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Precipitation Recycling in the Amazon Basin: A Study Using the ECMWF Era-Interim Reanalysis Dataset

Reciclagem de Precipitação na Amazônia: Um Estudo Utilizando as Reanálises do Era-Interim (ECMWF)

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Resumo: O objetivo deste trabalho é avaliar os componentes do balanço de umidade e abordar os mecanismos físicos envolvidos na reciclagem de precipitação na bacia amazônica, utilizando as reanálises do European Centre for Medium-Range Weather Forecasts – ECMWF (Era-Interim) para o período de 1980-2005. A reciclagem de precipitação refere-se ao mecanismo de retroalimentação entre a superfície e a atmosfera no qual a quantidade de água evapotranspirada da superfície de uma determinada região retorna na forma de precipitação sobre a mesma região. Em média, 20% da precipitação total sobre a bacia amazônica é decorrente do processo de evapotranspiração local; indicando que, a contribuição local para a precipitação total representa um percentual significativo no balanço de água regional e desempenha um importante papel no ciclo hidrológico amazônico. Contudo, a variabilidade e as mudanças no sistema climático devido às forçantes antropogênicas, tais como o aumento na concentração dos gases de efeito estufa na atmosfera e as mudanças de uso e cobertura da terra (por exemplo, desflorestamento) podem afetar a reciclagem de precipitação. Embora os resultados apresentados tenham produzido novos conhecimentos acerca da interação entre os processos de superfície e o ciclo hidrológico, os efeitos da mudança climática antropogênica sobre a reciclagem de precipitação na bacia amazônica necessitam ainda ser investigados.

Palavras-Chave: Interação Biosfera-Atmosfera; Balanço De Umidade; Evapotranspiração; Transporte De Umidade.

***Abstract**: The objective of this study is to evaluate the water budget components and to address the physical mechanisms involved in precipitation recycling in the Amazon basin using the European Centre reanalysis for Medium-Range Weather Forecasts – ECMWF for period 1980-2005. Precipitation recycling refers to the feedback mechanism between the Earth's surface and the atmosphere wherein the amount of water that is evapotranspired from a given region of the surface returns to the same area in the form of precipitation. Here we show, on average, 20% of the total rainfall in the basin is derived from local evapotranspiration processes indicating that the local contribution to the total precipitation represents a significant contribution to the regional water budget and plays an important role in the Amazon water cycle. However, the changes in the climate system due to anthropogenic forcings such as the increase in the concentration of greenhouse gases in the atmosphere and changes in land use and land cover (i.e. deforestation) can affect the precipitation recycling. Although the results presented here have produced new knowledge about the interactions between surface processes and the hydrologic cycle, the effects of anthropogenic climate change on the precipitation recycling in the Amazon basin requires further investigation.*

***KeyWords**: Biosphere-Atmosphere Interaction; Water Budget; Evapotranspiration; Moisture Transport*

1. Introduction

The Amazon is the only large continuous extension of rainforest in the world. With an area of approximately 6.5 million km^2, it comprises 56% of the Earth's tropical forests and plays an important role in the exchanges of energy, moisture, and mass between the land surface and the atmosphere. Additionally, the Amazon forest provides key environmental services for the maintenance of regional and global climate, such as storage and absorption of excess atmospheric carbon and the transport of trace gases, aerosols, water vapor to remote regions, and of principle importance, the recycling of precipitation to maintain its ecosystems. The Amazon forest also acts as an indispensable source of heat for the global atmosphere through its intense evapotranspiration and latent heat release in the middle and upper tropical troposphere, contributing to the generation and maintenance of the atmospheric circulation on regional and global scales (MARENGO, 2006; MALHI *et al.*, 2008; NOBRE *et al.*, 2009a,b; SATYAMURTY *et al.*, 2013).

Regarding the water budget, the Amazon basin behaves like a sink for atmosphere moisture, receiving water vapor from oceanic origin transport as well as from evapotranspiration produced by the tropical forest. With respect to regional circulation, the Amazon is an important source of moisture contributing to the precipitation regime in the central, southern and southeastern regions of Brazil, as well as to northern Argentina, including the La Plata basin (MARENGO *et al.*, 2004; MARENGO, 2004, 2005; VERA *et al.*, 2006). Arraut and Satyamurty (2009) showed that the convective activity over southern Brazil and northern Argentina is strongly influenced by moisture transported by the low level jet (LLJ) east of the Andes across the southern boundary of the Amazon basin.

The concept of precipitation recycling refers to the feedback mechanism between the surface and the atmosphere, where local evaporation contributes significantly to total precipitation in the same region. In other words, the precipitation recycling can be defined as the amount of water evapotranspired from a specific region of the earth's surface that returns to that same area in the form of precipitation (ROCHA *et al.*, 2015, 2017). Using observational data (MOLION, 1975; MARQUES *et al.*, 1977; BRUBAKER *et al.*, 1993) and reanalysis from different meteorological centers (ELTAHIR and BRAS, 1994; TRENBERTH, 1999; COSTA and FOLEY, 1999; NÓBREGA *et al.*, 2005; VAN DER ENT *et al.*, 2010; SATYAMURTY *et al.*, 2013; ROCHA *et al.*, 2017) several studies were conducted in order to quantify and describe the distribution of precipitation recycling in different regions of the world. Although quantitatively different, these studies demonstrate that the recycling mechanism is a strong indicator of the importance of surface processes and climate in the hydrological cycle, and the climate sensitivity related to changes in these processes. However, given the importance of the Amazon to the water budget at regional and global scales, it is of fundamental importance to understanding the distribution of precipitation recycling in the Amazon basin. Thus, this article presents an observational study of the water budget components and precipitation recycling in the Amazon, addressing the physical mechanisms associated with the recycling process.

