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Drought and wet episodes in Amazonia: the role of atmospheric moisture transport

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Abstract: The Amazon River basin (ARB) in South America contains the largest rainforest and biodiversity in the world, and plays an important role in the regional and global hydrological cycle. It consists of several sub-basins as the Negro River basin (NRB) in the north and the Madeira River basin (MRB) to the south, both considered of utmost importance in the Amazonia for the Amazon River. The precipitation annual cycle in both basins experiences an opposite annual cycle. Here we utilized the Standardized Precipitation Index (SPEI) to identify drought and wet conditions in the NRB and MRB along the period 1980-2016. Besides, the Lagrangian dispersion model FLEXPART v9.0 was used to track backward in time the air masses residing over the basins and to calculate along the trajectories the budget of $(E - P)$. This permitted to identify those regions from where air masses gain humidity $(E - P > 0)$ before arriving at the basins, what we consider as moisture sources. FLEXPART has been successfully utilized for the same goal in several studies. This study examines the variability of moisture uptake by the basins from these sources during drought and wet episodes in the basins. We consider this a new approach to be a useful method for understanding the causes and variability of drought and wet events in other regions worldwide.

Keywords: Drought and wet episodes, Amazon River basin, Negro River basin, Madeira River basin, moisture sources, Lagrangian analysis

1. Introduction

The Amazon River basin (ARB) (Figure 1) is the world's largest tropical rainforest and drainage basin on the planet, and the Amazon River, the world largest river, as average discharge around 210 000 m^3/s. Consequently, the ARB is the home of a high biodiversity and an important source of natural resources for human economic development, playing an important role in the regional and global hydrological cycle. Recent studies have investigated the hydrological cycle at the ARB, confirming the occurrence of several extreme hydrological events like droughts, floods, and a marked terrestrial water storage variability during the last years [1-5]. Future scenarios of a complete deforestation in the region point to a restrained water cycle [6, 7]. Moore et al. [6] suggest that total deforestation of the Amazon would result in a 10-20% decrease in annual rainfall across the entire Amazon basin. The acceleration of human-driven climate change poses serious questions and challenges for conservation strategies at the ARB [8]. However, a human activity like deforestation within the Amazon is one of the major challenges to face.

In the ARB the annual cycle of the water balance terms shows some differences between the northern and southern sections of the basin [9-11], but the hydrological cycle intensification in the ARB is concentrated overwhelmingly in the wet season, driving progressively greater differences in Amazon peak and minimum flows [12]. It has been also documented the great importance of the atmospheric moisture income to the basin and local evaporation and precipitation recycling on the regional hydrological cycle. Particularly, moisture transport in and out of the Amazon basin has been studied since the 1990's using a variety of upper air and global reanalyses datasets, as well as from climate model simulations [13]. Drumond et al. [14] investigated the annual cycle of the main sources of moisture for the Amazon Basin, as well as its own contribution as a moisture source for the rest of the continent. The diagnosis of moisture sources has become a major research tool in the analysis of extreme events (e.g., floods, droughts), and can be thought of as a basic tool for regional and global climatic assessments [15].

The ARB is formed by several sub-basins, some of the most important are the Negro and Madeira River basins, located to the north and southwestern respectively. In this study, we aim to identify dry and wet conditions at the NRB and MRB as well as the climatological sources of moisture for each basin. Finally, we pretend to investigate the moisture uptake anomalies during most intense wet and drought episodes at the basins. In a further research, we aim to investigate at monthly scale the role of the sources during a major number of episodes.

