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A Lagrangian identification of major sources of moisture over Central Brazil and La Plata Basin

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[1] This work examines the main sources of moisture over Central Brazil and La Plata Basin during the year through a new Lagrangian diagnosis method which identifies the humidity contributions to the moisture budget over a region. This methodology computes budgets of evaporation minus precipitation by calculating changes in the specific humidity along back-trajectories for the previous 10 d. The origin of all air masses residing over each region was tracked during a period of 5 years (2000–2004). These regions were selected because they coincide with two centers of action of a known dipole precipitation variability mode observed in different temporal scales (from intra seasonal up to inter decadal timescales) and are related to the climatic variability of the South American Monsoon System. The results suggested the importance of the tropical south Atlantic as a moisture source for Central Brazil, and of recycling for La Plata basin. It seems that the Tropical South Atlantic plays an important role as a moisture source for Central Brazil and La Plata basin along the year, particularly during the austral summer. The north Atlantic is also an additional source for both regions during the austral summer.

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1. Introduction

[2] According to *Vera et al.* [2006] and references therein, the seasonal cycle of precipitation over most of South America presents maximum values during the austral summer season and minimum in the winter, characterizing, therefore, the South American Monsoon System (SAMS) [*Zhou and Lau*, 2001].

[3] The general features of the SAMS configuration are described by *Grimm et al.* [2005]. According to the authors, in the austral summer, as the major heating zones migrates to the subtropics; a thermal low-pressure system develops over the Chaco region, in central South America. The low-pressure system over northern Argentina and western Paraguay is a climatological feature present throughout the year, but is strongest during this season. The southwest-northeast interhemispheric pressure gradient between the South American low and the northwestern Sahara strengthens. Then, the northeasterly trade winds intensify and anomalous cross equatorial flow penetrates the South America, carrying moisture. Over the continent, this flow becomes northwesterly, is channeled southward by the Andes, and turns clockwise around the Chaco low. Low-level wind and moisture convergence associated with the interaction of the continental low with the South Atlantic High and the northeasterly trade winds result in enhanced precipitation in the Amazon, Central and southeastern Brazil [*Lenters and Cook*, 1995]. The southeastward extension of cloudiness and precipitation toward the Atlantic Ocean is referred to as the South Atlantic Convergence Zone (SACZ) [*Kodama*, 1992; *Figueroa et al.*, 1995; *Liebmann et al.*, 1999].

[4] The Low Level Jet (LLJ) is another important system for the South American climate that modulates the precipitation over southern Brazil and La Plata Basin. It is observed over a region close to eastern Andes and contributes to the meridional moisture transport from the Amazon to the subtropics [*Marengo et al.*, 2002, 2004 and references therein]. Although the rainy season in Central Brazil is related to the SAMS, precipitation is observed in La Plata Basin throughout the year [*Berbery and Barros*, 2002], partially due to Mesoscale Convective Systems [*Velasco and Fritsch*, 1987].

[5] *Herdies et al.* [2002] verified two main summer circulation patterns over the continent during the 1999 austral summer: one associated with the occurrence of SACZ events and other with their absence. According to the authors, during SACZ events there is intense low-level wind flow carrying moisture from the Atlantic Ocean and Amazon to the subtropics, associated with moisture flux convergence and precipitation over the Amazon basin and southeastern Brazil. The weakening of the moisture trans-

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port to La Plata Basin causes the reduction of precipitation over northern Argentina, Paraguay, southern Bolivia and northern Chile. On the other hand, during the absence of SACZ events the low-level wind flow is displaced westward, weakening the moisture flux convergence over southeastern Brazil and restricting the moisture transport mainly over La Plata Basin.

[6] These results were reinforced by the same authors through analysis of moisture fluxes and budgets over South America. They also verified that the strongest South America moisture inflow comes from the southern tropical Atlantic Ocean. On the other hand, the strongest outflow is to southwestern South Atlantic Ocean during the SACZ regime and to Peru and the Eastern Pacific ocean during non-SACZ regime. These authors suggest that the most efficient transfer of moisture from the topics to the extra tropics in the South America is accomplished when the SACZ is present.

[7] The existence of the austral summer precipitation dipole pattern over South America can be verified through statistical analysis and it is usually related to intra seasonal [*Casarin and Kousky*, 1986], interannual or even lower frequencies variability scales [*Robertson and Mechoso*, 2000]. The dipole is a warm season feature, and several papers have discussed and related it to moisture transports, as in *Doyle and Barros* [2002] and *Diaz and Aceituno* [2003]. This work aims to identify the moisture sources for two regions affected by this climatological pattern, the Central Brazil and La Plata Basin, for all seasons of the year, through a Lagrangian method of diagnosis [*Stohl and James*, 2004, 2005]. The method is based on meteorological analysis data, a particle dispersion model, and a Lagrangian analogue to the Eulerian budget method for diagnosing the surface moisture flux and it has already been successfully applied in the identification of major moisture sources regions for Sahel and Iceland [*Nieto et al.*, 2006, 2007].

2. Data and Methods

[8] This study is based on the method developed by *Stohl and James* [2004, 2005], which uses the Lagrangian particle dispersion model FLEXPART [*Stohl et al.*, 1998]. FLEXPART is driven by operational analyses from the European Centre for Medium-Range Weather Forecasts [*ECMWF*, 2002] with $1^\circ \times 1^\circ$ resolution (derived from T319 spectral truncation). FLEXPART can calculate and track the trajectories of atmospheric moisture backward in time to produce information on the spatial distribution of moisture sources.