2. Materials and Methods

In this study, we use the method based on the atmospheric moisture balance as described by Brubaker *et al.* (1993) and Trenberth (1999) to quantify precipitation recycling. The ERA-Interim reanalysis dataset from the European Center for Medium-Range Weather Forecasts – ECMWF (DEE *et al.*, 2011) for the period 1980-2005 was used to estimate the spatiotemporal variability of the water budget components and precipitation recycling in the Amazon basin. The reanalysis data of precipitation, evapotranspiration, pressure at mean sea level, the specific humidity of the air, and zonal and meridional wind speed at the levels of 1000, 925, 850, 700, 600, 500, 400 and 300 hPa at a 1.0° × 1.0° resolution covering South America were used (http://apps.ecmwf.int/datasets/).

2.1. Precipitation recycling method

The method described by Brubaker *et al.* (1993) and Trenberth (1999) states that for a scale of length L, evapotranspiration E, and the total precipitation P for a given area, the vertically integrated water vapor flux F over the height Z entering (F_{in}) and exiting (F_{out}) the area (**Figure 1**) can be determined using equation 1.

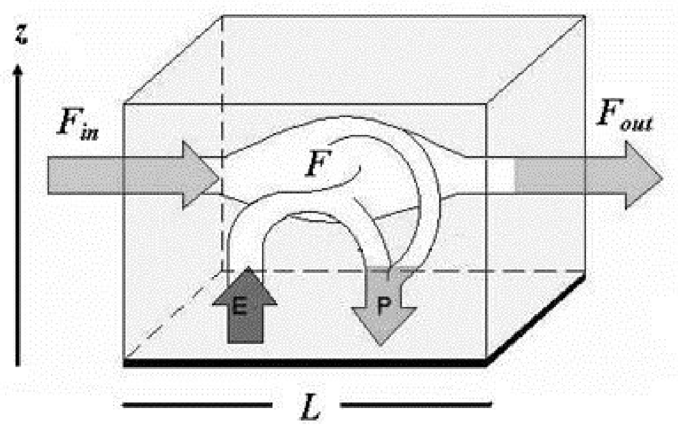

Figure 1: Conceptual diagram of the processes considered in precipitation recycling: total precipitation P (mmday^{-1}), evapotranspiration E (mmday^{-1}), average water vapor flux (kg m^{-1} s^{-1}) F where F_{in} and F_{out} are the vertically integrated water vapor fluxes (kgm^{-1}s^{-1}) that enter and leave the area respectively of scale of length L (km). Source: Adapted from Brubaker *et al.* (1993).

$$F_{out} = F_{in} + (E+P)L \quad (1)$$

Where the average horizontal water vapor flux of the area is defined as:

$$F = 0.5\,(F_{in} + F_{out}) = F_{in} + 0.5(E - P)L \quad (2)$$

In the method proposed by Brubaker *et al.* (1993) and Trenberth (1999), the total precipitation (P) in the region is partitioned into local source precipitation (P_l) and advective precipitation (P_a), namely:

$$P = P_l + P_l \quad (3)$$

Thus, the average horizontal flux from the advected moisture for the region is given by:

$$F_{in} - 0.5P_aL \quad (4)$$

And the average horizontal flux from the local evaporation is given by:

$$0.5(E - P_l)L \quad (5)$$

Assuming that the air is well mixed so that the ratio of precipitation due to advection versus that from evapotranspiration is proportional to the ratio between the flux of moisture advected and transpired, gives the following expression:

$$\frac{P_a}{P_l} = \frac{F_{in} - 0.5P_aL}{0.5(E - P)L} \quad (6)$$

Therefore, precipitation recycling (β) may be determined by:

$$\beta = \frac{P_l}{P} = \frac{EL}{EL + 2F_{in}} \quad (7)$$

Using equation 2, the precipitation recycling (β) can be rewritten as follows:

$$\beta = \frac{EL}{PL + 2F} \quad (8)$$

Therefore, the basic assumption of this method is that the atmosphere is well mixed and the change in the atmospheric storage of water vapor is negligible compared to the other terms. Brubaker *et al.* (1993) and Trenberth (1999) recommends using a length scale (L) of 2,750 km for the Amazon basin for the recycling estimation.

3. Results and Discussion

Most studies have shown that the precipitation recycling mechanism is strongly influenced by the total precipitation, surface evapotranspiration, and the water vapor transport over the region. This study evaluates the variability of the spatiotemporal components of the water budget and precipitation recycling in the Amazon basin for the domain area covering most of South America.

3.1. Precipitation and evapotranspiration

Figure 2 and **Figure 3** show, respectively, the average seasonal distribution of rainfall and evapotranspiration on the South American continent (austral summer – December-January-February, DJF; austral autumn – March-April-May, MAM; austral winter – Jun-July-August, JJA; austral spring – September-October-November, SON). In Amazon, rainfall shows significant spatiotemporal variability determined by the influence of different local scale, mesoscale, synoptic scale and large-scale systems acting in the region (MARENGO and NOBRE, 2009; NOBRE *et al.*, 2009b).

