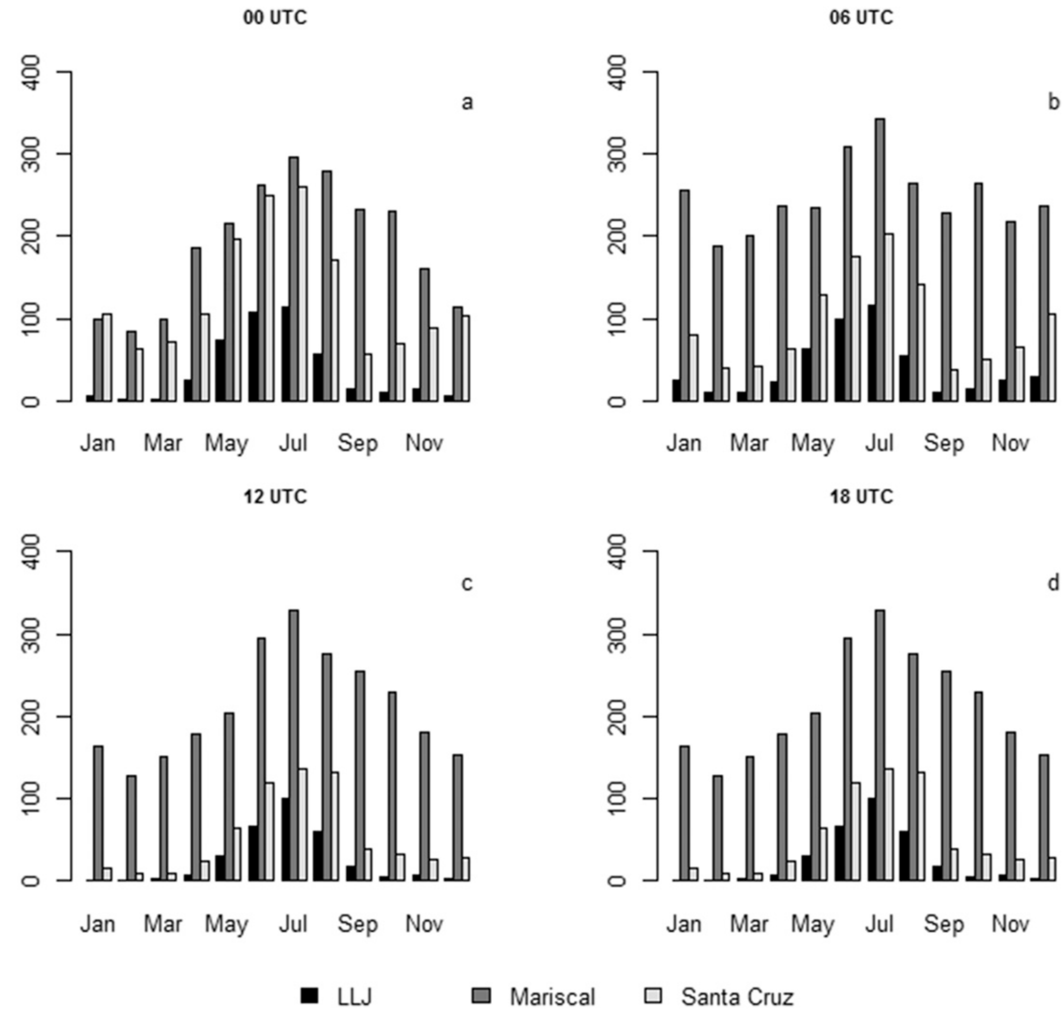

FIG. 6. Annual cycle of LLJ events in the cities of Mariscal (dark gray) and Santa Cruz (light gray), and in both cities simultaneously (black), from 1979 to 2008 for (a) 0000, (b) 0600, (c) 1200, and (d) 1800 UTC.

only 30% of the precipitation on average for the entire period, indicating that evaporation processes are fundamental to the water balance of the region. During any time of year, the region behaves as a moisture source to neighboring regions with moisture divergence. There is no closing of the water balance for the LPB, with a budget of 14.1 mm month^{-1}, which represents 17% of the precipitation (Table 1).

When we analyzed the north and south (Figs. 3c,d) of the LPB separately, we observed a clear difference in the behavior of the monthly mean water balance variables. North of the basin, the rainy season (November–April) and dry season (May–October) are well defined, and the lowest (highest) evapotranspiration values coincide with the lowest (highest) precipitation values. North of the basin, the largest precipitation values were observed in the summer, which is related to the extension of the monsoon system farther to the south (Horel et al. 1989; Zhou and Lau 1998). An analysis of the ET/P ratio indicated that the evapotranspiration corresponds to 87% of the precipitation and that the northern region behaves as a source of moisture between May and September. The moisture convergence is also the largest in the rainiest months and the smallest in the driest months (Fig. 3c), with a divergence between April and August, behaving as source of moisture for the atmosphere and the neighboring regions. The moisture convergence observed over the region represents approximately 20% of the precipitation.

Conversely, the mean precipitation gradient was not intense to the south of the LPB (Fig. 3d; Table 1); that is, the difference in the mean precipitation during the months was not as significant as for the north of the basin. The evapotranspiration and moisture convergence curves are not coherent with the precipitation curve, as in the previous cases; that is, the largest

