Sources of Atmospheric Moisture for the La Plata River Basin*

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ABSTRACT

The La Plata River basin (LPRB) is the second largest basin of South America and extends over a highly populated and socioeconomically active region. In this study, the spatiotemporal variability of sources of moisture for the LPRB are quantified using an extended version of the Dynamic Recycling Model. Approximately 63% of mean annual precipitation over the LPRB comes from South America, including 23% from local LPRB sources and 20% from the southern Amazon. The remaining 37% comes mostly from the southern Pacific and tropical Atlantic Oceans. The LPRB depends largely on external sources during the dry winter season, when local evaporation reaches a minimum and moisture outflow increases. Variations in the transport of moisture from the Amazon to the LPRB depend more on variations of the atmospheric circulation than on evaporation, at both the monthly and daily time scale. In particular, weak atmospheric flow allows the accumulation of moisture over the Amazon basin, followed by an above-normal release of moisture downwind when the atmospheric flow strengthens again. Water vapor transport with these characteristics was observed for 20% of the days of the summer season during the 1980–2012 period, leading to higher-than-average convergence of moisture of terrestrial origin over the LPRB. During the positive (negative) phase of the El Niño–Southern Oscillation (ENSO), more (less) moisture from Amazonian evaporation reaches the LPRB. The Amazonian contribution to the LPRB is reduced (increased) during the positive (negative) phase of the Antarctic Oscillation (AAO), when surface pressure over southern South America is above (below) normal.

1. Introduction

The La Plata River basin (LPRB) extends across one of the most densely populated regions of South America, spreading over parts of Brazil, Argentina, Paraguay, Bolivia, and Uruguay, as the second largest river system in South America (Lee and Berbery 2012). Water resources of the LPRB are important for human consumption, harvesting, and hydroelectric power generation for a large population (Berbery and Barros 2002). The LPRB is located south of the Amazon basin (Fig. 1),

downstream of the mean atmospheric circulation, which favors the transport of moisture evaporated from the Amazon forest to the LPRB (see, e.g., Marengo et al. 2004). The transport of atmospheric moisture of Amazonian origin constitutes a significant fraction of the LPRB's precipitation (Dirmeyer et al. 2009). Therefore, estimation of the magnitude and variability of this transport is important for the assessment and management of the water resources of the LPRB.

The transport of atmospheric moisture over South America has been studied using a variety of methods. From analysis of the horizontal atmospheric moisture flux, Berbery and Barros (2002) found that Amazonian moisture contributes to the LPRB throughout the year, with maximum transport during the austral summer. Based on a similar approach, Arraut et al. (2012) estimated the contribution to atmospheric moisture from the Atlantic, the Amazon, and local evaporation for a region between the southern Amazon and northern LPRB. They found that the Amazon contribution is on

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FIG. 1. Region of study includes parts of Central America (CEAM); northern South America (NOSA); Orinoco (ORIC); Guianas (GUYN); Peru–Chile coastal region (PECH); northern Amazon (NAMZ); southern Amazon (SAMZ); Tocantins River (TOCA); northeastern Brazil (NORD); subtropical Andes (ANDS); La Plata River basin (LPRB); southern tip of Brazil and east Uruguay (SBRU); southern South America (SOSA); adjacent tropical Pacific (SOPA); adjacent subtropical and extratropical Pacific (SOPA); adjacent tropical Atlantic (NOAT); and adjacent southern subtropical and extratropical Atlantic (SOAT).

the same order as that from the Atlantic, whereas the local contribution is smaller but comparable to the other sources. Using a one-dimensional equation to represent the hydrologic cycle, Lettau et al. (1979) estimated that the precipitation recycling increases from east ($\sim 19\%$) to west ($\sim 88\%$) of the Amazon basin. Drumond et al. (2008) used a 3D Lagrangian model [Flexible Particle (FLEXPART); Stohl et al. 1998] to study the sources of moisture for regions representing central Brazil and the LPRB. They found that both regions receive moisture from the Amazon, but the latter was not the dominant source of moisture in either case. By backtracking air parcels on isentropic surfaces, Dirmeyer et al. (2009) estimated that nearly 23% of the moisture over LPRB is of Amazonian origin (see moisture sources by river basin at <http://www.iges.org/wcr/>). By means of a 2D Eulerian approach, Van der Ent et al. (2010) estimated

that 70% of the precipitation over the LPRB is of terrestrial origin. Because of the LPRB's geographical location, most of the terrestrial contribution is presumably of South American origin. Using the same water accounting method, Keys et al. (2012) found that 57% of the rainfall for a region within the LPRB comes from terrestrial sources during the growing season. Using the same methodology as in Van der Ent et al. (2010) and Keys et al. (2012), R. J. Van der Ent (2014, personal communication) estimated the direct contribution from the Amazon to the LPRB to be 22% of LPRB's precipitation.

The transport of atmospheric moisture exhibits variability at multiple time scales. For example, Silva et al. (2009) and Silvestri and Vera (2003) identified variations in the transport of moisture from the Amazon to the LPRB under different phases of El Niño–Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO). Despite our improved understanding of the transport of atmospheric moisture to the LPRB on a climatological basis, many lingering questions remain about its variability. In particular, the link between the atmospheric circulation patterns and the estimated transport of atmospheric moisture is lacking. In this work we extend the Dynamic Recycling Model (DRM), developed by Dominguez et al. (2006), to quantify the transport of atmospheric moisture to the LPRB from multiple sources, with special emphasis on the Amazon basin. We describe the atmospheric circulation associated with the contributions from multiple sources to the LPRB, including the climatological mean and the variability associated with ENSO and AAO. In addition, we explore the common features in the vertically integrated moisture flux (VIMF) anomalies that determine the dominant role of terrestrial versus oceanic contributions to atmospheric moisture over the LPRB.