The average annual rainfall is about 2,300 mm, featuring three core locations with abundant rainfall. The first located in the northwestern Amazon, with rainfall above 3,500 mm yr^{-1} associated with the condensation of humid air by orographic effect on the Andes Cordillera (MARENGO and NOBRE, 2009). The second precipitation maximum, located on the mouth of the Amazon River, is associated with the Intertropical Convergence Zone (ITCZ) and local circulations (sea breeze) related to instability lines that appear along the coast, especially at the end of the evening period (COHEN *et al.*, 1995). The third center is located in the southern part of the Amazon region, especially during the months of January/February/March (austral summer), being influenced by the constant presence of convective clusters associated with frontal systems in the area of influence of the South Atlantic Convergence Zone (SACZ).

Most of tropical and subtropical South America receives more than 50% of its total annual rainfall in austral summer, in the form of convective precipitation with strong seasonal and diurnal variation (NOBRE *et al.*, 2009b; SATYAMURTY *et al.*, 2013). At the seasonal scale, **Figure 2d** shows the beginning of the rainy season, or strong convective activity in the southern Amazon during the spring (SON). Observe that rainfall maxima located in the western and central part of the Amazon occur in DJF, associated with the position of the Bolivian High. In the fall (MAM), the band of maximum rainfall is located in the central Amazon, extending from the west of the basin to the mouth of the Amazon River. In JJA, the center of maximum precipitation moves to the north and is located about Central America, establishing the dry season (no major convective activity) in the central and southern Amazon, which are under the descending branch of the Hadley cell. However, in this period, the maximum precipitation occurs in the northern Amazon. The driest quarters in northern Brazil gradually change from September/October/November in the far north, to August/September/October, on a long latitudinal line from the west in the northeastern region of Brazil; to July/August/September in the valley of the Amazon basin, especially in the west, and to June/July/August in the southern part.

Different studies point to the important role of vegetated surfaces, notably the Amazon rainforest, as a regional climate regulator factor to supply large quantity of water vapor into the atmosphere throughout the year through evapotranspiration (GASH *et al.*, 1996). The evapotranspiration coming from the Amazon forest is one of the main sources of water vapor in both the basin itself and for remote regions, playing a key role in the generation of the rainfall process. Moreover, the contribution of local evapotranspiration to precipitation over the Amazon basin represents a significant portion of the regional water budget and plays a prominent role in the Amazon hydrological cycle, influencing the spatial patterns of soil moisture, productivity and the occurrence of events extremes, such as flooding and drought (ROCHA *et al.*, 2009). Furthermore, this variable is directly associated with the recycling mechanism of precipitation over the continent.

According to **Figure 3d** it is observed that evapotranspiration is close to that found in micrometeorological experiments in the Amazon, such as: Large Scale Biosphere-Atmosphere Experiment in Amazonia – LBA (AVISSAR and NOBRE, 2002), with values ranging between 3.5 and 4.0 mm day^{-1}. The high evapotranspiration rates in the Amazon basin in SON and DJF are associated with greater availability of energy during the spring and summer seasons, respectively. During fall and austral winter, due to the seasonal variation of the ITCZ and the displacement of cloudiness band to the north, decreases the convective activity on the central and southern Amazon, increasing the incident solar radiation on the surface and consequently, evapotranspiration.

3.2 Moisture transport and convergence

Figure 4 and **Figure 5** show, respectively, average seasonal vertically integrated water vapor flux and moisture convergence for South America during the four seasons. In DJF, air movement has a persistent low thermal region situated over the Chaco, between 20° and 30°S, associated with maximum cloud cover over the central Amazon and the Bolivian High plane, the period of the most active and intense SACZ. An important feature of the equatorial circulation during the summer and fall are the trade winds that transport moisture into the Amazon basin, associated with increased atmospheric pressure in the tropical North Atlantic Ocean. As stressed by Arraut and Satyamurty (2009), Arraut *et al.* (2012), Satyamurty *et al.* (2013) and Drumond *et al.* (2014) the water vapor flux from the equatorial Atlantic is the principal source of moisture for Amazônia. When the trade winds reach the Andes, the water vapor flux is diverted south and moisture, in turn, is transported from the Amazon to the South-Central Brazil, La Plata basin and northern Argentina through the low level jet (LLJ) channeled to the east of the mountain range (**Figure 4a**). During this period, the convective activity and precipitation in the central and southern Amazon (**Figure 2a**) are associated with intense moisture converging on these areas (**Figure 5a**). The South American LLJ seems to occur throughout the year, carrying Amazon tropical rain air masses to the Mid-South of Brazil and northern Argentina, especially in the summer, and leading maritime tropical air masses of the South Atlantic Subtropical High (SASH) more often in the winter.

Drumond *et al.* (2008) adopted a Lagrangian method that identifies moisture contributions in the water budget of a region to investigate the main sources of moisture to Central Brazil and the La Plata basin during the period 2000-2004. The results showed the importance of the southern tropical Atlantic as a moisture source for Central Brazil. The atmospheric circulation characteristics observed over tropical and subtropical South America during the austral summer configure what Arraut and Satyamurty (2009) and Nobre *et al.* (2009b) called the Summer Monsoon Regime in South America (SMRSA). The SMRSA weakens between March and May, when the convective activity (**Figure 5b**) progresses towards the north. In this period, precipitation intensifies, especially in the northern Amazon and in the Northeast of Brazil (**Figure 2b**).