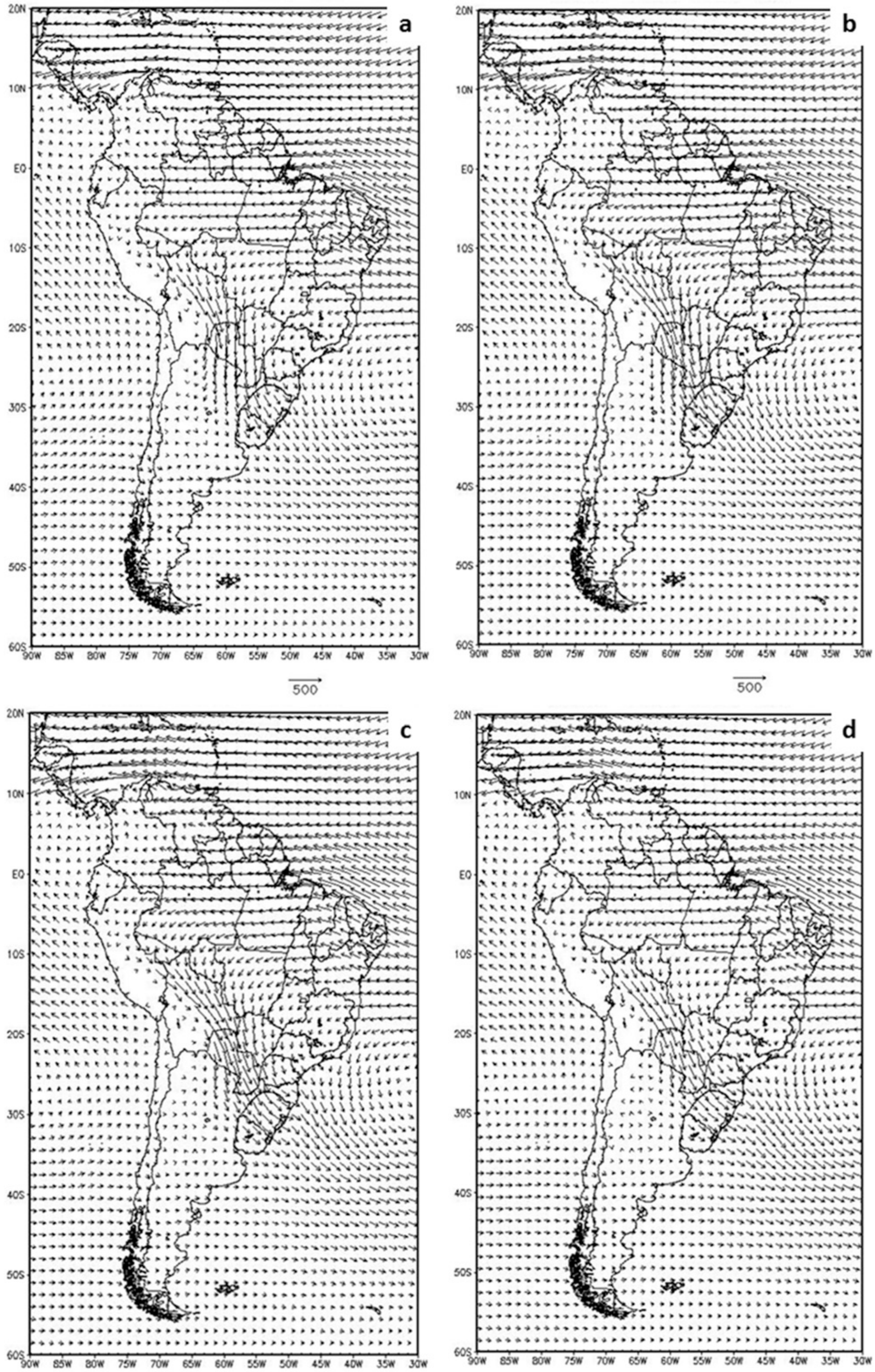

FIG. 7. Moisture flux (kg m s^{-1}) that was vertically integrated between 925 and 700 hPa from 1979 to 2008 for LLJ days at (a) 0000, (b) 0600, (c) 1200, and (d) 1800 UTC.

TABLE 2. Seasonal occurrence of days with (LLJ) and without (NLLJ) LLJs during the period between 1979 and 2008 in the cities of Mariscal Estigarribia and Santa Cruz de la Sierra.

	Summer	Autumn	Winter	Spring
LLJ (No. of days)	75	176	524	109
LLJ (%)	2.77	6.38	18.99	3.99
NLLJ (No. of days)	2633	2584	2236	2621
NLLJ (%)	97.23	93.62	81.01	96.01

precipitation and evapotranspiration values and the lowest moisture convergence value do not occur in the same period. The ET/P ratio shows that, to the south of the basin, evapotranspiration corresponds to 88% of the precipitation, which behaves as a source of moisture from November to January, but generally it behaves as a moisture sink. We also emphasize that the period when there is moisture divergence in the region, it acts as a source of moisture to the atmosphere (ET $>$ P)

Over the south of the LPB (Fig. 3d), the rainiest months were March, April, and October, and the largest values for evapotranspiration occurred in November, December, and January. The largest precipitation volumes observed are directly related to the passing of frontal systems over the region. The largest evapotranspiration values may be related to the larger quantity of energy available on the surface for evaporation and thus do not relate to the largest volumes of precipitation, as shown in the previous cases. Generally, the southern portion of the LPB behaved as a moisture sink and changed its behavior between November and January. When the northern portion of the LPB behaves as a source for neighboring regions, providing moisture by increasing the divergence, the southern portion behaves like a sink, indicating that the moisture from the north is also used for the precipitation process. South of the basin, the contribution of the moisture convergence that was calculated by the balance equation represents only 35% of the precipitation. Additionally, the moisture convergence over the region is higher during the dry season between May and October, and it is lowest during the rainy season. Berbery and Barros (2002) highlighted that during winter, the magnitude of the moisture flux over the south of the LPB is intensified by the westerly winds over the region, which influences the observed behavior and justifies our results.

4. Classification of the LLJ days

According to the proposed methodology for identifying days with LLJs, during the study period (1979–2008), 884 LLJ days were identified, 8.07% of all of the days analyzed. Figure 4 shows the LLJ events from 1979 to 2008. During every month, there is a LLJ event, as shown by various researchers, including Berbery and Barros (2002), but the largest occurrence is in winter (June–August) with a peak in July (221 events), which has a mean of seven LLJ events. The second largest occurrence of LLJ events is in autumn, and it peaks in May (119 events) with a mean of four events. Next, the seasons with the fewest LLJ events were summer, with 75 events, and spring, with 109 events. Berbery and Barros (2002) also have suggested that LLJs are more intense in summer only at latitudes below 15°S. South of this latitude, highly intense LLJs occur throughout the year in winter and spring. Salio et al. (2002) and Marengo et al. (2004) showed that the maximum frequency of jets varies according to latitude, whereas for latitudes below (above) 20°S, the maximum occurrence is in the summer (winter).

An analysis of the annual total LLJ events in the cities of Mariscal (Fig. 4) and Santa Cruz (Fig. 4) separately from 1979 to 2008 indicated that in Mariscal, 5363 LLJ events occurred during this period, which was 48.94% of all of the days analyzed. However, in Santa Cruz, there were 2329 events, and 21.25% of all of the days were analyzed, with the most LLJ events occurring during the winter in both cities. However, in Mariscal, the distribution is fairly homogenous compared with Santa Cruz. Similar results were obtained by Marengo et al. (2004), who observed a greater number of LLJ events during the winter in Mariscal with a fairly homogeneous distribution, relating mainly synoptic midlatitude disturbances. Some studies, such as those by Browning and Pardoe (1973), show that when LLJ events are not related to orographic effects, they are typically related to frontal systems that occur mainly in the regions that precede the arrival of cold fronts.