2. Data and methodology

a. Methodology

From a Lagrangian solution for the equation of conservation of the total column water vapor (i.e., precipitable water), Dominguez et al. (2006) found that the fraction R of atmospheric moisture collected by an air column along its trajectory between times $\tau' = 0$ and $\tau' = \tau$ is given by

$$R(x, y, t) = 1 - \exp \left[- \int_0^\tau \frac{E(x', y', \tau')}{W(x', y', \tau')} d\tau' \right], \quad (1)$$

where E and W represent the evaporation and the precipitable water, respectively, along the two-dimensional trajectory $[x'(\tau'), y'(\tau')]$. Based on (1), we have developed

FIG. 2. Schematics of the trajectory of an ideal air column. In this example, the rectangular domain has been divided arbitrarily into four regions, A_1 , A_2 , A_3 , and A_4 . According to the traversed region, the trajectory can be decomposed into five parts labeled by $\lambda = 1, 2, \dots, 5$. The trajectory goes backward in time, from time $\tau_0 = t$ to time τ_5 , traversing the points $[x'(\tau_i), y'(\tau_i)]$, where $i = 1, 2, \dots, 5$.

a new method to quantify the relative contributions from different sources to the atmospheric moisture over a given sink region. For example, consider the parts of trajectory $\lambda = 1$ and $\lambda = 2$, crossing regions A_4 and A_3 , respectively, in Fig. 2. The trajectory starts at time τ_2 and reaches the sink point (x, y) at time $\tau_0 = t$. Applying (1), we get

$$R(x, y, t) = 1 - \exp \left[- \int_{\tau_2}^{\tau_0} \frac{E(x', y', \tau')}{W(x', y', \tau')} d\tau' \right] \\ = R_1(x, y, t) + \alpha_1(x, y, t) R_2(x, y, t), \quad (2)$$

where

$$R_1(x, y, t) = 1 - \exp \left[- \int_{\tau_1}^{\tau_0} \frac{E(x', y', \tau')}{W(x', y', \tau')} d\tau' \right], \quad (3a)$$

$$R_2(x, y, t) = 1 - \exp \left[- \int_{\tau_2}^{\tau_1} \frac{E(x', y', \tau')}{W(x', y', \tau')} d\tau' \right], \quad \text{and} \quad (3b)$$

$$\alpha_1(x, y, t) = 1 - R_1(x, y, t). \quad (3c)$$

In (3), R_1 and R_2 represent the local collection of moisture from parts 1 and 2 of the trajectory, respectively. Additionally, α_1 represents that fraction of

moisture produced in part 2 of the trajectory that is not lost (via precipitation) in the intermediate part of the trajectory: that is, part 1. This idea can be generalized to a trajectory with an arbitrary number of parts (e.g., in Fig. 2 we show a trajectory with five parts). We refer to the net contribution from each part λ of the trajectory as c_λ . In our example $c_1 = R_1$ and $c_2 = \alpha_1 R_2$. In general, it can be shown that

$$c_\lambda(x, y, t) = \left[\prod_{j=1}^{\lambda-1} \alpha_j(x, y, t) \right] R_\lambda(x, y, t). \quad (4)$$

Finally, we can group the contributions from different parts of the trajectory according to some predefined regions. In our example, the total contribution from region A_4 to the moisture at point (x, y) is given by $a_4(x, y) = c_1(x, y) + c_4(x, y)$. In general,

$$a_k(x, y, t) = \sum_{\lambda \in A_k} c_\lambda(x, y, t), \quad (5)$$

where the sum is done over all those parts of trajectory λ that fall into the region A_k . The $a_k(x, y)$ fields provide an estimate of the fraction of moisture on each grid cell (x, y) that originated as evaporation from somewhere in the region A_k (see Fig. 2). Therefore,

$$R(x, y, t) = \sum_{k=1}^{N_A} a_k(x, y, t), \quad (6)$$

where (6) satisfies (1) and N_A represents the total number of regions.

The DRM is computationally efficient, and only a few hours using a single processor are needed to complete the calculations for 32 yr of daily data for South America, with a grid spacing of 0.75° in latitude and longitude. Because (1) is derived from the water balance equation for an atmospheric column, the corresponding trajectories follow an effective 2D wind field, which in the DRM is given by the VIMF divided by the precipitable water (Dominguez et al. 2006). This approach has been the subject of debate because the vertical wind shear of the horizontal winds can produce water transport patterns not accounted for in a vertically integrated moisture flux (Goessling and Reick 2013; Van der Ent et al. 2013). Rather than attempting a detailed quantification of the errors associated with the 2D nature of the DRM, we provide a careful comparison of our results with well-established facts about the transport of water vapor associated with major circulation patterns over South America at a range of spatial and temporal scales, as reported by multiple studies based on a broad spectrum of techniques and data sources.

b. Regional averages

To quantify the spatially averaged contributions from each source region to each sink region, we compute regional averages for each day. We quantify the contribution P_m from each source region A_k to the precipitation P over the sink region A_j , for each day t , as

$$P_m(A_k, A_j, t) = \frac{\sum_{(x,y) \in A_j} a_k(x, y, t) P(x, y, t) \delta A(x, y)}{\sum_{(x,y) \in A_j} \delta A(x, y)}, \quad (7)$$

where $\delta A(x, y)$ is the area of each grid cell with center at (x, y) . Note that, according to this definition, $P_m(A_k, A_j, t)$ depends on the spatial covariance between $a_k(x, y, t)$ and $P(x, y, t)$. Similarly, we quantify the contribution W_m from each source region A_k to the total precipitable water W over a sink region A_j , for each day t , as

$$W_m(A_k, A_j, t) = \frac{\sum_{(x,y) \in A_j} a_k(x, y, t) W(x, y, t) \delta A(x, y)}{\sum_{(x,y) \in A_j} \delta A(x, y)}. \quad (8)$$

Definitions (7) and (8) contain information about the temporal and spatial variability of P and W , respectively, in addition to the information about the relative exchange of atmospheric moisture given by the a_k fields. The a_k maps represent fractions of moisture, and these patterns can be different from those of precipitation and precipitable water originating from a particular source region. The existence of enough moisture content is a necessary but not a sufficient condition for the occurrence of precipitation. Upward movement by large-scale convergence, deep convection, or orographic lifting is also needed to produce precipitation.

c. Region of study

We subdivided the South American continent into 13 regions and the adjacent oceans into 4 regions (Fig. 1). These regions are based on the Pfafstetter delineation of basins, level 1, extracted from the global 30-arc-s digital elevation model dataset (GTOPO30)-derived 1-km watershed boundaries dataset (HYDRO1K), developed by the Earth Resources Observation and Science Center (Verdin and Verdin 1999). The data are available from the United Nations Environment Programme (UNEP) website (<http://geodata.grid.unep.ch/>). At the continental scale, the level 1 Pfafstetter delineation basically identifies the four major river basins draining to the ocean and the corresponding five inter-basin regions (Verdin and Verdin 1999). For this study, we modified the HYDRO1K data to better

represent the LPRB (based on Lee and Berbery 2012). We also subdivided the Amazon basin into northern and southern Amazon because the climatic characteristics of each subregion are different (Marengo 2004; Arias et al. 2011). These modifications produced more regions than present in the original HYDRO1K dataset.