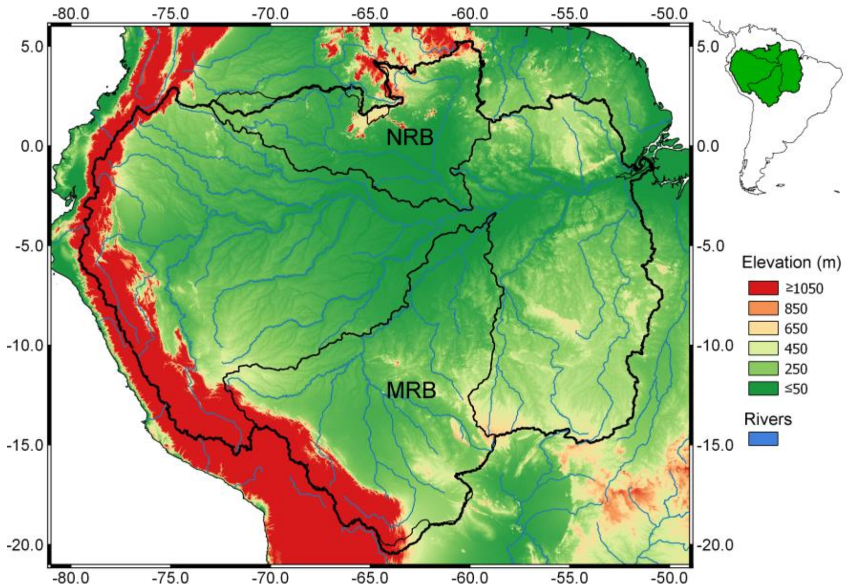

Figure 1. Black contour lines delimit the geographical location of the Amazon River basin (ARB) and two sub-basins: Negro River basin (NRB) and Madeira River basin (MRB), in the north and southwestern of the ARB respectively. Green and redish colours indicate the ground elevation (m), while the blue lines the rivers.

2. Materials and Methods

A large number of drought indices have been attempted to diagnose, monitoring and predict drought conditions in the Amazon River basin. In this study, we use the Standardised Precipitation-Evapotranspiration Index (SPEI) [16] to identify dry and wet conditions in the NRB. The period of study is 1980 - 2016. This index is based on the same methodology of the Standardized Precipitation Index [17], but computes the probability distribution of the difference between precipitation (P) and potential evapotranspiration (Pet), which is considered an advantage. Positive values of SPEI indicate above average moisture conditions (wet), while negative values reveal below normal (drought) conditions. So, a drought episode appears when the SPEI falls below zero, reaching a value of -1 or less and ending when returns to positive values [17]. The same criterion was used for identifying wet episodes, but taking into account positive SPEI values. Data of P and Pet are from CRU TS v. 3.25 [18].

The climatological moisture sources of the NRB and MRB where identified through the Lagrangian particle dispersion model FLEXPART v9.0 [19, 20]. In this approach, the global atmosphere is homogeneously divided into finite elements of volume (for this study, nearly 2.0 million "particles"). FLEXPART permits to track backward or forward in time each parcel and to compute the rate of moisture increase (through evaporation from the environment, e) or decrease (through precipitation, p) along the trajectory of the parcels by calculating the changes in the specific humidity (q) over time (t) by Equation (1), assuming a constant mass (m) of the particles:

$$(e - p) = m(dq/dt) \quad (1)$$

Integrating the $(e - p)$ values of all parcels in a vertical column over an area A, is possible to obtain the total surface freshwater flux, hereafter represented by $(E - P)$ in Equation (2):

$$E - P \approx \frac{\sum_{k=1}^{k}(e-p)}{A} \quad (2)$$

In this work, we perform a backward experiment from the NRB and MRB, in which the transport time was set to 10 days, considered like the average time that water vapour resides in the atmosphere [21]. FLEXPART has been previously applied for investigating the hydrological cycle at different river basins, as the whole ARB [14], the Congo River basin [22], the Yangtze River basin [23], the Danube River basin [24] and several worldwide river basins [20]. FLEXPART utilizes data from ERA-interim reanalysis datasets [25].