[9] The atmosphere is divided homogeneously into a large number of so-called particles and then these particles are transported by the model using three-dimensional winds, with their positions and specific humidity (q) being recorded every 6 h. The increases (e) and decreases (p) in moisture along the trajectory can be calculated through changes in (q) with time ($e\text{-}p = m\ dq/dt$), (m) being the mass of the particle. When adding ($e\text{-}p$) for all the particles residing in the atmospheric column over an area, we can obtain ($E\text{-}P$), where the surface freshwater flux (E) is the evaporation and (P) is the precipitation rate per unit area. The method can also track ($E\text{-}P$) from a region backward in time along the trajectories, choosing appropriate particles and finding sources of moisture and precipitation. The method is mainly limited to the trajectory accuracy and to the fact that a time derivative of the humidity is used (unrealistic fluctuations in humidity could be considered as moisture fluxes). However, the use of large time periods minimizes the effects of such unrealistic fluctuations. Full details of the method and its limitations are given by *Stohl and James* [2004, 2005].

[10] In the work reported here we used the tracks of 1,398,801 particles over a 5-year period (2000–2004) computed using ECMWF operational analysis available every 6 h (00, 06, 12, and 18 UTC) with a $1^\circ \times 1^\circ$ resolution and all 60 vertical levels of the analysis. We traced ($E\text{-}P$) backwards from Central Brazil (12°S–22°S; 60°W–40°W) and from La Plata Basin (23°S–38°S; 63°W–48°W) regions, limiting the transport times to 10 d, which is the average time that water vapor resides in the atmosphere [*Numaguti*, 1999]. All the particles residing over these two regions were identified every 6 h and tracked backwards for 10 d. For the first trajectory time step, all the target particles resided over the defined regions and ($E\text{-}P$) is the region-integrated net freshwater flux. For subsequent trajectory time steps, ($E\text{-}P$) represents the net freshwater flux into the air mass traveling to each region. We calculated ($E\text{-}P$) on a $1^\circ \times 1^\circ$ grid and averaged over seasonal and 5 years periods. ($E\text{-}P$) values for specific days are labeled $(E\text{-}P)_n$ here, so $(E\text{-}P)_1$ shows where the moisture over the regions was received or lost on the first day of the trajectory. The total ($E\text{-}P$) integrated over days 1 to 10 is labeled $(E\text{-}P)^{10}$. The analysis of ($E\text{-}P$) values tells us where and when the moisture over both analyzed areas was received or lost.

3. Results

[11] The air masses residing over Central Brazil and La Plata Basin were tracked back in time to see where the particles gained or lost moisture. Figure 1 shows the austral summer (January–February–March) $(E - P)_n$ fields on the first, fifth, and tenth days of transport (counting backwards) and also average over the 10-d period $(E\text{-}P)^{10}$ for both regions to facilitate the comparison between them.

[12] Despite the relative complexity of the backtracking method, the interpretation of these patterns should be fairly simple, providing a good representation of moisture source and sink regions. In order to facilitate their interpretation, results corresponding to regions characterized by E-P > 0 are represented by reddish colors and E-P < 0 by bluish ones. In the first case, evaporation dominates over precipitation, which indicates that air particles located within that vertical column (and bound to reach the analyzed areas) gain moisture. These regions are therefore identified as moisture source regions. In contrast, bluish colors (E-P < 0) reveal regions where precipitation dominates over evaporation. Consequently, air masses located over these regions in transit to the Central Brazil or La Plata Basin display a net loss of moisture, and these regions are identified as moisture sink regions. It should be stressed that the results shown in Figure 1 represent temporal averages for a period of 5 years with a time step resolution of 6 h. Thus each point of the mesh represents the aggregated average for a large number of individual particles. In consequence, Figure 1 should be interpreted strictly from a climatologic point of view. For example, a grid point that shows a positive value (i.e., E-P > 0)