d. Data

We use daily average E , W , and P fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) for the period 1980–2012. Data for the domain of interest were provided by the European Centre for Medium-Range Weather Forecasts at 0.75° resolution from their website (http://data-portal.ecmwf.int/data/d/interim_full_daily). We also use the vertical integral of the moisture flux in the horizontal direction $\mathbf{Q} = (Q_x, Q_y)$ to obtain the effective horizontal wind components (U, V) as $U = Q_x W^{-1}$ and $V = Q_y W^{-1}$. The horizontal wind field is updated every 6 h in order to compute the trajectories of the air columns. In general, ERA-Interim provides a better representation of the hydrological cycle (Dee et al. 2011) and of the transport of atmospheric moisture than other assimilated products (Trenberth et al. 2011). The largest uncertainties and errors are likely associated with the precipitation and evaporation estimates (Trenberth et al. 2011). ERA-Interim has a wet bias in precipitation over the Amazon and southern South America (see, e.g., Betts et al. 2009; Dee et al. 2011). There is larger uncertainty in the evaporation estimates because of the differences among satellite retrievals (Vinukollu et al. 2011) and reanalyses estimates (Decker et al. 2012). The evaluation of the ERA-Interim fields over South America is beyond the scope of this study.

We use monthly values of the oceanic Niño index (ONI) and the corresponding classification of ENSO years as provided by the Climate Prediction Center (CPC) from their website (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). To quantify the activity of the AAO, we use monthly values of the Antarctic Oscillation index as provided by the CPC from their website (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao/ao_index.html).

e. Significance test

In this study, we perform statistical significance tests for quantities that represent spatial averages over tens of grid points and temporal averages over hundreds of time steps. By the central limit theorem we expect the corresponding distributions to be nearly Gaussian and the sampling distributions of their moments (e.g., means) to

FIG. 3. Mean annual cycle of contributions to (a) precipitation and (b) precipitable water over the LPRB. In (a), the dark blue (light green) line represents total precipitation (evaporation) and the mean annual values (mm day^{-1}) are shown in the small legend inside the plot. In (b), the dark blue line represents total precipitable water and the mean annual value is shown in the small legend (mm). The dotted line (labeled Terr) is the sum of the contributions from South American sources. The long-term contributions from each source are shown in the larger legends as percentages of the mean annual value of total (a) precipitation and (b) precipitable water.

be close to Student's t distribution. Therefore, we use the t test to assess the significance level of our results.

3. Mean annual cycle of atmospheric moisture transport to the LPRB

Moisture from terrestrial origin over the LPRB reaches a maximum during the austral summer and a minimum during the winter (Figs. 3 and 4). Total terrestrial contributions (i.e., from South America) account for approximately 63% of the precipitation over the LPRB (Fig. 3a) (cf. 51% and 29% for the southern Amazon and northern Amazon, respectively). Local recycling (i.e., moisture evaporated from the LPRB that precipitates within the basin) is the single most important terrestrial contribution to atmospheric moisture over the LPRB. The mean annual contribution to precipitation by local recycling is 0.87 mm day^{-1} , which is 23.5% of the total mean annual precipitation (Fig. 3a). As a reference, the mean recycling estimated by the DRM for northern and southern Amazon is 17.3% and 25.5%, respectively. In terms of precipitable water over the LPRB, the local contribution is 26%, almost twice as large as the second largest contribution (Fig. 3b). Moisture from the LPRB does not reach regions far upwind of the mean VIMF (Figs. 4a,d). This is consistent with a vertical profile of moisture flux that is mostly northerly over the northern LPRB (see, e.g., Berbery and Barros 2002; Van der Ent et al. 2013, their Fig. 11). Most of the moisture of local origin stays within the basin, especially during the December–February (DJF) season (Fig. 4a). Consequently, the local recycling of precipitation is highest during the LPRB's wet season of DJF, with a peak value of almost 30% during January

(1.8 mm day^{-1}). During DJF, both large-scale convergence and net radiation are enhanced, increasing the atmospheric instability, precipitation, and evaporation. During the dry season (austral winter), recycled precipitation is the lowest in fraction (12%) and absolute value ($\sim 0.18 \text{ mm day}^{-1}$). Average precipitation is reduced in the dry season (Fig. 3a), which reduces the probability of local evaporation to precipitate back over the LPRB. Consequently, while the ratio of precipitation of local origin to the local evaporation is nearly 0.40 during January (wet season), it is 0.17 during July (dry season) (see Fig. 3a). This suggests that the LPRB is relatively more dependent on external sources for its dry season precipitation. However, errors in our estimates could be larger during the winter, when the atmosphere is more stratified, and the well-mixed atmosphere assumption in the DRM is less valid. During this season, the effects of the vertical wind shear are expected to be larger (Goessling and Reick 2013; Van der Ent et al. 2013). Our estimates of the local contribution during winter are lower than those of previous studies [$\sim 30\%$ according to Dirmeyer et al. (2009); see moisture sources by river basin available at <http://www.iges.org/wcr/>].

The annual average Amazonian contribution to the LPRB (sum of the northern and southern Amazon; see Fig. 1) is 23.9% (Fig. 3a), which is very close to the 23% estimated by Dirmeyer et al. (2009) (as reported at <http://www.iges.org/wcr/>). Most of this moisture comes from the southern Amazon and reaches the LPRB all year round. The southern Amazon contributes more to precipitation over the LPRB during the dry season ($\sim 24\%$) than the LPRB itself (Fig. 3a). However, the southern Amazon and the LPRB contribute almost the same amount of precipitable water to the LPRB in this

FIG. 4. Mean VIMF (vectors; $\text{kg m}^{-1} \text{s}^{-1}$) and mean moisture fraction (colors) originated from (left) the LPRB, (center) the southern Amazon, and (right) northeastern Brazil. Monthly averages for (a)–(c) January and (d)–(f) July for the period 1980–2012. Source regions different from the LPRB are delineated in blue. The LPRB is delineated in red. (For the contribution from the northern Amazon, see the figure in the supplemental material).

season ($\sim 5 \text{ mm}$ in July; Fig. 3b). This suggests that moisture of Amazonian origin is more efficiently converted to precipitation over the LPRB than moisture originating from the LPRB. Compared to the large seasonal changes of the LPRB as a moisture source, the contribution from the southern Amazon (SAMZ) is very consistent throughout the year, which means this region is a quasi-permanent source of moisture for the LPRB. This contribution is especially important during the dry season in the LPRB, when the local contribution

to precipitable water is less than half the local contribution during the wet season ($\sim 11 \text{ mm}$ in the wet season).