The presence of a LLJ that configures a moisture channel between the tropics and extratropics is evident when the behavior of the moisture flux was analyzed between 925 and 700 hPa between the years of 1979 and 2008 on days with (Fig. 5a) and without (Fig. 5b) LLJ events. During the LLJs, there is an intense flux east of the Andes, which begins over the Amazon region and heads to the southern region of Brazil, the northeast of Argentina and nearly all of Paraguay. Our analysis of the days without LLJ shows that to the east of the Andes, there is a flux with less intensity and more divergent than for days with LLJ events.

Figure 6 shows the total and diurnal cycle for the LLJ events in Mariscal and Santa Cruz simultaneously and for Mariscal and Santa Cruz separately from 1979 to 2008. Overall, a greater occurrence of LLJ events occurs, as determined by analyzing the two cities separately and together, during the winter and during the

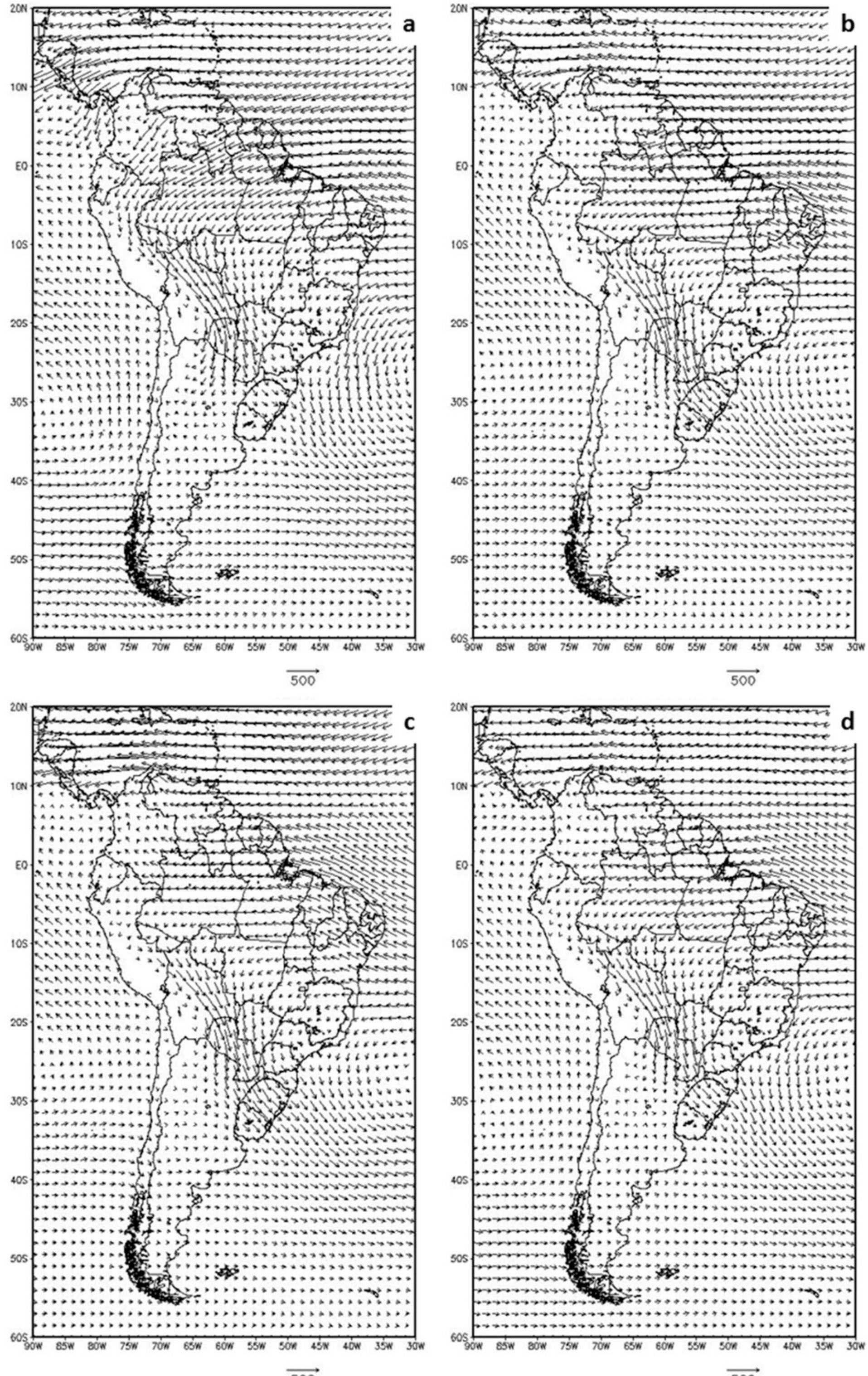

FIG. 8. Moisture flux (kg m s^{-1}) that was vertically integrated between 925 and 700 hPa from 1979 to 2008 for the LLJ days during austral (a) summer (December–February), (b) autumn (March–May), (c) winter (June–August), and (d) spring (September–November).

TABLE 3. Diurnal and seasonal intensity of moisture flux ($g\,m\,kg^{-1}\,s^{-1}$) for days with LLJs for the period between 1979 and 2008. DJF is December–February, MAM is March–May, JJA is June–August, and SON is September–November.

	LLJ					
	Box 1.1	Box 1.2	AMZ	Box 2.1	Box 2.2	LPB
0000 UTC	119.71	186.82	153.27	138.75	86.06	112.41
0600 UTC	139.62	200.18	169.90	169.49	98.27	133.88
1200 UTC	143.09	198.51	170.80	164.70	80.53	122.62
1800 UTC	121.25	155.62	138.44	126.15	67.55	96.85
DJF	174.60	195.51	185.06	143.67	55.11	99.39
MAM	131.69	213.02	172.36	156.40	105.36	130.88
JJA	114.94	177.32	146.13	149.13	112.69	130.91
SON	118.28	170.65	144.47	139.01	61.79	100.40

four times: 0000 UTC (2100 LST), 0600 UTC (0200 LST), 1200 UTC (0800 LST), and 1800 UTC (1400 LST).

An analysis of the frequency of events in Mariscal and Santa Cruz simultaneously indicated that the largest LLJ events occur at 0000 (Fig. 6a) and 0600 UTC (Fig. 6b). Seasonally, most LLJ events in the summer and spring were noted at 0600 UTC and in winter and fall at 0000 UTC. Next, we analyzed Mariscal and Santa Cruz separately. In Mariscal, the largest LLJ events occurred at 0600 (Fig. 6b) and 1200 UTC (Fig. 6c), with 0600 UTC presenting the largest seasonal frequency. In Santa Cruz, the largest LLJ event occurred at 0000 (Fig. 6a) and 0600 UTC (Fig. 6b). However, during the summer, the largest occurrence was at 0600 UTC, and it was at 0000 UTC during the other seasons.