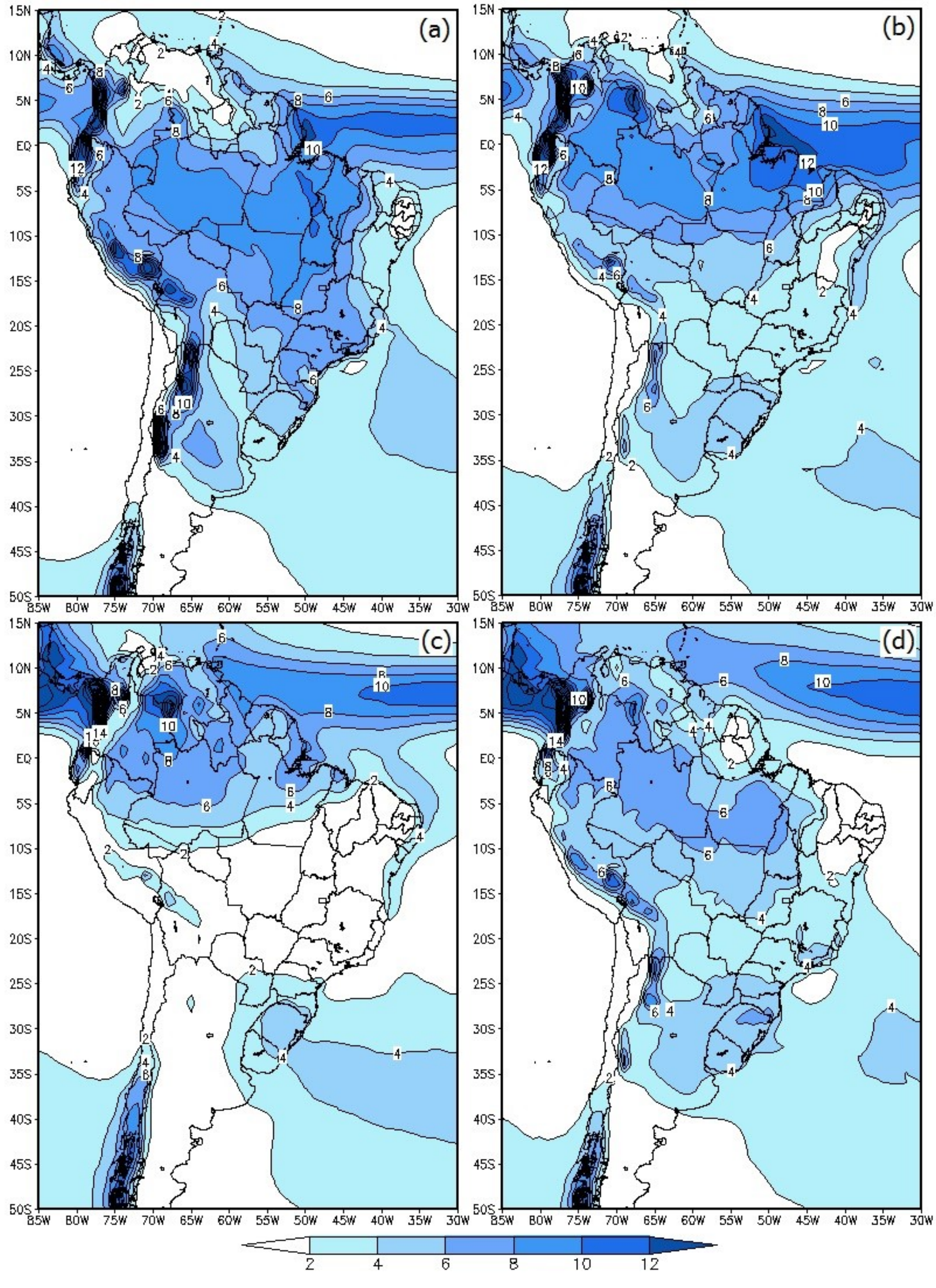

Figure 2: Average seasonal precipitation (mm day^{-1}) over South America using the reanalysis ERA-Interim (ECMWF) for the period 1980-2005: (a) summer–DJF; (b) autumn–MAM; (c) winter–JJA; (d) spring–SON.