The northeastern and central Brazil [northeastern Brazil (NORD) and Tocantins River (TOCA) in Fig. 1, respectively] are also important terrestrial contributors to the LPRB. Together they account for 7.3% (7.7%) of the mean annual LPRB precipitation (precipitable water). Note that the contributions from each of these regions are equal to or larger than those from the northern

FIG. 5. As in Fig. 4, but for moisture originated from the adjacent portions of the (left) southern Pacific, (center) tropical Atlantic, and (right) southern Atlantic. (For the contribution from the tropical Pacific, see the figure in the supplemental material).

Amazon (NAMZ) (Fig. 3). The oceanic contributions to the LPRB come mostly from the adjacent southern subtropical and extratropical Pacific (SOPA), tropical Atlantic (NOAT), and southern subtropical and extratropical Atlantic (SOAT) (see Fig. 5). The adjacent southern Pacific contributes with 7.1% (7.6%) of the mean annual precipitation (precipitable water) over the LPRB (Fig. 3), and this contribution takes place mostly during the austral winter. Because of the westerly mean VIMF and eddy transport by baroclinic disturbances, between 10% and 30% of the moisture over southwestern LPRB comes from the southern Pacific during the

austral winter (Fig. 5d). The tropical Atlantic contributes 6.1% (5.6%) of the mean annual precipitation (precipitable water) over the LPRB, and this contribution is larger in absolute value during the austral summer (Fig. 3). This transport is associated with cross-equatorial flow during the austral summer (Fig. 5b), while the large fractional contribution during the austral winter coincides with minimum values of precipitation and precipitable water (Fig. 3), making this contribution negligible in absolute value. The southern Atlantic contributes nearly 1.5% of the mean annual precipitation over the LPRB but almost 5.4% of the precipitable water

FIG. 6. Composites of anomalies of the contribution to monthly precipitable water (mm) over the LPRB by different regions during the extreme phases of (a) ENSO and (b) the AAO. The plus (minus) sign denotes the positive (negative) phase for ENSO and the AAO. The positive whisker extends from $q_{0.75}$ to $q_{0.75} + 1.5(q_{0.75} - q_{0.25})$ and the negative whisker extends from $q_{0.25} - 1.5(q_{0.75} - q_{0.25})$ to $q_{0.25}$, where $q_{0.25}$ and $q_{0.75}$ are the 25th and 75th percentiles, respectively.

(Fig. 3). Moisture from the southern Atlantic reaches the LPRB primarily during the austral summer (Fig. 5). This transport is not associated with the mean VIMF (Fig. 5) but rather with eddy transport by transient low pressure patterns that produce southeasterly flow off the coast of Uruguay and southern Brazil. The effect of transient systems and of those associated with the transport from the southern Pacific (both in the time scales of hours to days) seem to be well captured in our calculations by the use of 6-hourly wind fields. The contribution from the adjacent tropical Pacific (NOPA) is less than 0.7% and is mainly associated with the mean VIMF (see Fig. 4 for VIMF patterns and see the figure in the supplemental material).

4. Variability of moisture transport to the LPRB

In the following subsections we analyze the variability of the transport of precipitable water to the LPRB at several time scales. The analysis is primarily based on precipitable water because in ERA-Interim this field is more constrained by observations (e.g., specific humidity), while precipitation is generated by the forecast (Dee et al. 2011).

a. Interannual variability: ENSO

ENSO is one of the modes of climate variability that most affects the precipitation and temperature patterns over South America (see e.g., Garreaud et al. 2009). In general, it has been found that there is a strong correlation between precipitation over northeastern and southeastern South America and the sea surface temperature in the Niño-3.4 region (Van der Ent and Savenije 2013). Figure 6a shows the regional monthly

anomalies of the contributions to precipitable water over the LPRB originating from selected subregions. The contributions are grouped according to the two extreme phases of ENSO, according to the classification of the CPC following the ONI [as in Silva et al. (2009)]. In Fig. 6, the plus (minus) sign represents the El Niño (La Niña) phase of ENSO. The differences of means for different ENSO phases are statistically significant beyond the 99% level (see Table 1). Note that, even when the values in Fig. 6a may seem small, an anomaly of 0.5 mm over the entire LPRB corresponds to an equivalent of 1.75 Gt ($1 \text{ Gt} = 10^{12} \text{ kg}$) of liquid water. Furthermore, the contributions from each source do not spread uniformly over LPRB, so the local anomalies can be much larger.

We find that during El Niño the anomalies in total W and in the contributions from the Amazon and southern Pacific tend to be positive, while those from the LPRB and the southern Atlantic tend to be negative (Fig. 6). The opposite is observed during La Niña events. The anomalies in total W are consistent with the correlation between ENSO and precipitation over southeastern South America (e.g., Garreaud et al. 2009). There is also an enhanced southward transport of moisture from Brazil to southeastern South America (Fig. 7). Because of the anomalous circulation, the Amazonian contribution to the mean monthly precipitable water over the LPRB is almost 1 mm higher during El Niño than during La Niña months (see Table 1). Figure 7 shows that during El Niño the excess precipitable water is concentrated over central and northern LPRB, consistent with its Amazonian origin, while during La Niña the deficit in precipitable water is larger over southern LPRB, as the reduced moisture arriving from the Amazon stays mostly over northern LPRB.

TABLE 1. Differences between the mean values of the anomalies in precipitable water between different ENSO and AAO phases (see Fig. 6). The Δ_{ENSO} corresponds to the mean value during the positive ENSO phase (El Niño) minus the mean value during the negative ENSO phase (La Niña). The $Z(\Delta_{\text{ENSO}})$ and $p(\Delta_{\text{ENSO}})$ are the Z score and the p value (probability of occurrence) of each difference Δ_{ENSO} . Analogous definitions hold for the AAO.