The diurnal cycle of moisture flux over South America (Fig. 7 and Table 3) shows that whenever there is an LLJ event, there is a flux from north to south between 10° and 30°S, with the largest intensity at 0600 (Fig. 7a) and 1200 UTC (Fig. 7b). At 0600 and 1200 UTC, there is an intensification of the flux related to the South Atlantic high pressure system in the southern region of Brazil, which may influence the intensification of the flux that is related to the LLJ.

These results are in accordance with Salio et al. (2002) and Marengo et al. (2004), who showed that the largest LLJ event occurrence in the South American summer is between 0600 and 1200 UTC at latitudes below 20°S (Santa Cruz), and more frequent between 0000 and 0600 UTC in winter at latitudes above 20°S (Mariscal). The results in Table 2 show this seasonality, in which winter represents nearly 60% of the LLJ events, of which 19% are from all of the winters analyzed.

An analysis of the moisture flux behavior over South America that is related to the occurrence of the LLJ events (Fig. 8 and Table 3) indicated that there are different configurations for different seasons. Although most of the LLJ events occur in winter, the associated moisture flux is not directly related to the penetration of trade winds from the northeast over the Amazon and their convergence at the Andes but rather the presence and intensification of the flux related to the high pressure system over the southwest South Atlantic. During the other seasons, mainly summer and spring, the moisture flux related to the LLJ events is directly related to the penetration of the trade winds from the northeast, their convergence with the Andes and the change in their direction to the south, thus forming the LLJ.

5. Water balance during LLJ events

a. *The Amazon basin*

The water balance, its components, and the ET/P ratio were analyzed for composites of the LLJ days over the four regions that were identified in section 2, and they were compared to the climatology presented in section 3. Considering the location of the LLJ, the largest impacts are expected in the LPB. The water balance for the Amazon basin, which is upstream of the LLJ, may instead reflect changes in the availability of moisture to the LLJ.

The Amazon water balance for the days with and without LLJ events is presented in Fig. 9. On average, the monthly rainfall in the LLJ composite is 132.3 mm month^{-1}, indicating a reduction from the climatology of days without LLJ events (160 mm month^{-1}). By analyzing the monthly mean volume of precipitation on the days with LLJ events, we determined that this volume represents 45% of the total volume of precipitation.

According to Table 2, the summer months had a lower occurrence of LLJs (75 cases) compared with the other seasons. During autumn, there was a greater volume of precipitation relative to the number of the days with LLJ events at approximately 213 mm month^{-1}, whereas the relative precipitation volume was approximately 173 mm month^{-1} in summer. Additionally, there was approximately 74 mm month^{-1} during the spring.

The Amazon evapotranspiration during LLJs shows the maximum values corresponding with the maximum volumes of precipitation; thus, similar to precipitation, the largest values for evapotranspiration also occur on average during the autumn. Summer has the second-largest amount of precipitation and the second-highest evapotranspiration values.

Figure 9a also presents the mean annual cycle of the ET/P ratio during the LLJs, showing that for the annual average, the Amazon region acts as a source of moisture to the atmosphere primarily during the dry season (June–October). There was a short period, between July and September (Fig. 9b), when the region behaves as source of moisture for days without the occurrence of LLJ events.

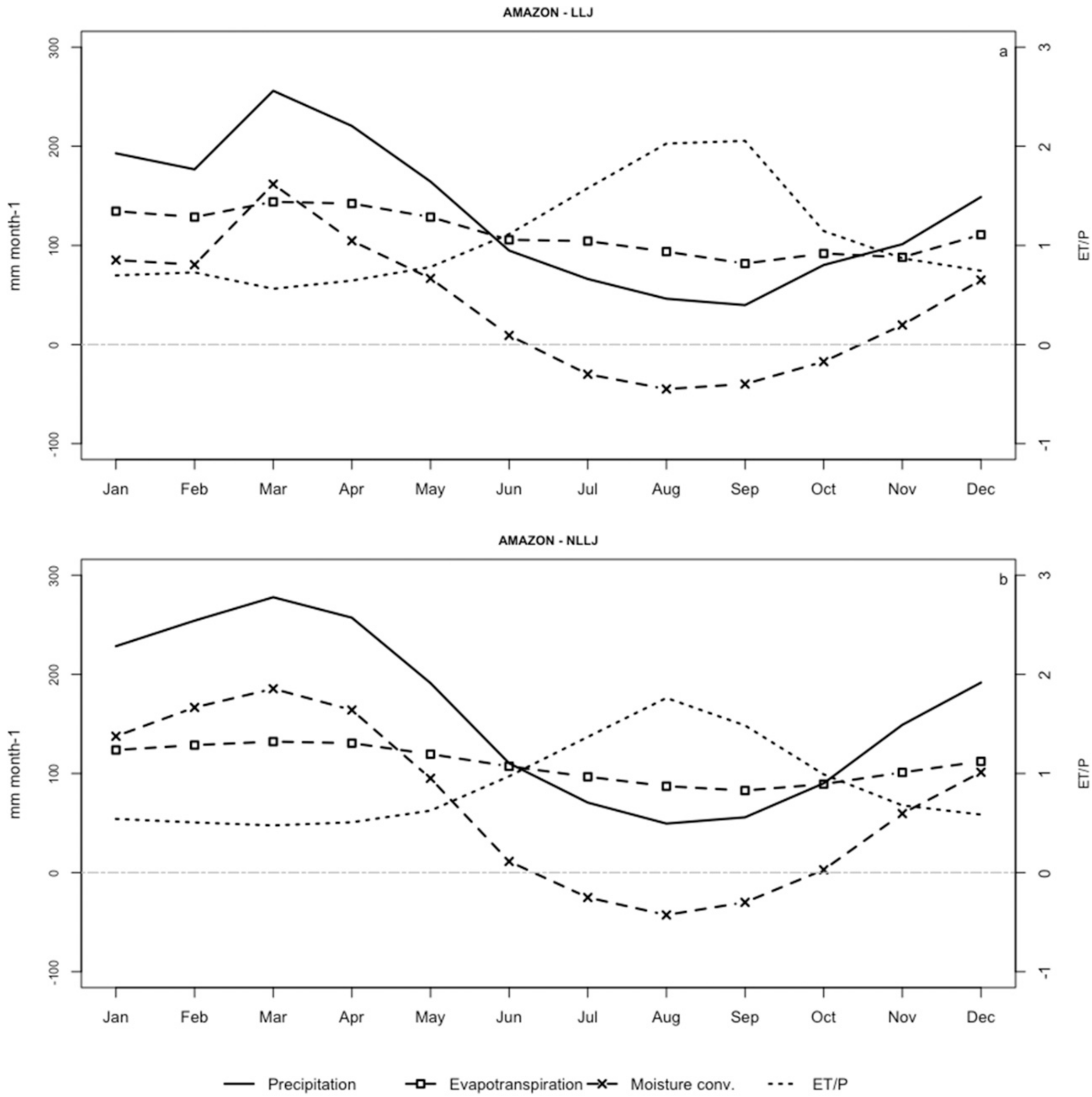

FIG. 9. Water balance variables (mm month^{-1}) over the Amazon region during (a) the LLJ events and (b) non-LLJ events from 1979 to 2008. Primary axis: precipitation, evapotranspiration, and moisture convergence. Secondary axis: ET/P ratio.