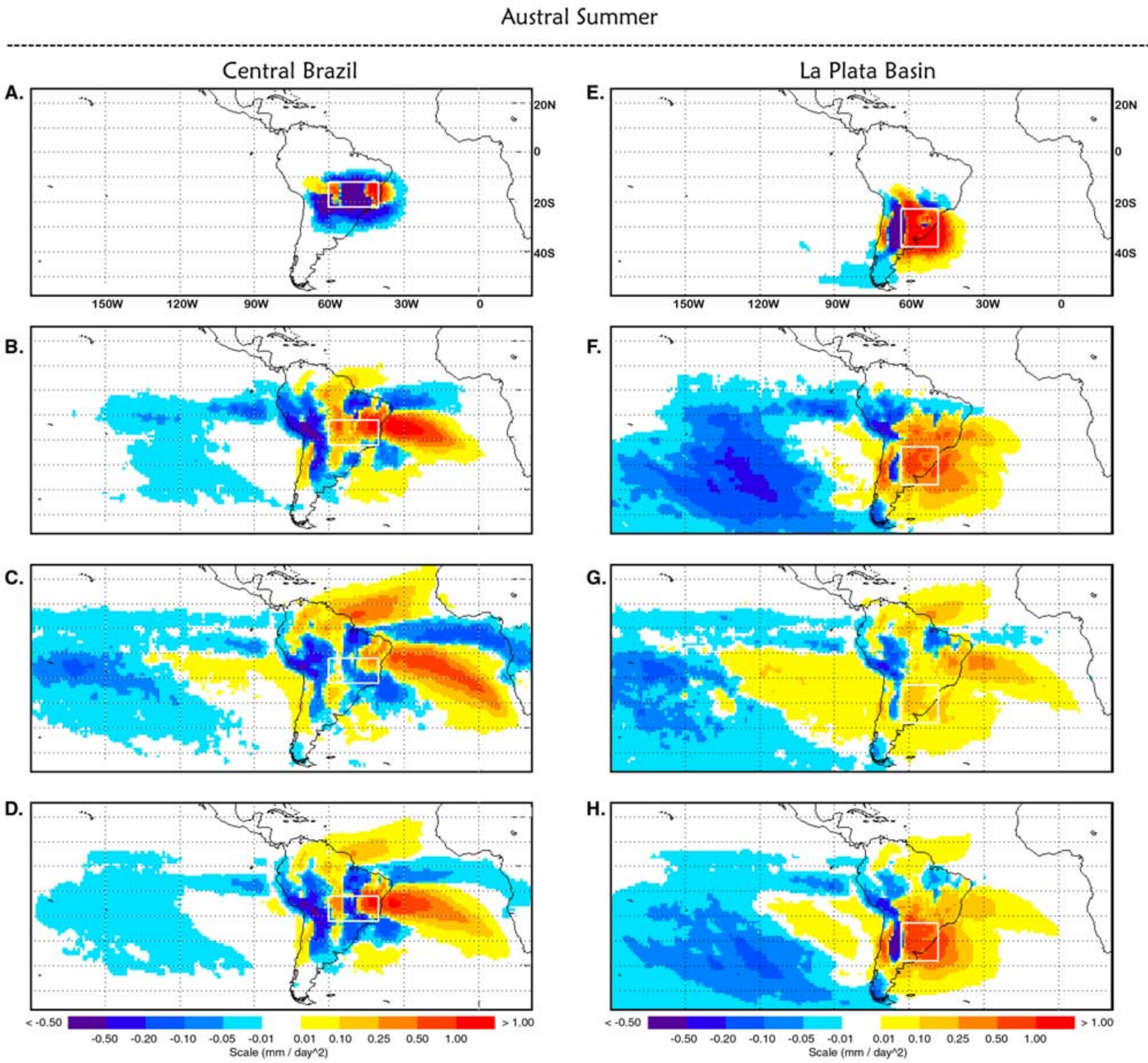

Figure 1. (a) Austral summer average $(E\text{-}P)_1$ field of the Central Brazil region from the backward tracking; (b) same as Figure 1a, for $(E\text{-}P)_5$; (c) same as Figure 1a, for $(E\text{-}P)_{10}$; (d) same as Figure 1a, for $(E\text{-}P)^{10}$; Figures 1e, 1f, 1g, and 1h same as Figures 1a, 1b, 1c, and 1d for La Plata Basin.

indicates that, on average, most of the particles (not necessarily all) that pass through the grid point (and that have the Central Brazil or La Plata Basin as their final destination) gain moisture.

[13] For the Central Brazil, all the air resides close to South America and South Atlantic 1 d back in time (Figure 1a). The value $(E - P)_1$ is negative in an area surrounding the box and over its centre, indicating that precipitation dominates evaporation over these regions. On the other hand, the value $(E - P)_1$ is positive over the western and the eastern boundaries of the box, indicating that particles coming from Western Amazon and Tropical South Atlantic have a strong contribution from evaporation. Five and ten days back in time (Figures 1b and 1c, respectively), the strongest positive values over the South Atlantic ocean suggests the importance of the winds associated with the South Atlantic Subtropical High in providing moisture for the Central Brazil, which has already been suggested by *Herdies et al.* [2002], though their results only refer to one specific year. Another important moisture source is configured over tropical northern Atlantic, from where air masses are carried by the northeasterly trade winds over the Amazon toward Central Brazil following the mechanism suggested by *Grimm et al.* [2005] and *Vera et al.* [2006]. In the 5 and 10 d back in time (Figures 1b and 1c, respectively), positive values are also observed over La Plata Basin. However, the negative values of $(E\text{-}P)_1$ in this area indicate that part of the moisture could be lost through precipitation during the day prior to reach Central Brazil. The average over all 10 d of transport (Figure 1d) shows a strong moisture uptake over the Atlantic eastern Brazilian coast and a weaker one over tropical northern Atlantic (hereafter EBC and NA, respec-