	Total	LPRB	Southern Amazon	Southern Atlantic	Southern Pacific
Δ_{ENSO} (mm)	1.66	−0.65	0.76	−0.62	0.44
$Z(\Delta_{\text{ENSO}})$	5.07	−3.95	6.20	−3.96	3.57
$p(\Delta_{\text{ENSO}})$	<0.0001	0.0002	<0.0001	0.0002	0.0009
Δ_{AAO} (mm)	−1.55 mm	1.14	−0.88	0.83	−0.29
$Z(\Delta_{\text{AAO}})$	−2.08	4.16	−3.29	3.96	−3.59
$p(\Delta_{\text{AAO}})$	0.0673	0.0011	0.0081	0.0016	0.0033

The same anomalies in the circulation produce a reduction of 0.65 mm in the contribution from the LPRB to its own monthly mean precipitable water during El Niño compared to La Niña. Even when the average evaporation over the LPRB is $0.087 \text{ mm day}^{-1}$ higher during El Niño compared to La Niña (this difference is significant at the 99% level), the stronger northerly VIMF during El Niño takes that moisture originated as local evaporation out of the LPRB at a faster rate. The same circulation patterns produce a decrease in the contribution from the southern Atlantic of nearly 0.62 mm during El Niño compared to La Niña. Increased transport from the southern Atlantic during La Niña months might be the result of larger and more frequent eddy transport associated with cyclonic circulations off the coast of southeastern South America. On the other hand, there is an increase in the contribution from the southern Pacific of nearly 0.44 mm during El Niño compared to La Niña. Enhanced transport from the southern Pacific is a combination of both a strengthening in the mean westerly VIMF in the band 20° – 30°S (Fig. 7) and the increase in the baroclinic activity over southern South America during El Niño events (Grimm et al. 1998).

Composites analogous to those in Fig. 6a were realized for the DJF and September–November (SON) seasons separately (not shown), when the effects of ENSO on southeastern South America are stronger (e.g., Garreaud et al. 2009). In general the results are the same as those presented above. All the anomalies are larger in magnitude during DJF, except those associated with the southern Pacific, which are larger during the spring season of SON because of the anomalous activity of extratropical cyclones during each of the ENSO phases. Results in Fig. 6a show that the sign of the anomalies are present all year round, which is consistent with previous studies [e.g., the sign of the correlations in Garreaud et al. (2009) is the same for all seasons].

b. Interannual variability: AAO

The Antarctic Oscillation (AAO) is the leading pattern of tropospheric variability south of 20°S . During the

AAO, positive (negative) anomalies in pressure over the Antarctic are associated with negative (positive) anomalies over the latitudinal band around 40° – 50°S (Thompson and Wallace 2000). Gong and Wang (1999) found variability in the AAO at intermonthly (periods of 2.7 and 4.2 months) and interannual (period of 45.7 months) time scales. The positive AAO phase is associated with increased pressure and temperature and less precipitation over southern South America (e.g., Garreaud et al. 2009; Gillett et al. 2006). The correlation between the AAO index and precipitation over southern South America is larger during the late spring season, particularly during November–December (Silvestri and Vera 2003). Therefore, during this season we expect to see noticeable changes in the transport of water vapor to the LPRB that are associated with the AAO. In this study we have classified the contributions to precipitable water over the LPRB according to the sign of the average AAO index for the November–December period. The present analysis focuses on the interannual variability of the late spring season because only the November–December periods of different years are compared.

In general, negative anomalies in total precipitable water over the LPRB during the positive phase of the AAO are related to decreased transport from the southern Amazon and the southern Pacific, while anomalous contributions from the LPRB and the southern Atlantic tend to be positive (see Fig. 6b and Table 1). The negative anomalies in total precipitable water and the increased saturation vapor pressure associated to higher temperatures in the positive phase of the AAO lead to reduced precipitation over the LPRB. At the same time, the contributions from the LPRB and the southern Atlantic tend to be larger, because of the weakening of the mean eastward flow associated with the poleward shift of the westerlies and the subsequent increase in the westward eddy transport from the east (Fig. 7). However, these positive anomalies are in general not large enough to lead to positive anomalies in the total precipitable water. During the negative phase of the AAO, the signs of the anomalies just described

FIG. 7. Composites of anomalies in the monthly VIMF (vectors; $\text{kg m}^{-1} \text{s}^{-1}$) and monthly precipitable water (colors; mm) fields associated with the different phases of (top) ENSO and (bottom) the AAO. The vectors and the colored grid cells represent ENSO (AAO) anomalies that are statistically significant at the 99.5% (90%) level. The contours represent the anomalies in the monthly precipitable water, even if not significant.

change as a consequence of the opposite changes in the circulation. Note that the anomalies during the negative phase of the AAO are similar to those of El Niño months (Fig. 7). However, the anomalous circulation is stronger in the higher latitudes for the AAO, whereas during El Niño tropical anomalies have the meridional component associated with the change in the Hadley circulation. In addition, less than half of the negative AAO years are El Niño years. Something analogous

happens when comparing the La Niña and the positive AAO composites.

c. Interannual variability: Covariability of precipitation, evaporation, and precipitable water

We performed a correlation analysis for the monthly anomalies in precipitation (P'), precipitable water (W'), and the contributions from different regions (see Table 2) to understand how moisture contributions from different

TABLE 2. Correlation coefficients between time series of monthly anomalies: (P' , P'_k) represent correlations between anomalies in total precipitation over LPRB (P') and the corresponding contributions from each source P'_k (columns); (W' , W'_k) represent the same as (P' , P'_k), but for precipitable water; (P'_k , W'_k) represent correlations between the contributions from each source to precipitation (P'_k) and precipitable water (W'_k); (P'_k , E'_k) represent the same as (P'_k , W'_k), but E'_k refers to anomalies in evaporation in the corresponding source region k (columns); and (W'_k , E'_k) represent the same as (P'_k , E'_k), but for precipitable water. All correlations are statistically significant at the 99% level, except those values in italics.