The Amazon moisture flux convergence during days with LLJs is positive for most of the year, except for July to October, which exhibited moisture divergence (Fig. 9a). This is the same time of the year when the region has increased availability of moisture in the atmosphere via evapotranspiration. Thus, according to the methodology presented by Satyamurty et al. (2013), the Amazon region behaves as a source of moisture to neighboring regions. The total contribution of moisture convergence over the Amazon during LLJ events corresponds to 29% of the total precipitation, which is less than that observed (42%) for the period without LLJ events.

Figures 10a and 10c present the water balance and its variables in the western part of the Amazon during days with and without LLJs. During autumn, the precipitation and evapotranspiration have the largest values at approximately 210 and 129 mm month^{-1}, respectively. The monthly precipitation mean for days with LLJs is 24% higher than the monthly mean for days without LLJs over the western Amazon. The region has

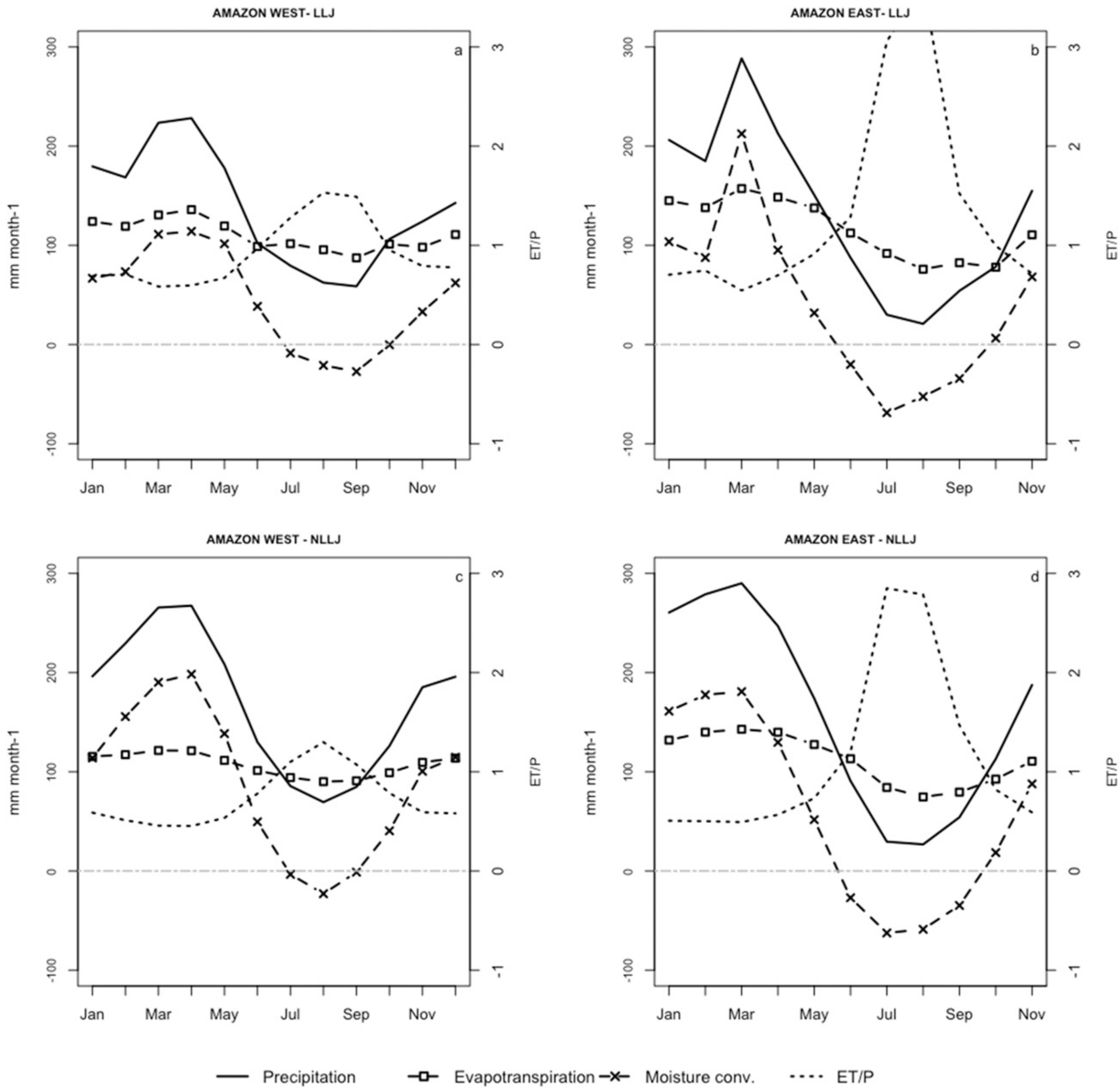

FIG. 10. Water balance variables (mm month^{-1}) over the west and eastern Amazon regions during (a),(b) LLJ events and (c),(d) non-LLJ events from 1979 to 2008. Primary axis: precipitation, evapotranspiration, and moisture convergence. Secondary axis: ET/P ratio.

high values of moisture convergence throughout the year, which corresponds to approximately 32% of the average rainfall over the region. The ET/P ratio for the LLJ composite in this part of the basin shows that the evapotranspiration corresponds to a high proportion of the precipitation (79%), which is different from the monthly mean for days without LLJs (62%), suggesting that it is the main contributor to the water balance in the western Amazon and characterizes the region as a sink of moisture to the atmosphere for days with LLJs. In the western portion of the Amazon, based on the ET/P ratio and for days with LLJs, there is more moisture available in the atmosphere than for days without LLJs.