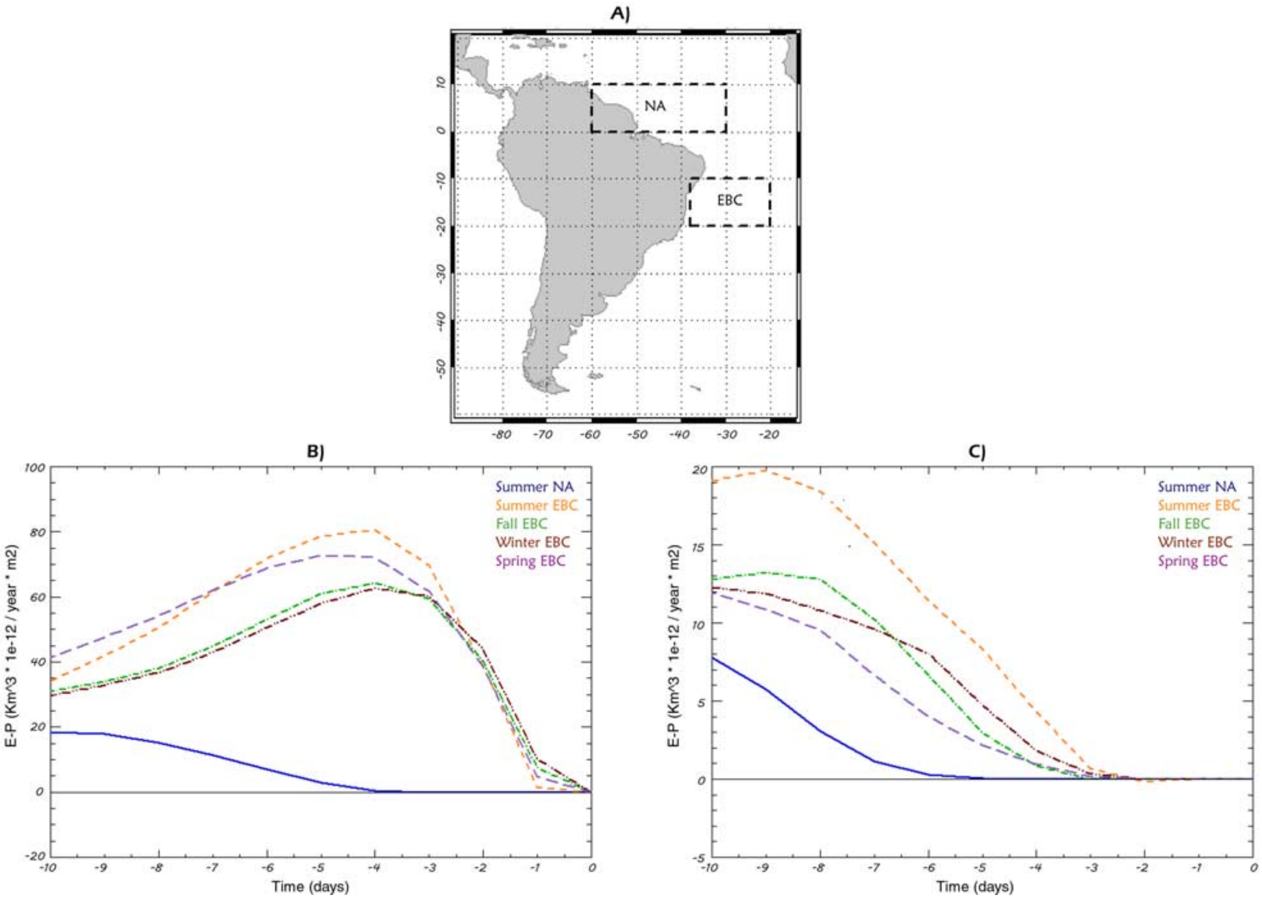

Figure 2. (a) Time series of $(E\text{-}P)_n$ calculated backward for moisture over Central Brazil and La Plata Basin and integrated over the regions indicated: North Atlantic (NA) and Eastern Brazilian Coast (EBC); (b) relative values of NA (for the austral summer) and EBC (for all seasons) $(E\text{-}P)_n$ time series for moisture over Central Brazil, taking into account the area of each source region (scale multiplied by a factor of 10^{12}); (c) same as Figure 2b, but for La Plata Basin.

tively), agreeing with the climatological low-level moisture flux analysis of *Doyle and Barros* [2002]. These authors verified during this season that a moisture flux from continental low latitudes follows a southeasterly direction, converging with the southwestward transport carried by the winds of the South Atlantic high in the vicinity of the SACZ, at about 20°S. The convergence of water vapor flux in the continent near the SACZ is accompanied with abundant precipitation.

[14] For La Plata Basin, positive $(E - P)_1$ values are observed over the basin area suggesting the importance of recycling (i.e., the process by which a portion of the precipitated water that evapotranspired from a given area contributes to the moisture over the same area). In the eastern and the southern boundaries of the box, particles coming from southwestern South Atlantic Ocean (SSA) have a strong contribution from evaporation. In the 5 and 10 d back in time (Figures 1f and 1g, respectively), positive values are observed over SSA, Central Brazil, and EBC. The NA area also presents positive values 10 d back in time, but in 5 d back, the negative values over northern Brazil indicates that much of the moisture is lost by precipitation during its trajectory to La Plata Basin. In this way, average over all 10 d of transport (Figure 1h) shows five main moisture sources: recycling, SSA, EBC (though weaker than the observed for the Central Brazil), Central Brazil, and over the NA, where much of the moisture is lost by precipitation during the particles trajectory coming from NA.

[15] Comparing the summer results for both regions, two areas are emphasized as sources of moisture: EBC (20°S–10°S; 38°W–20°W) and NA (0°–10°N; 60°W–30°W). In order to evaluate the relative importance of each source for each region of interest, a quantification of the water vapor transport is provided, by quantifying the $(E\text{-}P)_n$ series calculated backwards from each region and integrated over these two areas (Figure 2). Figure 2a shows the limits of the source regions and Figures 2b and 2c depicts the values of $(E\text{-}P)_n$ divided by the area of the source regions. As the values of $(E\text{-}P)_n$ obtained for the Central Brazil are higher than the ones for La Plata Basin, the scales used to plot the values for Central Brazil (Figure 2b) varies between 0 and 100 and for La Plata Basin (Figure 2c) between 0 and 20.