	LPRB	NAMZ	SAMZ	NOAT	SOAT	NOPA	SOPA	NORD
(P' , P'_k)	0.47	0.62	0.82	0.72	−0.17	0.34	0.47	0.54
(W' , W'_k)	−0.22	0.47	0.68	0.69	−0.42	0.21	0.23	0.54
(P'_k , W'_k)	0.57	0.90	0.71	0.71	0.79	0.86	0.65	0.65
(P'_k , E'_k)	0.07	0.31	0.27	0.21	0.09	0.32	0.28	0.17
(W'_k , E'_k)	−0.08	0.28	0.33	0.23	0.10	0.31	0.40	0.13

sources affect the variability of precipitation and precipitable water over the LPRB. In this section P'_k represents the anomaly in the contribution to precipitation [$P_m(A_k, A_j)$] over the LPRB (A_j : LPRB) from different sources (regions A_k) (see section 2b). An analogous definition of W'_k is used for precipitable water, while E'_k represents the anomalous evaporation in region A_k . The regions A_k for this part of our analysis are listed at the top of the columns in Table 2.

The correlations between P' and W' and the anomalies from different sources are shown in the first two rows of Table 2. Note that the correlations are higher for the contributions from upwind regions like the southern and northern Amazon, northeastern Brazil, and the tropical Atlantic. In particular, the correlation of total precipitation over the LPRB with the contribution from the southern Amazon is much larger (0.82) than the correlation with the contribution from the LPRB itself (0.47). The correlations with the contributions from the southern Atlantic are negative (see section 4d for physical mechanism). At the monthly time scale, the contributions from the southern Pacific show a lower covariability with P and W over the LPRB than the contributions from tropical South America. However, anomalous contributions from the southern Pacific, especially during the winter–spring season, can be as large as those from the southern Amazon (see Fig. 6b).

The correlations between the anomalous contributions to precipitation and precipitable water over the LPRB from each source are shown in the third row of Table 2. These correlations capture the frequency of events when anomalous contributions to precipitable water from each source are converted into a corresponding contribution to precipitation. These values suggest that anomalous precipitable water arriving to the LPRB from all external sources in Table 2 is more linked to precipitation events than contributions from the LPRB itself. For example, the anomalous contributions from the southern Pacific can be smaller than those from the LPRB, but the former are more likely to

fall as precipitation than the local contributions. This effect is even more pronounced for some remote regions such as the northern Amazon. Similarly, note that anomalous precipitable water arriving from the southern Atlantic is highly and positively correlated with the contribution to precipitation from that region to the LPRB, even when the corresponding relationships with the total anomalies (i.e., P and W) are small and negative. The higher correlations between the remote contributions to precipitable water and the corresponding precipitation contributions show the role of large-scale convergence in the generation of precipitation over the LPRB (as represented by ERA-Interim).

The last two rows in Table 2 show the correlations between the anomalies in the contributions to precipitation and precipitable water over the LPRB and the anomalous evaporation in each source. Most of them are smaller in magnitude than the correlations in the previous rows, and some of them are not significant. These correlations are relatively larger for upwind regions but still small in magnitude. Comparison of the correlations in the first three rows of Table 2 with those in the last two rows suggest that, at the monthly time scale, the effect of the circulation on the contributions from each source is larger than effect of the variability of the evaporation field in each source region.

d. Daily variability

To identify the relative roles of the South American (SA) and non-South American (No-SA) contributions to daily anomalies of total precipitable water in the LPRB during the wet season, we classified each of the 2970 days in DJF (between 1980 and 2012) as belonging to one of eight types (Table 3). In the discussion that follows, we will refer to South American sources as terrestrial and non-South American sources as oceanic, but keep in mind that, while non-South American sources are dominated by oceans, there could be small terrestrial contributions from other continents. The classification in Table 3 encompasses all the combinations in

TABLE 3. Composites of precipitable water anomalies (mm) contributed by different sources to LPRB during the season of December–February. The first (second) plus or minus signs in the parenthesis in the first column represent the sign of the oceanic (terrestrial) anomalous contribution. The double plus or minus signs indicate which of these two sources is dominant in the total W anomaly. All values are significant at the 95% level or higher, except those in italics.

Cases	Frequency (%)	Total	No-SA	SA	LPRB	SAMZ	SOAT	NOAT	NAMZ	SOPA
I: (+ +, +)	9.4	4.29	3.10	1.19	−1.52	1.61	−0.84	1.02	0.55	<i>0.21</i>
II: (+ +, −)	14.9	2.34	4.45	−2.10	−2.59	<i>0.18</i>	−0.79	0.65	<i>0.08</i>	0.22
III: (− −, +)	13.4	−1.70	−3.35	1.65	2.26	−0.37	<i>0.04</i>	−0.52	−0.24	−0.15
IV: (− −, −)	8.7	−4.24	−2.93	−1.31	1.16	−1.54	0.47	−0.82	−0.43	−0.12
V: (+, + +)	9.4	4.14	1.09	3.05	<i>0.08</i>	1.65	−0.79	0.93	0.74	<i>0.01</i>
VI: (−, + +)	20.3	2.05	−1.99	4.04	2.06	1.28	−0.44	<i>0.06</i>	0.21	−0.09
VII: (+, − −)	11.9	−2.26	1.93	−4.20	−2.07	−1.33	0.83	−0.29	−0.28	<i>0.10</i>
VIII: (−, − −)	11.9	−5.77	−1.53	−4.24	−0.42	−2.10	1.79	−0.98	−0.60	−0.13

which the anomalous contributions from two sources (terrestrial versus oceanic) can add up to produce the total anomaly over a target region (total anomaly in precipitable water over the LPRB). We use this decomposition for several tasks: (i) to quantify the frequency of occurrence of events when both major sources add “constructively” (same sign of anomaly) or “destructively” (opposite sign of anomaly); (ii) to identify South American sources that add constructively or destructively to the total terrestrial anomalous contribution; and (iii) to identify the patterns of moisture flux and evaporation associated with opposite contributions from terrestrial and oceanic sources.