3. Results and discussion

3.1. Precipitation and Potential Evapotranspiration annual cycle

The P and Pet annual cycle at NRB and MRB appear in Figure 2 (bars and lines for P and Pet, respectively). At the NRB the monthly average P (light gray) increases from January to May when reaches the annual maximum average rainfall (~11.0 mm/day). After May the average P decreases reaching a minimum in October (~4.9 mm/day) to later slightly increase until December. In the MRB (dark gray) which is totally located in the southern hemisphere, the P annual cycle differs from that over the NRB. In this basin, the maximum average P (> 6 mm/day) occurs during the Austral summer months (December-March) and minimum values in June, July, and August. Monthly average rainfall tends to be greater in the NRB. Indeed, the annual average rainfall over the NRB (7.0 mm/day) is greater than that over at the MRB (4.6 mm/day). Regarding Pet, both annual cycles (at the NRB and MRB) seem very similar, although they differ between July and December when Pet at the NRB (red line) is higher than at the MRB (green line). On the contrary, in February and March Pet is higher at the MRB. At both basins, Pet tends to increase after P does, reflecting a lag in time best appreciated at the NRB.

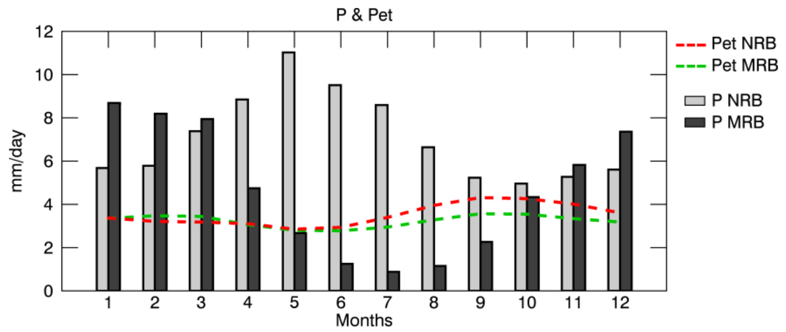

Figure 2. Precipitation (P, in bars) and Potential evapotranspiration (Pet, in lines) climatological annual cycle at Negro and Madeira River basins (NRB and MRB, respectively). Period: 1980 – 2016.

3.2. Moisture sources identification

In Figure 3 the average monthly budget of *(E – P)* obtained in a backward experiment from the NRB and MRB are shown. Positive values indicate those areas where the moisture uptake occurs, while negative values indicate those regions from where air masses lose humidity before arriving at the basins. From January to May the spatial pattern of *(E – P)* suggests that the NRB uptakes more humidity from the Tropical North Atlantic region (TNA) while air masses gain less humidity from the Tropical South Atlantic region (TSA) and the northeast of the basin. Indeed, the NRB mainly acts as water vapour sink for the atmospheric moisture income from April to July, when higher precipitation occurs over this basin (Figure 2). From June to October, the main source of moisture for the NRB seems to be the TSA as well as the east of the ARB and the NRB itself. In December the spatial pattern of *(E – P)* is different, and the highest moisture uptake takes place over the TNA.