[16] Figures 2b and 2c suggest that the EBC seems to be the most important austral summer moisture source for both regions when compared with NA. For Central Brazil

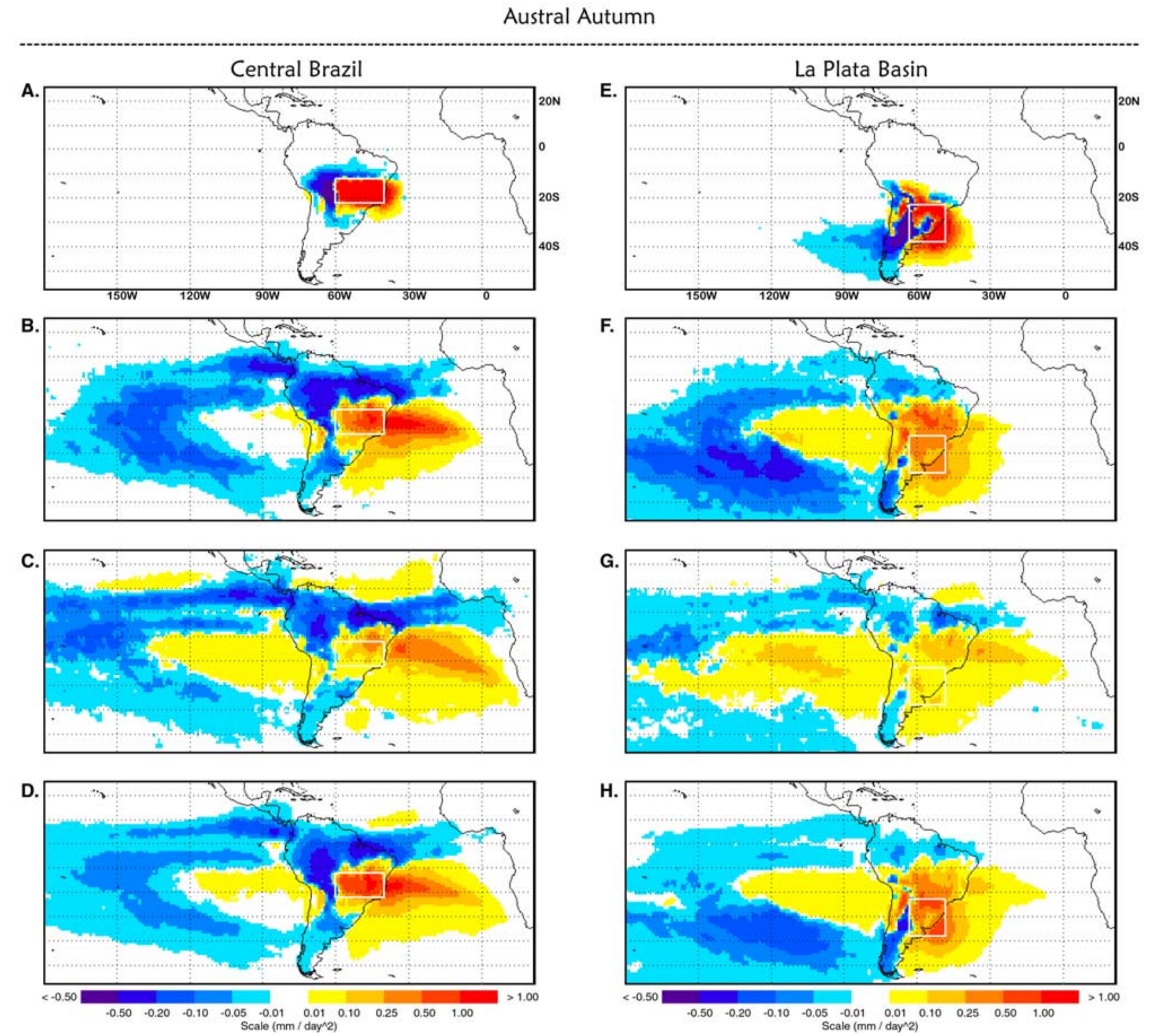

Figure 3. Same as Figure 1, but for the austral autumn.

(Figure 2b), the supply of moisture from the EBC reaches its maximum 4 d back, while the maximum supply from NA occurs 10 d back in time. On the other hand, the supply from both sources for La Plata Basin is less intense (Figure 2c), and the maximum supply from EBC happens 9 d back and from NA, 10 d. In order to study the mean annual cycle of moisture sources for both regions, the same analysis was done for the other seasons.

[17] During the austral autumn (April–May–June) and winter (July–August–September), we can see positive $(E\text{-}P)_n$ values over Central Brazil (Figures 3a to 3d and 4a to 4d), suggesting that the evaporation prevails over precipitation in this region. Similar results are also observed over tropical southern Atlantic, indicating that this source persists during these seasons. Contributions from NA can be verified 10 d back for the two seasons, but the negative values observed close to the equator suggest that most of the moisture from NA is lost through precipitation in the Inter Tropical Convergence Zone (ITCZ). According to *Gu and Adler* [2006] and references therein, the ITCZ is a narrow band of deep convection and rainfall usually observed north of the equator with the northeasterly and southeasterly trade winds converging into it. The ITCZ appears primarily over the open ocean, but extends to the northeast coast of tropical South America during austral autumn and to the West African continent in austral winter, roughly following seasonal movement of warm sea surface temperature. Thus the average over all 10 d of transport (Figures 3d and 4d) shows major contributions from the EBC region during the autumn and winter.