The anomalies used to obtain the results in Table 3 are computed as the value of regional averages for each day minus the average value for the corresponding Julian day over the 1980–2012 period. We selected the wet season of DJF because that is when the largest mean contributions from the South American continent are observed (Figs. 3 and 4) and the wind shear effects are expected to be smaller (Goessling and Reick 2013; Van der Ent et al. 2013). In Table 3 the first plus or minus signs in the parenthesis in the first column represent the sign of the oceanic anomalous contribution. Similarly, the plus or minus signs in the second part of the parenthesis represent the sign of the terrestrial anomalous contribution. The double signs indicate which of these two sources is dominant in the total W anomaly. As an example, the (−, ++) indicates a day when oceanic sources were below average but terrestrial sources were anomalously high and overall there was anomalously high precipitable water. The second column in Table 3 contains the frequency of occurrence of each case. The other columns show the average value of the anomalous contributions to precipitable water over the LPRB from selected source regions. To narrow our analysis we focus in detail only on cases II and VI. These represent conditions of above-average precipitable water where either oceanic sources dominate with negative terrestrial

anomalies (case II) or terrestrial sources dominate with negative oceanic anomalies (case VI). Because our analysis is at the daily time scale, we focus exclusively on above-average precipitable water events relevant for intense precipitation; below-average anomalies relevant for drought conditions would be important only if persistent over long periods of time.

Case II groups 442 days when anomalous W is positive and determined by the oceanic contribution while the terrestrial anomaly is negative. The associated precipitation is 1.06 mm day^{-1} above average with an oceanic contribution of 0.81 mm day^{-1} above normal. The corresponding VIMF and evaporation anomalies are shown in Fig. 8, for the corresponding case II day and 2 and 4 days before. Only those anomalies that are significant at the 99.5% level are plotted. In this case the contributions from the Amazon are slightly above normal while the LPRB contributes less than in case I (hence the negative anomaly of terrestrial sources). The VIMF composites suggest that the strengthening of the subtropical circulation is common in case II (especially in the 13° – 23°S band, close to the adjacent Atlantic), but anomalies in the cross-equatorial flow do not show a preferred direction. Figure 8 also shows that the anomalous circulation is noticeable 4 days before the case II day (similar patterns are observed up to 9 days before, but they are not statistically significant). Note that the positive evaporation anomalies over southeastern Brazil are mostly outside the Amazon, and the northerly flow is so strong that moisture is transported southeastward beyond the LPRB region, producing very small Amazonian anomalies and negative LPRB anomalies. On the other hand, the transport from the southern Atlantic has two components: decreased eddy transport of moisture from the exit region of the circulation anomalies and the increased moisture coming from northern region of the southern Atlantic.

The largest South American contributions to the LPRB take place during case VI, when the anomalous W

FIG. 8. Composites of anomalies in the VIMF (vectors; $\text{kg m}^{-1} \text{s}^{-1}$) and evaporation (colors; mm day^{-1}) fields associated with positive anomalies of W over the LPRB at $t = \text{day } 0$ during the wet season of DJF. (a)–(c) Case II, when oceanic sources dominate total W' . (d)–(f) Case VI, when terrestrial sources dominate total W' . Composites for the day of the anomaly in W (day 0) and 2 (day –2) and 4 (day –4) days before. See Table 3 and text for details. Only anomalies significant at the 99.5% level are shown.

is positive despite reduced oceanic contributions. The continental contribution is larger than in other cases, with average excess close to 4 mm (more than 10% of the mean W ; see Fig. 3b). The resulting precipitation is an excess of 0.83 mm day^{-1} , with a terrestrial contribution 0.90 mm day^{-1} above normal (the largest among all cases) and a decrease of oceanic contribution of $-0.07 \text{ mm day}^{-1}$. During case VI days, the Amazon plays an important role, with a contribution to precipitable water of almost 1.5 mm above normal (equivalent to 5.25 Gt of extra liquid water), while the excess contribution from the LPRB is 2.1 mm (7.35 Gt of extra

liquid water) (see Table 3). Case VI is important also because it is the most common among all eight cases (602 days). In this case the anomalous contributions from the LPRB and the southern and northern Amazon tend to be positive simultaneously. This combination is produced by an interesting change in the circulation during the days prior to the case VI day (Fig. 8). Four days prior to the case VI day, the anomalous circulation is southerly over the LPRB and Brazil. A similar pattern is observed up to 9 days before the case VI day, but they stop being statistically significant at the 7th day before the case VI day. Two days before the case VI day the

significant anomalies in the VIMF are mostly over the southern Atlantic and suggest weaker outflow from the LPRB to the Atlantic. The accumulation of moisture from continental origin over the Amazon region is due to the sustained weakening of the mean flow and not evaporation, as we see that anomalous evaporation over Brazil is relatively small. The contribution to precipitable water from the southern Amazon to the southern Amazon itself (the accumulation of evaporation in the overlying atmosphere) is almost 1 mm larger than average during the 5th–2nd day before the case VI day. This increase in the contribution from the southern Amazon is the largest among all the cases. Finally, during the day of arrival of the moisture to the LPRB (day 0), the VIMF from the southern Amazon to the LPRB is enhanced while the flow over the south of the LPRB is close to average, leading to an accumulation of moisture of Amazonian origin. The weakening of the flow over the LPRB also leads to an accumulation of moisture of local production, despite the fact that local evaporation anomalies are small. In addition, an anticyclonic anomaly in the VIMF over the southern Atlantic starts to form. The weaker northerly flow over the LPRB on the previous days and the anticyclonic anomaly during the case VI day allow for a slightly larger contribution from the southern Atlantic to the LPRB compared to case V.

Once a given anomaly type takes place, it can persist for several days. On average, cases II and VI last for 2.2 and 2.6 days, respectively, while all other cases do not last longer than 2 days. Our results suggest that terrestrial contributions can help support positive anomalies in both precipitable water and precipitation over the LPRB during several days, even when the oceanic contribution decreases (case VI).

Interestingly, there are some similarities between the anomalous patterns in Fig. 8 and the low-level circulation associated with different configurations of the South Atlantic convergence zone (SACZ) [see Fig. 8 in [Carvalho et al. \(2004\)](#)]. In particular, case II might be associated with a SACZ that is weak or confined over southeastern South America, while case VI might be associated with a SACZ that either is more intense over the Amazon or travels from the north of the LPRB eastward to the South Atlantic. The explicit role of the SACZ in the anomalous terrestrial contribution to precipitable water over the LPRB would require a date-by-date comparison with the different configurations of the SACZ, which is beyond the scope of this study.