The analysis of the eastern part of the Amazon is shown in Figs. 10b and 10d. A correlation between the largest values of precipitation and evapotranspiration was found, and for the days with LLJs, the region behaves as a source of moisture for the atmosphere on average. The average ET/P ratio of 1.4 shows that evapotranspiration is 40% higher than the mean volume

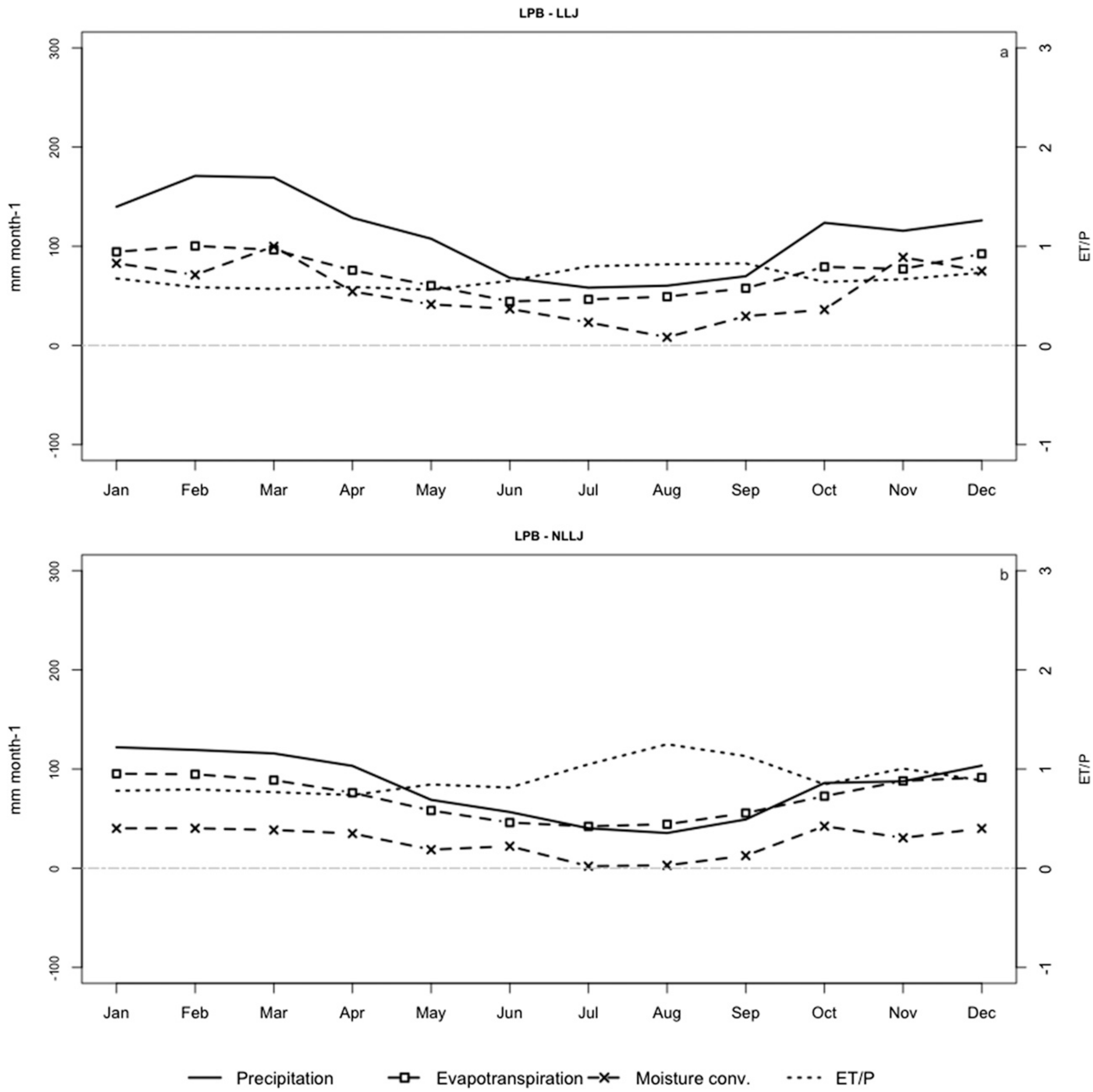

FIG. 11. Water balance variables (mm month^{-1}) over the LPB during (a) LLJ events and (b) non-LLJ events from 1979 to 2008. Primary axis: precipitation, evapotranspiration, and moisture convergence. Secondary axis: ET/P ratio.

of precipitation observed over the eastern Amazon, unlike what was determined for the climatology (Fig. 2a). During LLJs, the monthly mean precipitation is less than for days without LLJs. The large availability of moisture for the atmosphere over the eastern region occurs primarily during the dry season and, more precisely, between June and September, in which evapotranspiration exceeds precipitation by more than 40%. Additionally, during these months, the region showed intense moisture divergence, suggesting that during these months the east portion of the Amazon is a source of moisture to the atmosphere and neighboring regions. The divergent moisture behavior of this region during the dry season is directly related to the intensity of the flow at low levels, which is associated with the increased number of LLJ event days during this period.

b. La Plata basin

During any season of the year, the LPB acts as a sink of moisture during LLJ events (Fig. 11). During the LLJ events, the monthly mean precipitation over the region