[18] Except by the interruption of the contribution from NA due to the same mechanisms described for the Central Brazil, the results obtained for La Plata Basin during the autumn and winter (Figures 3e to 3h and 4e to 4h) are similar to those observed in the summer, though the contribution from EBC is weaker. In agreement with our

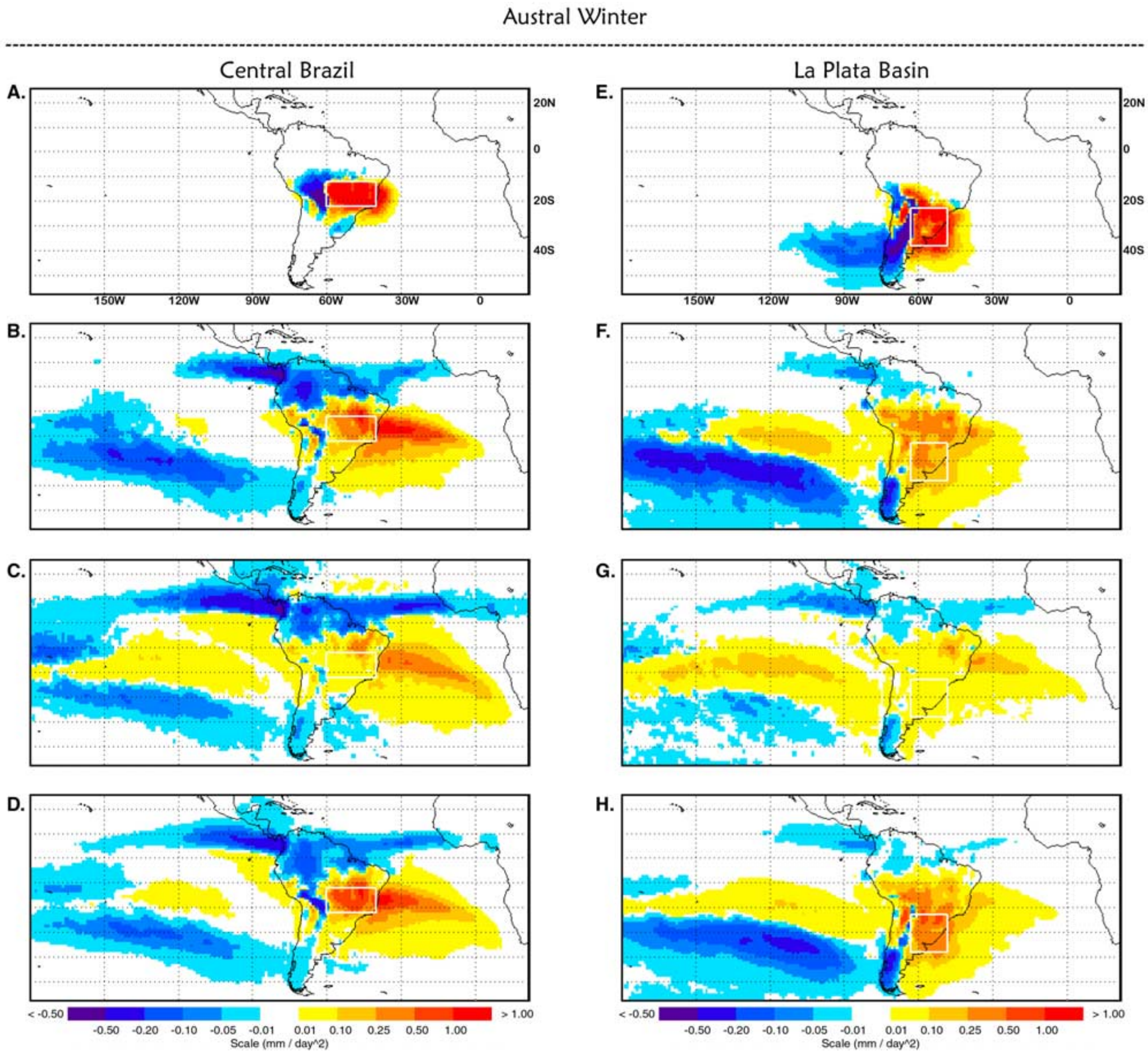

Figure 4. Same as Figure 1, but for the austral winter.

results related to the importance of Central Brazil as a moisture source for La Plata Basin, *Doyle and Barros* [2002] found a maximum precipitation located in southern Brazil and northern Uruguay related to a strong southward flow that starts at 15°S, becomes more intense at about 25°S, and turns southeastward south of 30°S during the austral winter.

[19] In the spring (October–November–December), one can observe again the contribution from NA besides of the one from EBC for the moisture over Central Brazil (Figures 5a to 5d). The prevalence of evaporation over precipitation observed during autumn and winter over the whole region is reduced in the western and eastern boundary of the area (Figure 5a).

[20] The contribution from NA is also observed for La Plata Basin 10 d back during spring (Figure 5g), though it is not showed in the average (Figure 5h). SSA, Central Brazil and EBC are the main moisture sources for La Plata Basin. The results also suggest the importance of recycling.

[21] As EBC is one of the most important moisture sources for Central Brazil and La Plata Basin, Figure 2 also presents the seasonal relative contribution from the EBC area for both regions in order to compare the seasonal variations. For the Central Brazil, the higher contributions occur during the austral summer and spring. As discussed before, the maximum contribution from EBC occurs 4 d back during the summer. In the spring, the maximum values are observed between 4 and 5 d back. The contributions observed during the austral autumn and winter are very similar.