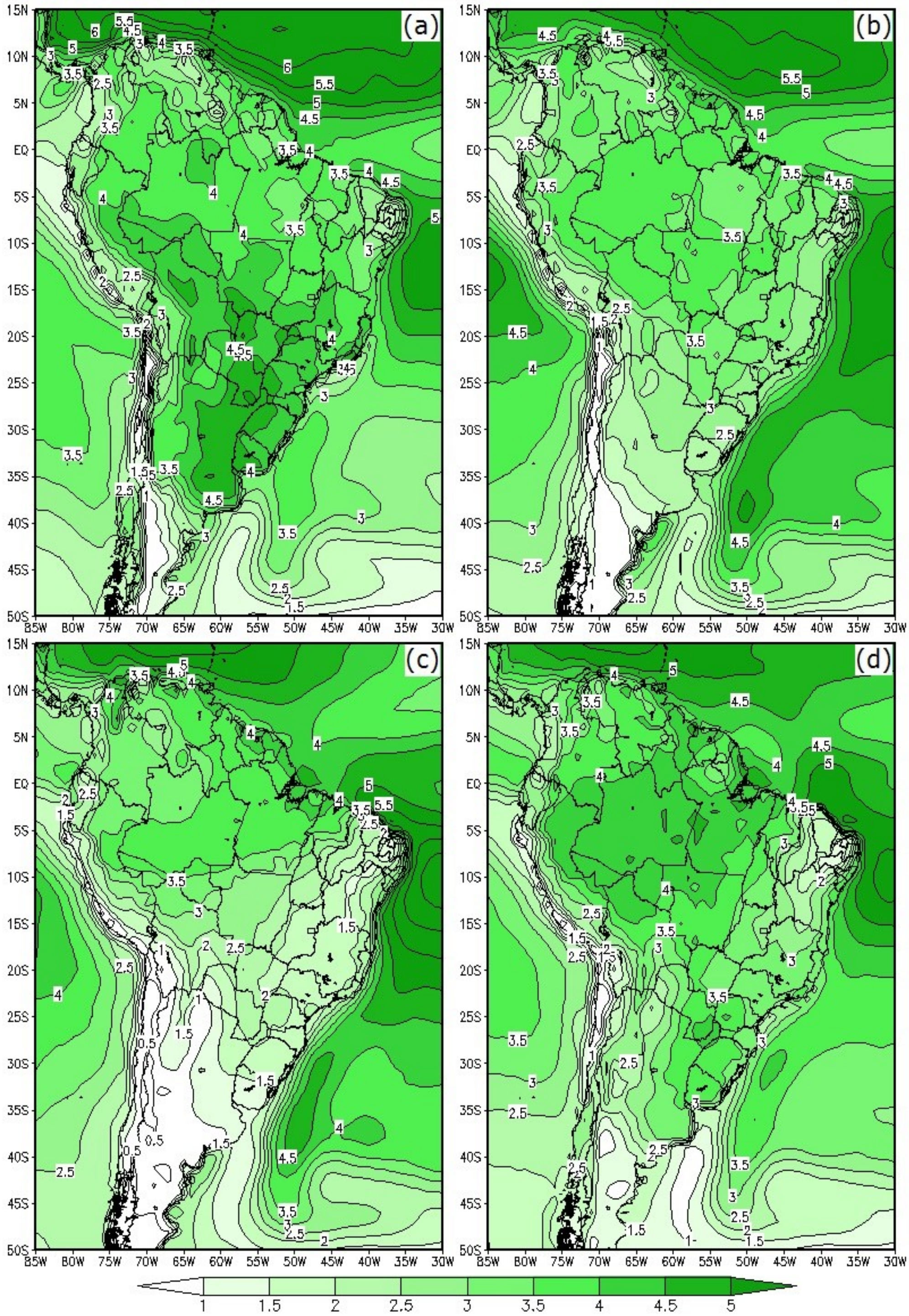

Figure 3: Average seasonal evapotranspiration (mm day^{-1}) over South America using the reanalysis ERA-Interim (ECMWF) for the period 1980-2005: (a) summer–DJF; (b) autumn–MAM; (c) winter–JJA; (d) spring–SON.

In JJA, the seasonal circulation climatology at low levels (**Figure 4c**) shows that there is a convergence of the trade winds from the southeast and northeast transporting moisture to Central America, as well as to the east of Northeast Brazil and northwestern South America, which increases the precipitation in these areas. On the other hand, the moisture divergence is predominant over the southern Amazon and the central portion of the continent (**Figure 5c**), determining the reduction of convective activity and therefore precipitation, setting up the dry season in South America.

