Surface And Atmospheric Patterns For Early And Late Rainy Season Onset Years In South America

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Abstract

The biosphere-atmosphere interactions associated with the rainy season onset in South America (SA) are not well understood. This study aimed to analyse the atmospheric and surface patterns associated with early, neutral and late rainy season onset years in SA. The years 2006, 2004 and 2008 were characterized as having early, neutral and late rainy season onsets, respectively, in comparison to the climatological mean (1998–2016). Distinct atmospheric conditions were identified in the early and late rainy season onset years. In the early onset year, the northwesterly moisture flux and moisture advection were higher than average over SA's centre-east, promoting precipitation. In the late onset year, precipitation was enhanced in SA's northwest and the configuration of multiple atmospheric blocking episodes contributed to the rainy season onset delay. Surface conditions also contributed to both the early/late rainy season onset. In the early onset year, there were wetter and cooler pre-onset conditions over centre-east SA. In the late onset year, atmospheric conditions were dry and warm prior to onset. Despite the atmospheric instability promoted by the increase in sensible heating, dry atmospheric conditions were not favourable to convection, thus delaying rainy season onset. These findings highlight the importance of the land-surface as well as atmospheric conditions for the rainy season onset in SA, and also how the onset variability promotes different atmospheric and surface patterns. The results will help develop modelling capability for better prediction of rainy season onset focusing on biosphere-atmosphere processes improvements.

1. Introduction

The area between the southeast of the Amazon and the Midwest and Southeast regions of Brazil (the central area of South America) experiences an annual precipitation cycle, in which maximum rainfall is recorded in the austral summer (December to February, DJF) and minimum in the austral winter (June to August, JJA) (Gan et al., 2004). The area is characterized as a monsoon region, experiencing a dry season and a rainy season every year (Zhou; Lau, 1998; Gan et al., 2004; Vera et al., 2006; Marengo et al., 2012). The high rainfall accumulated during the rainy season over tropical Brazil, associated with the South America Monsoon System (SAMS; Zhou; Lau, 1998; Marengo et al., 2012), involves the circulation associated with the following structures: Bolivian High, Northeast Trough, Chaco Low, South Atlantic Convergence Zone (SACZ) and South America Low Level Jet (SALLJ).

The rainy season onset related to the SAMS refers to the period when a persistent precipitation increase is observed. Nieto-Ferreira and Rickenbach (2011) developed a conceptual model of the rainy season onset over SA's central area using a pentad precipitation Global Precipitation Climatology Project version 2 (GPCP-v2; rainfall estimates from satellite and gauge data) dataset. On average, the first stage of the rainy season onset occurs between 18th and 22nd October, when precipitation is established over SA's northwest region. In the second stage it gradually extends to southeast between 28th October and 1st November, characterized by the SACZ. The third stage, which occurs from December and can extend until mid-February and March of the following year, involves the monsoon arrival at the Amazon River mouth

and in Ecuador, which, in turn, is associated with the Intertropical Convergence Zone's (ITCZ) slow migration to the summer hemisphere.

Understanding and identifying the atmospheric patterns that modulate rainy season onset variability is important for managing agricultural production and also for energy and water resources management (Minuzzi et al., 2007; Franchito et al., 2010; Marengo et al., 2012; Bombardi et al., 2019). Delays in rainy season onset can cause crops losses (Resende et al., 2019), energy generation deficiencies and water rationing (Marengo et al., 2015).

Several studies have already been developed in order to understand the SAMS behaviour (Gan et al., 2004; Vera et al., 2006; Raia; Cavalcanti, 2008) and its representation in weather and climate numerical models (Jones et al., 2012; Cavalcanti; Raia, 2017). Other studies have evaluated how interannual variation in the rainy season onset is influenced by remote features, such as the El Niño Southern Oscillation (ENSO) warm phase affecting the rainy season onset over the central area of the Amazon basin (Liebmann; Marengo, 2001; Marengo et al., 2001), the South Atlantic Ocean's sea surface temperature (SST) dipole influencing the rainy season onset both in the Amazon region (Marengo et al., 2001) and in the Southeast region of Brazil (Bombardi et al., 2014).

Most studies aimed to verify how rainy season onset variability was influenced by large scale atmospheric and oceanic conditions, however, few studies investigated the interactions between atmosphere and land surface processes during the rainy season onset (Fu; Li, 2004; Marengo et al., 2012; Bombardi et al., 2019). Surface processes are increasingly being recognised as having an influence on the rainy season onset (Fu; Li, 2004; Wright et al., 2017), and land surface processes are themselves directly affected by variations in rainy season onset date. Fu and Li (2004) observed that the late rainy season onset is associated with a longer preceding dry season. Under these conditions, the latent heat flux (LE) is reduced due to lower water availability both in the soil and in the atmosphere. The vegetation suffers water stress affecting its metabolic processes, leading eventually to stomatal closure. The mass and gas exchange between the plant and the adjacent air reduces, including the photosynthesis rate (Pirasteh-Anosheh et al., 2016). Surface radiation is re-partitioned, with reductions in LE and increases in the sensible heat flux (H), promoting a drier and more stable atmosphere (Convective Inhibition Energy increase), which is less favourable to convection (Fu; Li, 2004).

The processes described above are consequences of biosphere-atmosphere interactions. This study aimed to contribute to the understanding of these interactions associated with the rainy season onset, based on the hypothesis that variation in the rainy season onset date affects the surface processes, modulating the energy fluxes and the biogeochemical cycles (carbon, water). Therefore, the objective of this study was to determine and analyse the atmospheric and surface patterns associated with selected early, neutral and late rainy season onset years in SA.