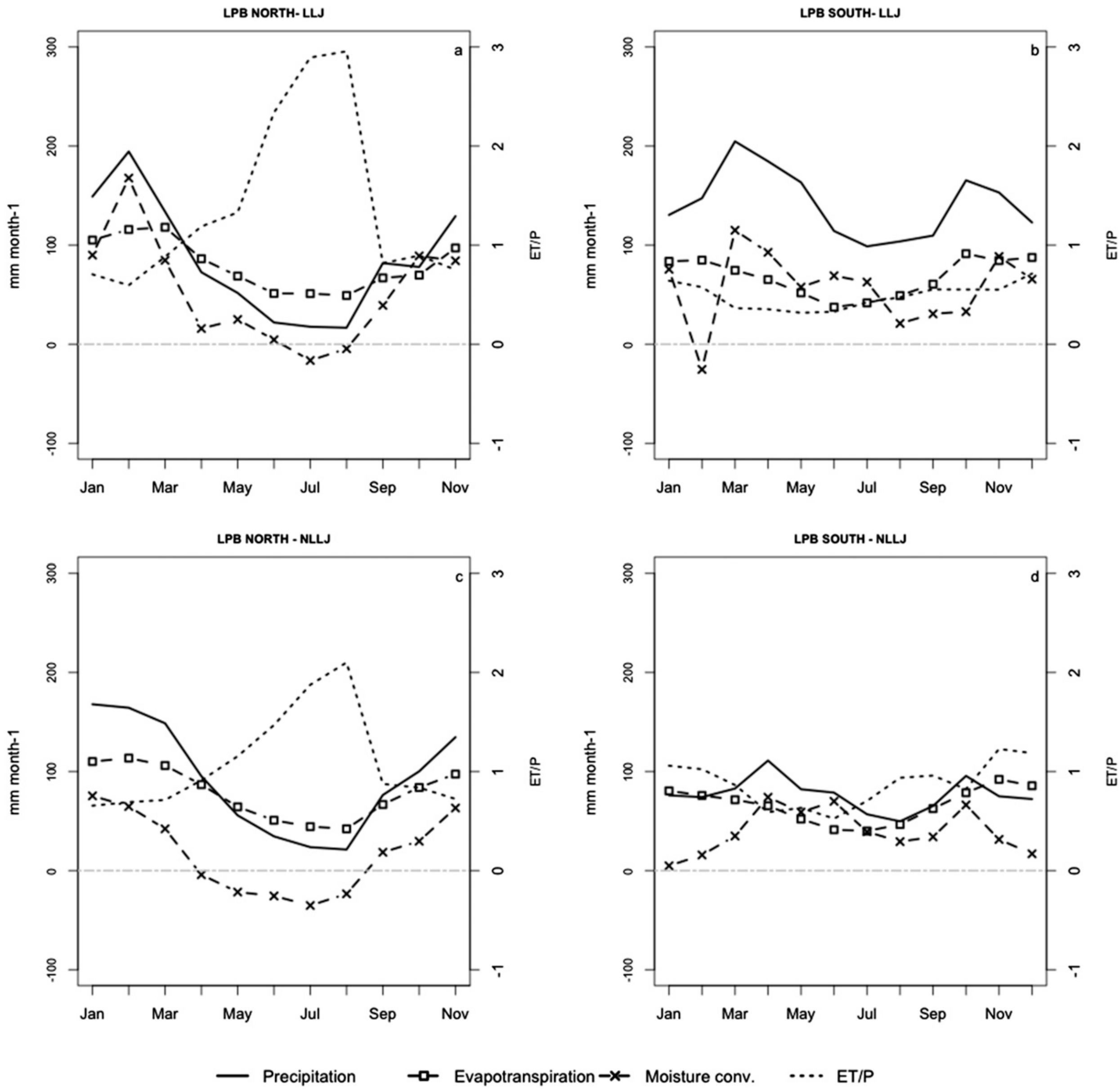

FIG. 12. Water balance variables (mm $month^{-1}$) over the northern and southern regions of the LPB during (a),(b) LLJ events and (c),(d) non-LLJ events from 1979 to 2008. Primary axis: precipitation, evapotranspiration, and moisture convergence. Secondary axis: ET/P ratio.

represents more than 100% of the monthly mean precipitation for days without LLJ events.

Overall, the precipitation average was 111 mm $month^{-1}$, which followed the evapotranspiration over the months. During the rainy (dry) months, there is higher (lower) availability of moisture to the atmosphere via the evaporation process. With regard to the convergence of the moisture, there was a greater convergence during the same period in which the largest volumes of precipitation relative to the monthly number of LLJ events occurred, which was primarily during the wet season. The role played by the LLJs in the modulation of precipitation over the LPB is fundamental, showing that it is important to the reduction of divergence over the region, thus boosting the availability of moisture to the atmosphere and consequently generating a larger precipitation volume. Thus, we observed that the moisture convergence on the LPB during the LLJs corresponds to 48% of the monthly mean precipitation, which is approximately 50% for the entire period without LLJ events, which corresponded to only 32%.

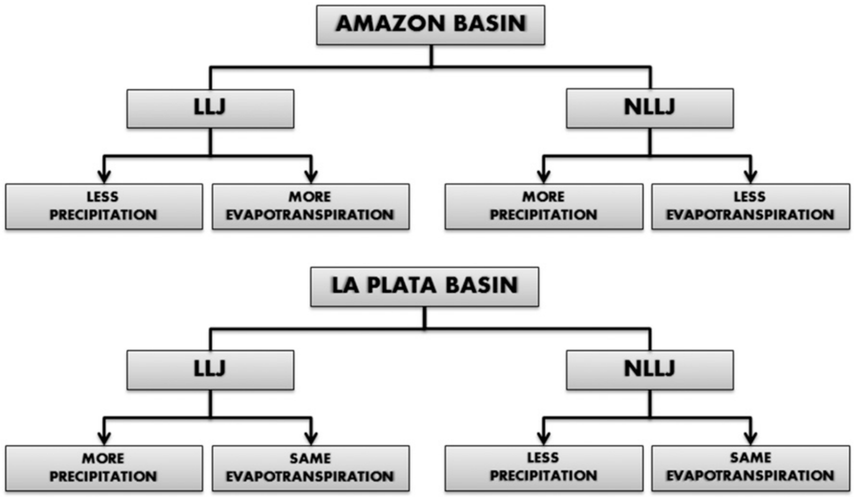

FIG. 13. Flowchart of the main water balance features over the Amazon basin and LPB for the days with and without LLJs.

Figures 12a and 12c show the water balance and its variables on the northern part of the LPB (box 2.1) on LLJ and NLLJ days. During the LLJ events, the largest volumes of precipitation were in the summer and autumn. Compared with the seasonal mean for the period without LLJs, the monthly mean precipitation was 7% smaller when an LLJ was present. There was a difference only in the summer when the monthly precipitation mean during LLJ events was higher than for the period without the occurrence of LLJs. Although the highest total volume of precipitation occurs during the winter, and the summer has the larger precipitation intensity in relation to the monthly number of LLJ events.

The largest values of evapotranspiration during LLJ days over the north of the LPB were observed in summer ($\sim$106 mm month^{-1}) and autumn ($\sim$91 mm month^{-1}). An analysis of the availability of moisture to the atmosphere due to evaporation processes demonstrated that the north portion of the LPB behaves as a source of moisture primarily between April and September with evapotranspiration corresponding to more than 100% of the monthly mean observed precipitation over the region, showing the seasonality difference of the ET/P ratio between the periods with and without LLJ events.

Regarding the moisture convergence, a similarity in behavior with precipitation throughout the year was observed: lower (higher) values of precipitation that were related to lower (higher) values of moisture convergence were observed during all seasons. Thus, moisture flux convergence contributed to the accumulated precipitation in this region. During LLJ events, the total moisture convergence contributed to 62% of the monthly precipitation, suggesting that this behavior over the north of the LPB suffers from the direct influence of the western portion of the Amazon.