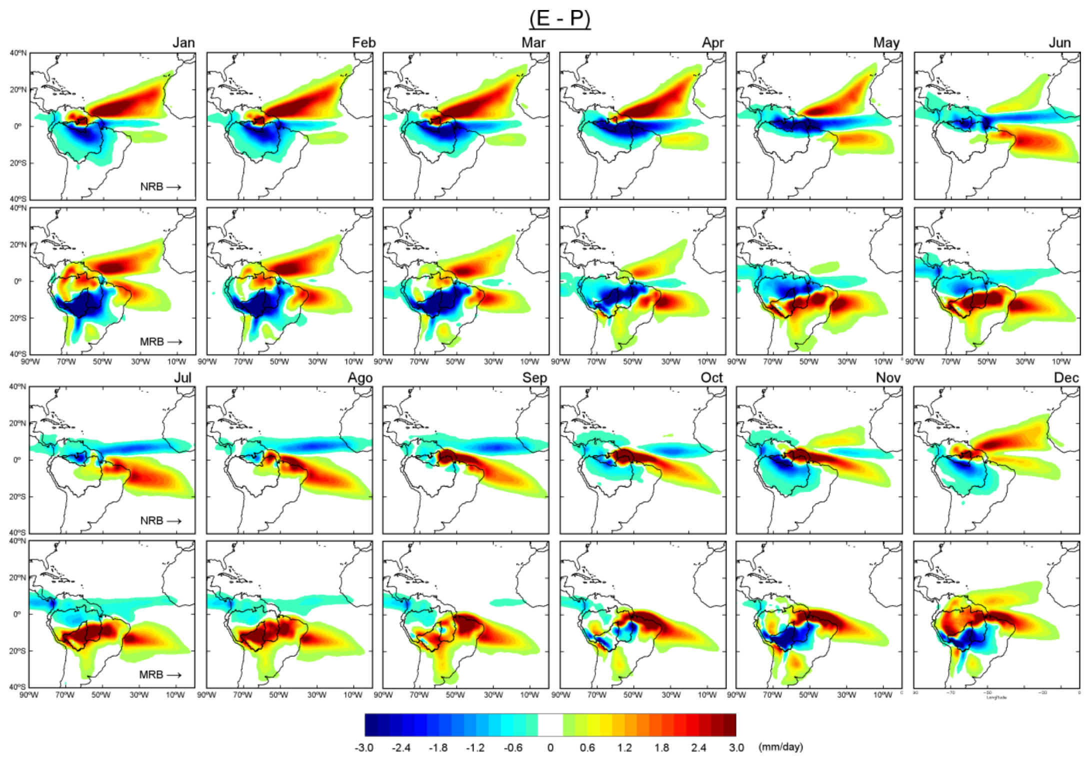

Figure 3. Monthly *(E - P)* patterns obtained in a backward experiment from the NRB and MRB. Period: 1980 – 2016.

Air masses tracked backward in time from the MRB uptake humidity from both regions, TNA and TSA from December to April. In these months this basin mainly acts as a sink of moisture in concordance to the major annual rainfall. In June, the onset of the Austral Winter, moisture uptake for the NRB takes places from the TSA and the southern half of the ARB and Sudamerica. This happens until September, because in October areas with *(E – P) < 0* values (moisture lose) are appreciated over parts of the MRB, and the eastern and northern ARB. In November and December, the moisture lose prevails over the MRB. However, the moisture income still persists from the east of the continent and the Atlantic Ocean. As already commented, in December the TNA becomes a source of moisture for the MRB.

3.3. Drought and wet conditions at the basins

The temporal evolution of the SPEI at temporal scales of 1.-6.- and 12 months (SPEI1, 6, 12) along the period 1980-2016 for the NRB and MRB appears in Figure 4. At the NRB dry conditions prevailed in the period 1980 – 1992 and 2013 – 2016, while wet conditions prevailed during 1996 – 2008. For the MRB it is highlighted the period 1980-1986 as the longest under wet conditions. But also in others years like 1992, 2009 or 2013 – 2014 the MRB experienced wet conditions. Likewise, dry conditions at MRB are best-appreciated in 1987 –1989 and 1994 – 1998. These results confirm that water balance conditions may greatly differ within the ARB. However, in 2015-2016 both basins were affected by dry conditions, while during 2008-2009 by wet.