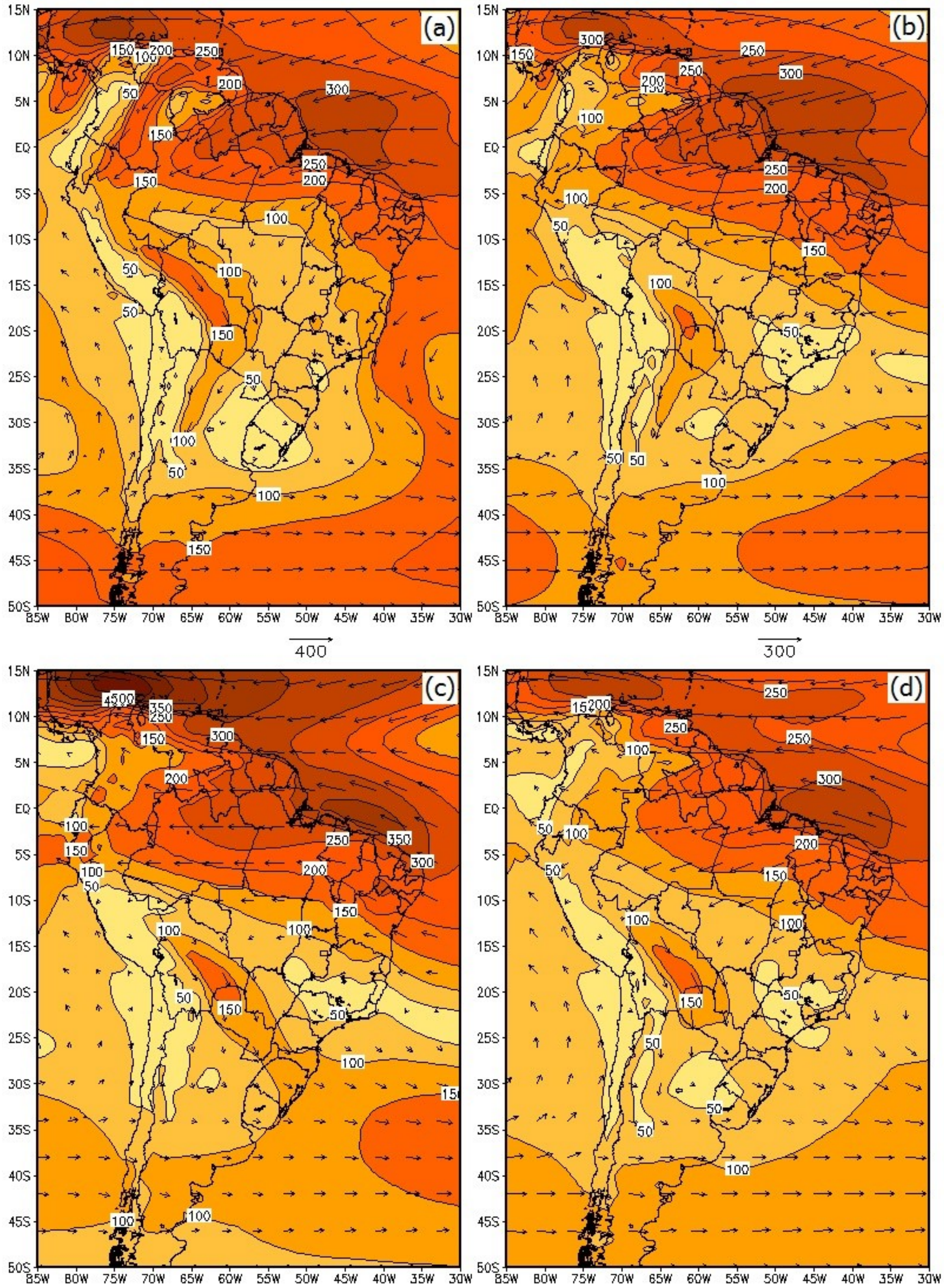

Figure 4: Average seasonal vertically integrated water vapor flux (kg m^{-1} s^{-1}) over South America using the reanalysis ERA-Interim (ECMWF) for the period 1980-2005: (a) summer–DJF; (b) autumn–MAM; (c) winter–JJA; (d) spring–SON.

3.3 Precipitation recycling

The moisture which gives rise to precipitation over continental regions comes from two sources: (i) advection of water vapor originating from other regions by means of air mass movements and (ii) the local water vapor through evapotranspiration from the surface of the region. Evapotranspiration has a pronounced effect when the water vapor flux is less significant. The regional moisture transport depends on the atmospheric dynamics and moisture sources. Evapotranspiration, in turn, depends on the availability of moisture in the area or sub-surface (unsaturated region), which is evaporated directly or through transpiration from vegetation. Consequently, any change in land use, land cover, or climate that can modify these processes can affect the amount of precipitation in the region, as well as precipitation recycling.