5. Summary and discussion

We present an extended version of the DRM for estimating the exchange of atmospheric moisture among

different regions. This method is computationally efficient and has been used to study the transport of atmospheric moisture to the LPRB for the period 1980–2012. The largest errors in our estimates are likely related to the effect of the vertical wind shear. The transport of moisture of local origin and that of remote origin can be in different directions when there is substantial vertical wind shear ([Goessling and Reick 2013](#); [Van der Ent et al. 2013](#)). In our study, the potential errors given by the wind shear are expected to be relatively small as shear is not too large over most of South America, especially over the LPRB [e.g., see Fig. 11 in [Van der Ent et al. \(2013\)](#)]. Accordingly, [Goessling and Reick \(2013\)](#) found that the differences in the absolute values of recycling and transport of moisture from 2D and 3D moisture tracking methods is around 10% (5%) during winter (summer) over South America. We acknowledge that the DRM is not able to explicitly capture the dynamics associated with the wind shear. However, the transport of moisture to southern South America as estimated by the DRM is in general agreement with a number of previous studies that have used different methodologies. We think that, in combination with a sound analysis of the atmospheric circulation in the region of interest, the DRM can be used as an efficient tool to diagnose first-order patterns and magnitudes of moisture transport at continental and regional scales.

We find that local recycling (i.e., precipitation originated as evaporation from the same region) is the most important terrestrial contribution to atmospheric moisture over the LPRB, accounting for 23.5% of the mean annual precipitation over the region. The southern Amazon contributes almost 20% of the annual mean precipitation over the LPRB, with little seasonal variability in the contribution to absolute precipitation and precipitable water. Interestingly, during the dry season, the moisture of Amazonian origin seems to be more efficiently converted to precipitation over the LPRB, than moisture originating from the LPRB. This might be the case when more Amazonian moisture is transported and precipitated over the LPRB during the passage of synoptic disturbances, while larger contributions from the LPRB take place during days with no precipitation. This is consistent with the southward moisture flow over the LPRB and the precipitation events over southeastern LPRB associated with baroclinic waves during the cold season, as found by [Vera et al. \(2002\)](#). Other important sources for the LPRB are the southern Pacific and southern Atlantic. South Pacific moisture is also consistent with the patterns resulting from westward-propagating synoptic-scale waves during the cold season ([Vera et al. 2002](#)).

During El Niño, we find positive anomalies in total precipitable water and in the corresponding contributions

from the adjacent southern Pacific and southern Amazon regions, while less moisture comes from the LPRB itself and the adjacent southern Atlantic. The opposite tendencies are observed during La Niña. During El Niño events, the weakening of the Walker circulation in the vicinity of South America induces anomalous subsidence over Brazil, which coincides with anomalous upward motion at midlevels over southeastern South America (Andreoli and Kayano 2005). This dipolar pattern is also evident in the negative anomalies of precipitable water over northeastern South America and positive anomalies over southeastern South America (Fig. 7), which coincide with reduced precipitation over Brazil and increased precipitation over southern South America (Grimm et al. 2000; Vera et al. 2004). The resulting weakening of the lower branch of the Hadley circulation between tropical and subtropical South America (Wang 2005) is associated with an enhanced southward transport of moisture from Brazil to southeastern South America. There is also evidence of more South American low-level jet (SALLJ) events during El Niño than during La Niña years (Silva et al. 2009). We also find that there is an increase in the contribution from the southern Pacific during El Niño compared to La Niña. This could be due, in part to anomalous upper-level circulation patterns (200 hPa) during El Niño, where stronger subtropical westerlies occur (Ropelewski and Halpert 1987), and an anomalous cyclone is observed over the southern Pacific along with an anomalous anticyclone over the southern Atlantic, both features off the coasts of southern South America (Grimm et al. 1998; Vera et al. 2004; Andreoli and Kayano 2005). Some anomalously high contributions from the adjacent southern Pacific are also observed during La Niña, which could be related to transport events from the southeastern Pacific and southern Argentina, as reported by Silva et al. (2009). Silva et al. suggest these events could be produced by the weakening of the SALLJ during La Niña and the coexistence of anticyclonic and cyclonic anomalies on the west and east sides of southern South America, respectively.

During the positive AAO phase in the late spring the contributions from the LPRB itself and the adjacent southern Atlantic tend to be larger, as a consequence of the weakening of the mean northwesterly flow. During the positive AAO phase, the westerlies are shifted poleward (Garreaud et al. 2009), which in general decreases the transport from the Pacific. Additionally, the increased pressure over the LPRB reduces flow from the Amazon region toward the south of the continent (Silvestri and Vera 2003). Consequently, despite the positive contribution from the LPRB, the decreased transport from the Pacific and the Amazon lead to

a decrease in total precipitable water over the LPRB. During the negative phase of the AAO, we find the opposite tendencies.

Linear correlation analysis suggests that the variability in precipitation and precipitable water over the LPRB is more related to the variability in the contributions from upstream regions than with the variability of the local contribution. We also find that the variability of moisture contributions from different source regions depends on atmospheric circulation, rather than on the regions' evaporation variability. This behavior is also evident at the daily scale during the wet season of DJF, when 20% of the days have positive anomalies in the transport from continental upstream regions that is not associated with positive anomalies in evaporation. During the days leading to the moisture contribution of continental origin event, there is an accumulation of evaporated moisture over the Amazon because of weaker flow, which is then suddenly "released" downwind, when the large-scale circulation from the Amazon to the LPRB gets stronger. Conversely, relatively higher evaporation can occur simultaneously with close to average local moisture contributions, because the excess moisture can be transported out of the source. Thus, evaporation anomalies over a particular region do not determine the anomalies in the local contributions to atmospheric moisture from that region. Therefore, we expect evaporation changes to be important to the contributions to the LPRB only if there is a relatively large variation in the mean evaporation, which could happen under dramatic land use and/or land cover changes (see, e.g., Pires and Costa 2013; Lee and Berbery 2012). Particularly, important land cover changes have been observed and projected over the southern Amazon (Soares-Filho et al. 2006).

Our present results rely on the ERA-Interim estimates of evaporation over South America. However, important differences in the mean evaporation over South America are present among satellite-derived products (e.g., Vinukollu et al. 2011), reanalysis (Decker et al. 2012), and land surface models (e.g., Miguez-Macho and Fan 2012). Comparison of atmospheric moisture pathways from different datasets is an important task that needs further research. Nevertheless, the analysis presented in this study shows the importance of terrestrial sources for water vapor content and precipitation over the LPRB, both as components of the mean state and also to balance the deficits of oceanic origin. In this sense, atmospheric moisture over the LPRB is particularly sensitive to the mean evaporation in source regions like the southern Amazon and the northern LPRB and also to the variability of the atmospheric circulation that brings moisture from these regions.

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