[22] The contributions from EBC for La Plata Basin are smaller than the one for Central Brazil. In all seasons, the higher contributions occur at least 8 d back. Summer and spring are the seasons presenting the highest and the smallest contributions from the EBC, respectively. The contributions during the autumn and winter are quite similar. *Doyle*

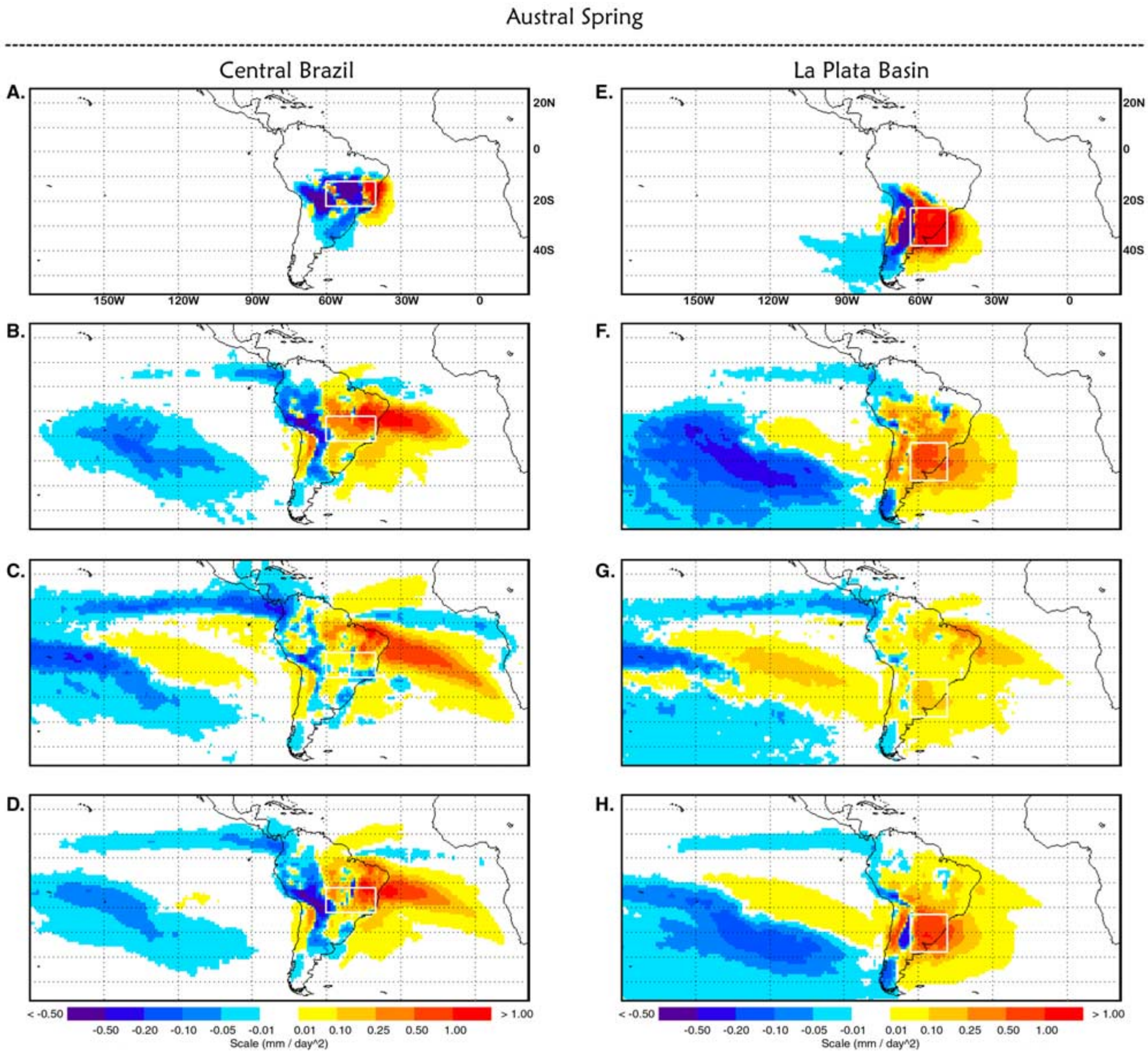

Figure 5. Same as Figure 1, but for the austral spring.

and Barros [2002] also verified that the low-level moisture transport over the continent is quite similar between autumn and winter, as well as between spring and summer.

4. Discussion

[23] An analysis of the major sources of moisture over Central Brazil and La Plata basin was done using a Lagrangian method of diagnosis, focusing on the relative importance of the tropical north Atlantic and eastern Brazilian coast in providing humidity. The seasonal mean conditions over a 5-year period (2000–2004) were studied. According to *Stohl and James* [2005], this period can be considered typical on a global climate scale, because there were no extremes of climate variability, such as those associated to the El Niño-Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO).

[24] During the austral summer, while the Eastern Brazilian Coast (EBC) in the Atlantic Ocean and the tropical North Atlantic Ocean (NA) are the main moisture sources for the Central Brazil region, it seems that recycling is an important moisture supply for La Plata Basin region, associated with the southwestern South Atlantic (SSA), Central Brazil, the EBC and the NA regions. However, the contributions from recycling, Central Brazil and from SSA have not been quantified in this paper, and a more detailed analysis will be provided in a future work. The importance of tropical south Atlantic in providing moisture for South America has already been suggested by *Herdies et al.* [2002], though their results referred to only 1 year. *Doyle and Barros* [2002] have also suggested that the circulation associated to the western part of the subtropical South Atlantic high carries water vapor from the South Atlantic Ocean to the subtropical South America.

[25] In the austral autumn and winter, EBC persists as moisture supply for the Central Brazil region. However, most moisture from NA is lost through precipitation in the ITCZ. Central Brazil, SSA, and EBC also persist as moisture sources for La Plata Basin along these seasons, while the transport from NA is interrupted. The results also suggest the importance of recycling in both regions.