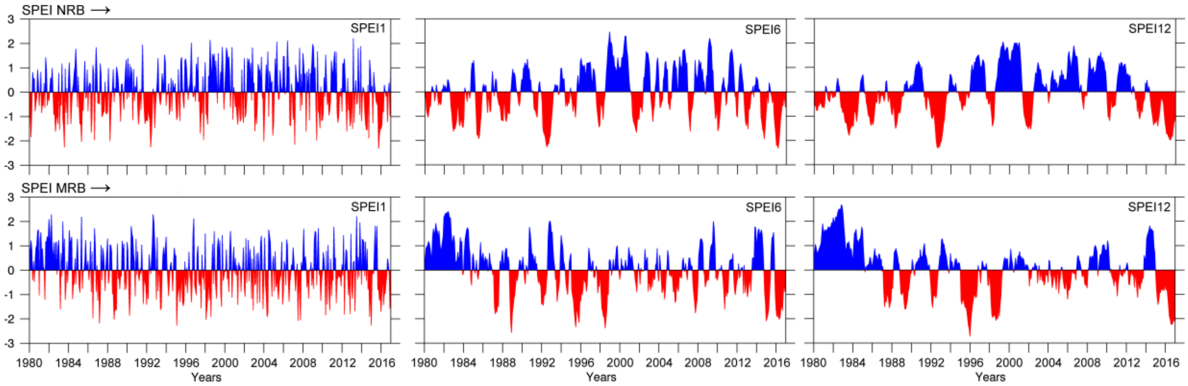

Figure 4. SPEI time series at 1.-6.- and 12 months temporal scale for the Negro (top, NRB) and Madeira (bottom, MRB) River basins. The blue (red) color represents wet (dry) conditions. Period: 1980 – 2016.

Droughts and wets episodes at the NRB and MRB were identifid. In Table 1 (Table 2) appears the drought (wet) episode detected at both basins in the period 1980 – 2016, with the minimum (maximum) peak value of the SPEI1 and the duration of the event.

Table 1. The most intense drought episode in the NRB and MRB basins according to the SPEI1 minimum peak value. Period: 1980–2016.

Basin	Episode	Duration	Peak
NRB	5/2015 - 3/2016	11	-2.32
MRB	1/1995 - 10/1995	10	-2.27

Table 2. The most intense wet episode in the NRB and MRB basins according to the SPEI1 maximum peak. Period: 1980–2016.

Basin	Episode	Duration	Peak
NRB	4/1998-2/1999	11	2.15
MRB	6/1992 - 11/1992	10	2.30

3.4. Moisture uptake anomalies during drought and wet episodes

For each episode documented in Table 1 and 2, there was calculated the anomalies of moisture uptake $((E-P)>0)$ in the backward experiment for both basins (Figure 5). Anomalies are calculated taking into account the month of start and end of each episode for the climatological period. For the drought episode at the NRB occur positive anomalies of $(E-P)>0$ mostly over the entire basin, but are most intense to the east, extending to the northeast over the tropical Atlantic Ocean. Negative anomalies are appreciated to the northeast and southeast of the NRB, also over the TNA and TSA regions. For the wet episodes the pattern of $(E-P)>0$ anomalies slightly change, and now the positive anomalies of moisture uptake are most intense over the TNA, while negative anomalies appear to the east of the NRB. As documented and here described, the TNA and TSA regions play an important role during extreme conditions at the NRB.

For the MRB, the pattern of $(E-P)>0$ anomalies shows the occurrence of negative anomalies over a great part of the ARB, but the most intense are at the northeast of Brazil, which extends to the ocean mainly between 0° and 10°S. Over the TNA region, there are mainly positive anomalies, as well as over the MRB, which means that moisture uptake is favored. In the wet episode the region of the northeast Brazil, where negative anomalies occurred for the drought episode, now appears with the highest positive anomalies, which confirm its important role providing moisture to the MRB during extreme conditions. In this episode, air masses arriving at the MRB from the north of the ARB and the TNA region uptake less humidity.