The south of the LPB during the LLJs behaved as a moisture sink during every month (Fig. 12b); the ET/P ratio was only 50%. When compared with the northern portion, precipitation and moisture convergence were significantly higher, especially during autumn. In this portion of the basin, the lowest (highest) values of evapotranspiration coincide with the lowest (highest) values of precipitation. The observed behavior is directly related to the moisture convergence intensity, which is clearly seasonal. The total moisture convergence on the southern portion of the LPB represents 50% of the monthly mean precipitation over the region, which is the same as what was observed for the ET/P ratios. This result indicates that the transport between the tropics and extratropics through the LLJ and its convergence over the southern continent, together with the availability of moisture (ET/P), are essential for the precipitation over the region. These results are in accordance with those obtained by Martinez and Dominguez (2014). Additionally, the monthly mean precipitation during LLJ events corresponds to more than 100% of the monthly mean precipitation of the days without LLJ events, with the largest intensity during autumn.

During winter, the precipitation and moisture convergence has the lowest values for the entire LPB region, showing that the influence of LLJ events is more significant during the other seasons and primarily during the wet season. According to Berbery and Barros (2002), the relationship between the LLJ and the precipitation during winter in the Plata basin is not yet fully understood, but the interaction between the LLJ and transient systems, especially at the exit region of these jets (southern portion of the basin), contributes significantly to the moisture convergence and rainfall. We also highlight the importance of the LLJ in the creation of precipitation, its intensity and volume patterns, especially during summer and autumn, and showing that for the southern portion of the LPB basin, the precipitation during LLJs is twice the precipitation for days without LLJs.

6. Discussion and conclusions

This study conducted a climatological analysis of the water balance over a 30-yr period (1979–2008) using reanalysis data from NCEP CFSR. In addition, the days with LLJs were classified in order to investigate their contribution to the moisture transport between the tropics and extratropics and to determine their influence on the water balance variables in the Amazon region and LPB.

The results showed that on average, for the period between 1979 and 2008, the Amazon region behaved like a sink of moisture ($\mathrm{ET} < P$), and it behaves as a source only between July and October. Furthermore, during the dry season, the moisture produced in the region is more efficient in producing precipitation than the moisture convergence. Using the variables generated from the reanalysis data, we estimated that on average, for the entire period, the moisture convergence corresponds to 44% of precipitation, indicating that local evapotranspiration is critical to precipitation in the Amazon. When analyzed separately, for the western and eastern regions, the region acted as a sink of moisture, and it was a source only during the dry season.

The LPB also behaved as a sink ($\mathrm{ET} < P$) on average for the entire period, and it behaved as a source of moisture only during the dry season. In the LPB, the moisture convergence was only 30% of the precipitation for the entire period, indicating that the evaporation processes are fundamental to the water balance of the region. An analysis of the northern and southern sectors of the basin indicated that both behaved as a sink. However, when each portion behaved as a source, the other portion behaved as a sink. The northern portion acted as a source between May and September, whereas the south acted as a source between November and January. We highlight the relationship between the increase in the ET/P ratio and reduced moisture convergence observed for the two regions, especially during the dry season.

For the entire period across the Amazon and LPB, precipitation was greater than evapotranspiration, and considering the water balance equation, the residue shows a value of 19.93 mm for the Amazon and 14.33 mm for the LPB, which represents only 12% and 17% of the precipitation over these areas, respectively. This characteristic may be related to uncertainties in the reanalysis data, primarily for precipitation as a result of the model, as noted by Marengo (2005) and Karam and Bras (2008).

Given the importance of the moisture transport by the LLJs between the tropics and extratropics, and especially its influence on the water balance on the LPB, days with LLJ events were classified. During the study period, we recorded 884 days with LLJs distributed over the months, and the winter period had the highest number of occurrences. Although winter was the season with the largest number of LLJ events, the associated flow was not directly related to the penetration of the northeast trade winds in the Amazon and its convergence in the Andes. Instead, the flow was related to the presence and intensification of the flux associated with high pressure systems present over the southwest Atlantic Ocean.

As observed by several researchers, including Salio et al. (2002) and Marengo et al. (2004), during other seasons and especially during the spring and summer, the flow associated with the LLJ is directly related to the penetration of the northeast trade winds, their convergence when they reach the Andes, and the subsequent change in direction to the south, thus forming the LLJ.

On days with LLJs, the Amazon region behaved as a source of moisture ($\mathrm{ET} > P$), but in the wet season the region behaved as a sink of moisture for the atmosphere. When the west and east sectors were analyzed separately, during the LLJ events, the eastern Amazon behaved as a source, especially during the dry season, whereas the west region remained a sink for the entire period. The western region was a source only between June and September. This different behavior between the eastern and western parts of the Amazon demonstrates the importance of the moisture transport associated with the trade winds penetration over the western portion of the region, which is essential to feed the moisture required for precipitation. Even the western portion of the Amazon behaved as a sink of moisture during LLJ events, and the available moisture (ET) was lower that for days without LLJs.

On days with LLJ events, the LPB behaved as a sink during all months. The moisture convergence over the LPB during LLJ events is 50% of the monthly mean precipitation over the basin, whereas the mean for the period without LLJ events is 32%. An analysis of the northern and southern sectors of the basin separately indicated that the north behaved as a source of moisture ($\mathrm{ET} > P$), but it behaved as a sink during the wet season. From the total moisture convergence observed over this region, 62% corresponds to the monthly mean precipitation during LLJ days, whereas it was only 16% for the period without LLJ events. The southern LPB behaved as a sink ($ET < P$) during all months. From the total moisture convergence observed in the south portion during LLJ days, 40% corresponds to the average monthly precipitation, indicating that the moisture transport between the tropics and extratropics and its convergence in the south of the continent, together with moisture recycling, is essential for the precipitation. A main pattern on days with LLJs is that precipitation over the LPB is 32% higher than for days without LLJ events.

A flowchart of our results for LLJ days is shown in Fig. 13. Locally, the presence of LLJs and the trough moisture convergence is crucial for the precipitation on the LPB, whereas in the Amazon basin, the evapotranspiration is more important for the water balance. Furthermore, the presence of the LLJ, primarily on the LPB, influences the intensity of precipitation, indicating that this flow is directly associated with more intense weather systems and extreme events over the region. Thus, from the results presented and future work, the potential impacts of land-use and land-cover changes over South America water balance must be investigated.

Acknowledgments. The authors thank the Research Support Foundation of the State of São Paulo (FAPESP-Ref. 2008/09969-6) for the financial support. This work was carried out with the aid of a grant from the Inter-American Institute for Global Change Research (IAI) CRN3035, which is supported by the U.S. National Science Foundation (Grant GEO-1128040).

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