[26] During the austral spring, the contribution from NA reappears besides of that from EBC for the moisture over Central Brazil, while the possible contribution of recycling is reduced in the western and eastern boundary of the area selected. The figures also suggest that Central Brazil and the SSA are still the main moisture sources for La Plata Basin, as well as the possible role of recycling.

[27] In order to summarize the main results discussed in the previous paragraphs, a conceptual diagram of the main moisture sources observed for Central Brazil and La Plata Basin regions along the year is shown in Figure 6. It is important to note that only the width of the EBC (red) and NA (blue) arrows is associated with the magnitude of their relative contributions. Recycling (indicated by dots inside the square), SSA and Central Brazil contributions (green and grey arrows) are only qualitatively representations.

[28] As the analyses indicated that the EBC and NA are common moisture sources for Central Brazil and La Plata Basin regions, the next step was to quantify the contribution from each source in both regions in order the compare their relative importance. The NA contribution was only evaluated during the austral summer because this is the season when its influence is more evident. On the other hand, the seasonal variations of the EBC contribution were evaluated in both regions. A quantification of the water vapor transport shows that the contribution from EBC is higher than NA during the austral summer. From the analysis of the contribution from the EBC during the other seasons, it was observed that the higher contributions occur for the austral summer and spring in the Central Brazil region, reaching their maximum 4 d back.

[29] The contributions from EBC for La Plata Basin are smaller than the one for Central Brazil. During all seasons, the higher contributions occur at least 8 d back. Summer and spring are the seasons presenting the highest and the smallest contributions from the EBC, respectively. The contributions during the autumn and winter are quite similar.

[30] This study contributes for a better understanding of the main moisture sources for two regions in the South America associated with an important precipitation variability mode through the application of a new methodology. The same analyses can be applied over other South American regions, such as the Amazon or Brazilian Northeast, in order to study their mean moisture sources, or even in case studies.

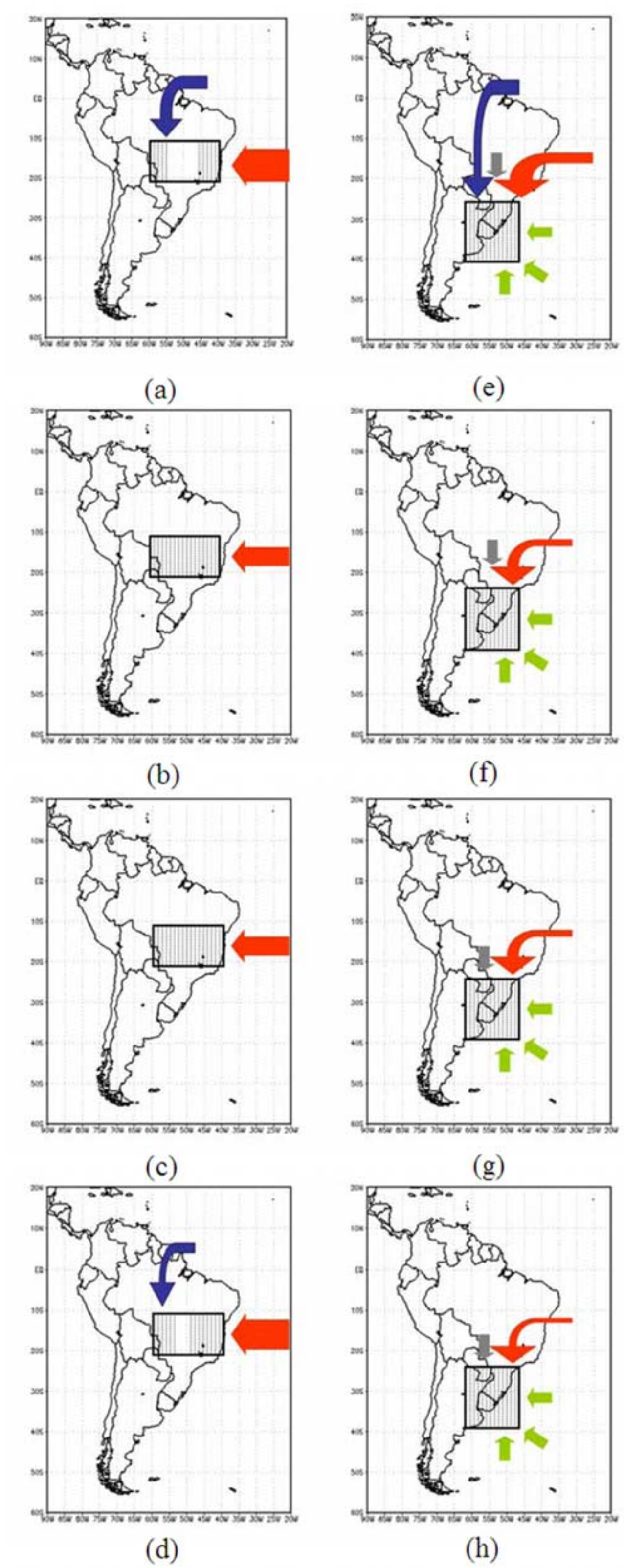

Figure 6. A conceptual diagram of the main moisture sources observed for Central Brazil region during the austral (a) summer, (b) autumn, (c) winter, and (d) spring; the same analyses is showed for La Plata Basin region in Figures 6e–6h. The red and blue arrows indicate the EBC and NA sources, respectively, and their width is associated with their relative contribution. The green and grey arrows indicate the SSA and Central Brazil qualitative contributions, respectively. Recycling contribution is indicated by dots inside the square.

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