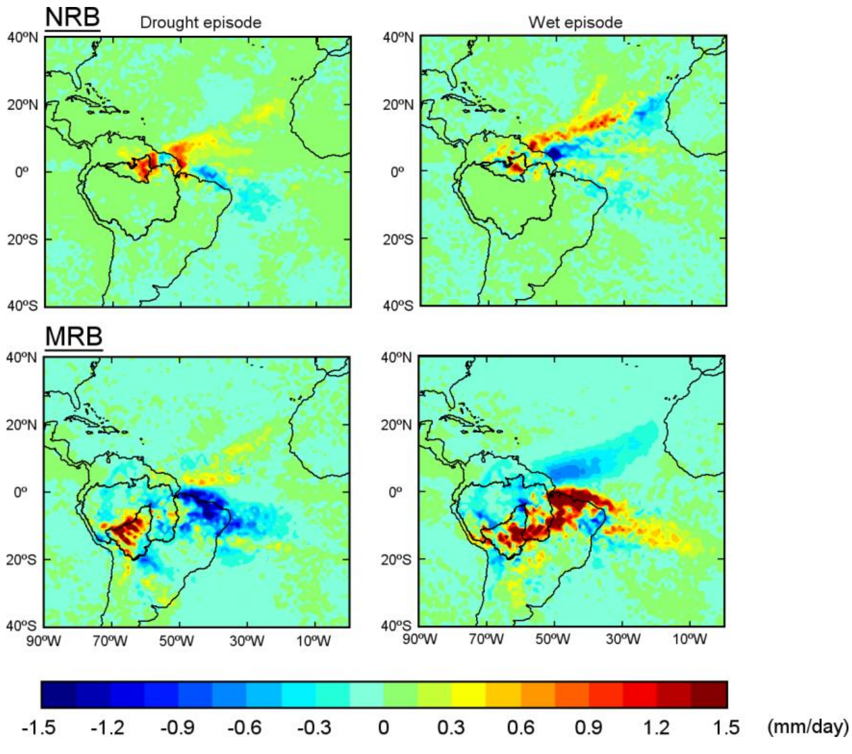

Figure 5. $(E-P)>0$ anomalies during drought and wet episodes (see Table 1 and 2) at the NRB and MRB.

4. Conclusions

The Standardised Precipitation-Evapotranspiration Index (SPEI) was used to identify dry and wet conditions in the Negro and Madeira River basins (NBR and MRB), which are located in the north and southwestern of the Amazon River basin (ARB). The study was conducted for the period 1980-2016. The temporal evolution of the SPEI at 1.-6.-12 months temporal scale show that dry and wet conditions within the Amazon River basin do not occur simultaneously, as expected, taking into account the differences in the precipitation annual cycle over each basin. Indeed, the MRB experienced a longest wet period in 1980 decade, when dry conditions affected the NRB. At the NRB dry conditions prevailed in the period 1980-1992 and 2013-2016, while wet conditions prevailed during 1996 – 2008. Also, in years like 1992, 2009 or 2013-2014 the MRB experienced wet conditions. Likewise, dry conditions at MRB are best-appreciated in 1987 – 1989 and 1994 – 1998. These results confirm that water balance conditions may greatly differ within the ARB. However, in 2015-2016 both basins were affected by dry conditions, while during 2008-2009 by wet.

The monthly climatological moisture sources of the NBR and MRB were identified. To do it was utilized the Lagrangian model FLEXPART v9.0 to track backward in time the air masses residing over the basins. Along the trajectory of each parcel was calculated the budget of evaporation minus precipitation $(E-P)$ in the atmospheric vertical column. The results confirm the important role of the Tropical North Atlantic and South Atlantic regions providing moisture to the NRB and MRB. However, the MRB also receive moisture from the half south and north of the ARB along the year. The moisture uptake anomalies $((E-P)>0)$ during drought and wet episodes with the highest SPEI1 peak at both, NRB and MRB confirm the previous results. However, a deepest analysis will be performed in order to quantify at monthly scale the moisture uptake from the sources and evaluated during more drought and wet episodes the role of the continental and oceanic moisture sources separately.

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Author Contributions: R.S., J.M., R.N., L.G. designed, proposed and conducted the research; R.S. performed the experiments and R.S., J.M., R.N., L.G. analysed the data; all the authors wrote the paper.

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Abbreviations

The following abbreviations are used in this manuscript:

ARB: Amazon River basin
NRB: Negro River basin
MRB: Madeira River basin
TNA: Tropical North Atlantic
TSA: Tropical South Atlantic
P: Precipitation
Pet: Potential Evapotranspiration
SPEI: Standardised Precipitation-Evapotranspiration Index

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