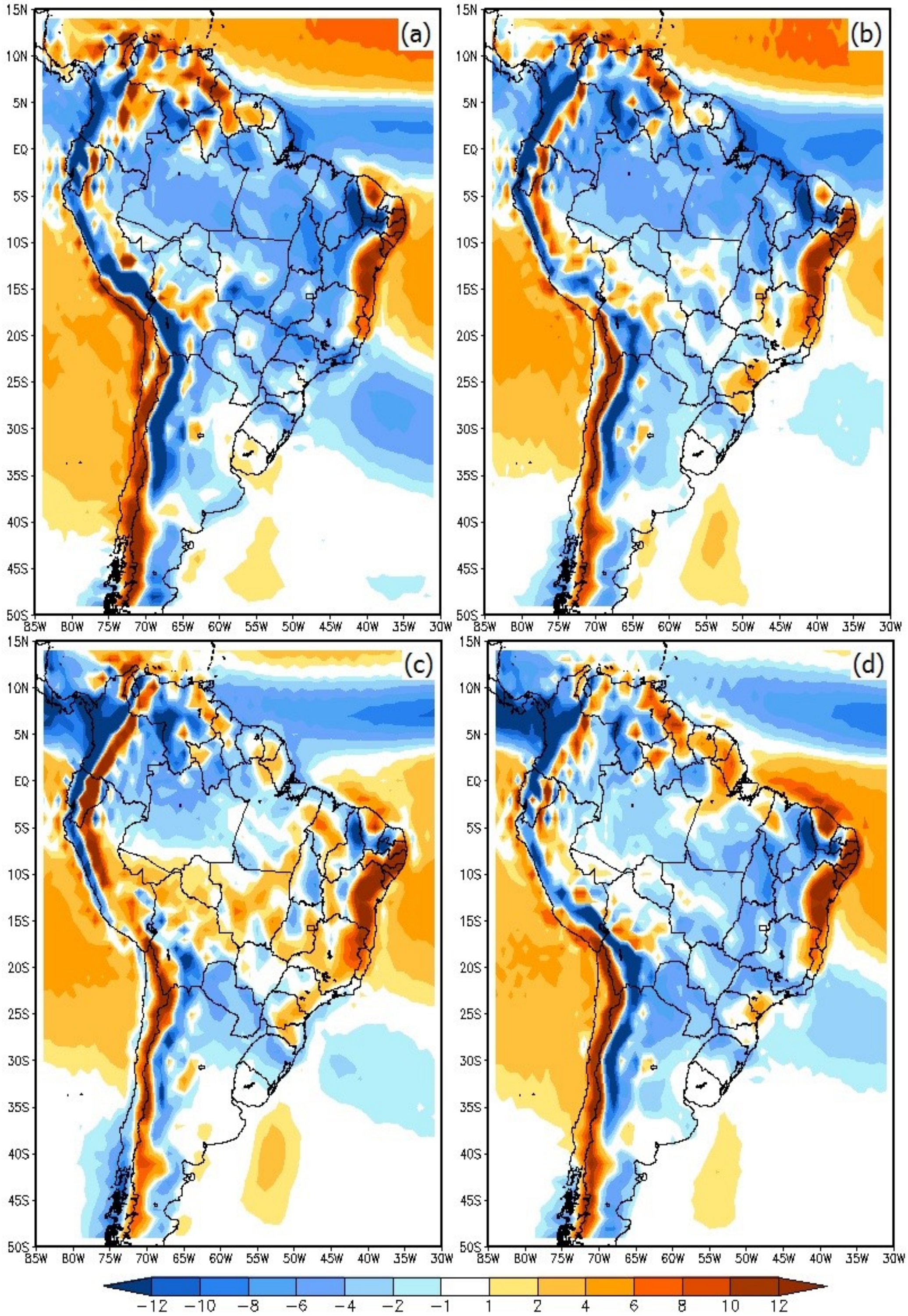

Figure 5: Average seasonal moisture convergence (mm day^{-1}) over South America using the reanalysis ERA-Interim (ECMWF) for the period 1980-2005: (a) summer–DJF; (b) autumn–MAM; (c) winter–JJA; (d) spring–SON.

Figure 6a-d shows the seasonal average precipitation recycling over South America. In general, precipitation recycling is more intense in the central-south of the continent, being directly influenced by evapotranspiration in the region. In DJF, precipitation recycling is higher (lower) in the southern sector (north) of the Amazon basin associated with lower (higher) intensity of the water vapor flux and high (low) values of evapotranspiration. However, the regional maximum precipitation recycling is recorded in the La Plata basin, specifically in southern Brazil, Uruguay, eastern Paraguay and northeastern Argentina, an area where evapotranspiration has significant values and where the deintensification of the LLJ occurs, east of the Andes.

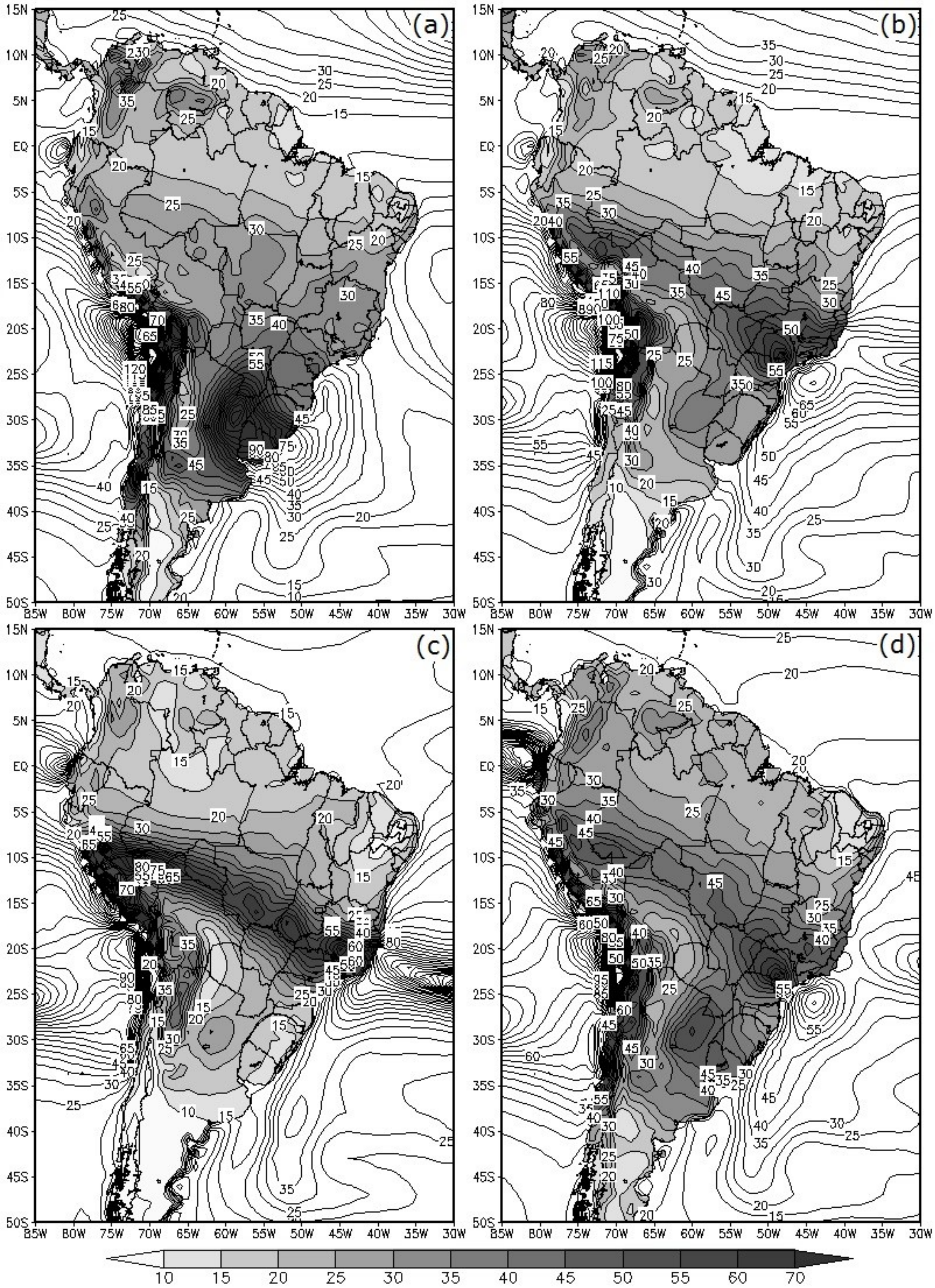

Figure 6: Average seasonal precipitation recycling (%) over South America using the reanalysis ERA-Interim (ECMWF) for the period 1980-2005: (a) summer–DJF; (b) autumn–MAM; (c) winter–JJA; (d) spring–SON.

Precipitation recycling in the Amazon tends to increase from east to west due to reducing the intensity of the water vapor flux to the west. This pattern is clearly identified during the fall, where the largest recycling values were observed in southwestern Amazon basin, showing that the effect of increased evapotranspiration overlaps with the reduction of water vapor transport in the region. The maximum precipitation recycling observed on the continent occurred in the Pantanal and Southeast of Brazil and, according to Trenberth (1999), Nóbrega *et al.* (2005) and Rocha *et al.* (2017) were associated with evapotranspiration driven by high soil moisture content, and reduced moisture transport near SASH.

In JJA, although over the northern Amazon the evapotranspiration, moisture convergence and precipitation have presented higher values, the increase in the intensity of moisture flux dominated and the precipitation recycling showed lower values (~ 16%) in relation to the southern Amazon (~ 28%). The maximum precipitation recycling observed over South America extended from the western Amazon basin to southeastern Brazil, including the

Pantanal, areas that are also associated with a deintensification of water vapor flux. Spring is the season where precipitation recycling showed the highest values in the Amazon Basin (~ 27%). The forest evapotranspiration, which is higher in this period, overlapped the effect of water vapor flux and presented itself as the leading factor for regional precipitation recycling.

The average precipitation recycling values across South America ranged between 10% and 80% with extreme rates on the order of 70% to 80% over the Andes. Seasonally, the values decrease from summer to winter. The annual average for precipitation recycling in the Amazon basin was 22%, with values ranging from 50% in the southern portion to 10% in the northern portion. Based on the results of previous work and this study, it is estimated that precipitation recycling is on the order of 20-35% in the Amazon basin. Thus, of the total precipitation over the Amazon basin, approximately 20% is derived from local evapotranspiration processes, showing that the local contribution to the total precipitation is significant in the regional water budget. The advective contribution is more important for precipitation over the Amazon basin than the local evapotranspiration contribution. In other words, the moisture advection largely dominates the water vapor supply in the region, however, the role of local evapotranspiration is most important for precipitation recycling in southern basin. However, the variability and natural and/or anthropogenic climate system changes can affect the components of the water budget, and consequently, precipitation recycling in a significant way, influencing spatial soil moisture patterns, productivity, and the occurrence of extreme events such as droughts and floods. Although studies on precipitation recycling have produced new knowledge about the interactions between surface processes and the hydrologic cycle, the effects of climate change on the precipitation recycling in the Amazon basin need to be further investigated.

4. Conclusions

This work is an observational study of precipitation recycling in the Amazon basin, addressing the physical mechanisms involved in this process. Observational analysis was based on the European Centre for Medium-Range reanalysis Weather Forecasts – ECMWF (ERA-Interim), from 1980 to 2005. To estimate the precipitation recycling we used the method based on the water budget in the atmosphere described by Brubaker *et al.* (1993) and Trenberth (1999). It was found that, generally, the Amazon basin behaves like an atmospheric moisture sink, getting water vapor transported from the ocean and as forest evapotranspiration through precipitation recycling processes. On a regional scale, the Amazon is an important source of moisture contributing to the precipitation regime in other regions of South America.

Quantification of the precipitation recycling mechanism is a strong indicator of the importance of surface processes and climate in the hydrological cycle, as well as the climate sensitivity related to changes in these processes. Generally, precipitation recycling in the Amazon basin was on the order of 22%, with values ranging from 10% in the northern portion to 50% in the southern portion. The results show that of the total rainfall in the Amazon basin, approximately 20% is derived from local evapotranspiration processes; indicating that the local contribution to the total precipitation represents a significant contribution to the regional water budget and plays an important role in the Amazon water cycle. The climatological recycling of rainfall over South America shows that the advective contribution is more important for precipitation over the Amazon, while in the south-central region of the continent the local contribution plays an important role in precipitation. However, the variability and changes in the climate system due to both natural variations (non-linear) inherent in the system and anthropogenic increases in the concentration of greenhouse gases in the atmosphere and changes in land use and land cover (i.e. deforestation, agricultural activities, desertification and urbanization), may adversely affect the dynamics of Amazonian ecosystems, reducing their ability to absorb carbon from the atmosphere, increasing the surface temperature by modifying the regional hydrologic cycle, influencing the spatial soil moisture patterns, the occurrence of extreme events (drought and flooding), and consequently affecting precipitation recycling. Although the results presented here produced new knowledge about the interaction between surface processes and the hydrologic cycle, the effects of variability and natural and anthropogenic climate change on precipitation recycling in the Amazon requires further investigation.

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