2. Data

2.1 Rainy and Dry Season (RADS)

The RADS dataset was used to select years based on the rainy season onset Julian day. This dataset uses the LM01 method (Liebmann; Marengo, 2001), with five adaptations made by Bombardi et al. (2019). The Tropical Rainfall Measuring Mission (TRMM; Huffman et al., 2007) satellite product, and the Climate Prediction Center Unified Gauge-Based Analysis of Global Daily Precipitation data (CPC_UNI; Xie et al., 2007; Chen; Knutson, 2008) were used to determine the rainy season onset available in a global grid on RADS. TRMM data have a spatial resolution of 0.25° latitude x 0.25° longitude, with spatial coverage between 50°S to 50°N, from 1999 to 2016. The CPC_UNI dataset, on the other hand, has a spatial resolution of 0.5° latitude x 0.5° longitude, for the period from 1979 to 2018.

2.2 ERA5, ERA5-Land and GPCP

ERA5 and Global Precipitation Climatology Project (GPCP) data were used in the atmospheric analysis while the ERA5-Land was used in the surface analysis, as this product has been specifically calibrated for analyses over land (see Table 1 for references and further information).

Carvalho et al. (2012) evaluated the ability of several datasets to represent seasonal variation in precipitation due to the SAMS. The authors found that the GPCP dataset represents the precipitation annual cycle well, and precipitation data from CPC_UNI and TRMM were showed to be very similar in terms of spatial patterns and onset timing.

3. Methodology

Figure 1 shows the RADS dataset's rainy season Julian day onset climatology (1998–2016) over SA. The rainy season onset over central SA (outlined in black) occurs between the end of September and November (Julian day interval from 260 to 330), consistent with Gan et al. (2004), Raia and Cavalcanti (2008), Nieto-Ferreira and Rickenbach (2011). This area was delimited as the study area and the precipitation regime here is within the SAMS domain.

To select the years characterized by the early and late rainy season onset, onset date anomalies were calculated for each year available in RADS using data from CPC_UNI and TRMM. The proportion of the study area grid points in which the rainy season onset occurred early (negative anomalies) and late (positive anomalies) was obtained by an algorithm. The early (late) characterized years were selected from those whose percentage of positive (negative) grid points within the study domain was greater than 60%. The neutral rainy season onset was determined by the nearly 50% percentage of positive/negative points.

To ensure that the year selection method was consistent, the results obtained with the TRMM and CPC_UNI databases were compared and are presented in Table 2. There were fewer years with early onset rainy seasons than with late onset rainy seasons. Of the three years with early onsets, two years (1998 and 2006) were identified using both precipitation datasets. All of the late onset years identified by

TRMM were also identified by CPC_UNI (2002, 2003, 2007, 2008, 2015), though there were three years that were identified as late onset in the CPC_UNI data only (1999, 2012, 2014, note that here we exclude years before the start of the TRMM data product in 1980). Therefore, the identification methodology used in the RADS database (Bombardi et al., 2019) is shown to be largely consistent between the TRMM and CPC_UNI databases. In this study we selected years that were indicated as either early, late or neutral by both products.

The years 2006 and 2008 were selected as early and late rainy season onset years, respectively. These years were selected considering the percentage of negative/positive points (Table 2). The year 2008 had the highest percentage of positive points (indicating late rainy season onset), both in TRMM and in CPC_UNI, equal to 76.62 and 78.42%, respectively. For the early onset year, although 1998 presented the highest negative points percentage, the year 2006 was selected because of its proximity to 2008, therefore, avoiding low-frequency climatic variability. The years not shown in Table 2 were considered as neutral onset, and 2004 was selected as a neutral year because the positive and negative grid points percentage was nearly 50%.

For each selected year, the grid points with the same rainy season onset Julian day were counted to obtain a frequency series. Then, a 5-day moving average was applied to smooth out high-frequency variabilities. Figure 2 (a) shows the rainy season onset Julian day smoothed frequency series over the study area. The red series represents the early onset year (2006), a peak was observed on Julian day 288, equivalent to October 15th. The neutral onset year is represented by the yellow series, in which a well-configured peak was observed in October 11 (Julian day 284). The blue series represents the late onset year (2008), the peak occurred in November 11, equivalent to Julian day 315. From Fig. 2 (a), it was noted that in the year selected as neutral (2004), the rainy season onset occurred in October, according to what was found in the literature (Kousky, 1988; Marengo et al., 2001; Gan et al., 2004; Vera et al., 2006; Silva; Carvalho, 2007; Raia; Cavalcanti, 2008). The 2008 frequency series shows that, in fact, the rainy season onset was delayed. In the other hand, the highest frequency peak in 2006 was relatively after the neutral onset year. For this reason, the frequency series were also obtained for the area between 10°S and 20°S latitudes and 50°W and 60°W longitudes shown in Fig. 2 (b). According to Wang et al. (2011) this area is within the monsoon precipitation index domain. Thus, it was observed that 2006 presented two frequency peaks between the second half of September and the first half of October. The most common onset date was Julian day 270, therefore, before the neutral rainy season onset year (2004). Over this area, the frequency peaks observed for the neutral (2004) and for the late onset (2008) year were mid-October (Julian day 283) and between late October and early November (Julian day 292), respectively.

Therefore, based on the onset-date time series analysis, we verified that the selected years characterised by early, neutral and late rainy season onsets are consistent, and also determined that the period between September and December, is most important for the atmospheric and land surface patterns analysis, though we extended the analysis within the summer months (January and February) to identify land-atmosphere interactions that occur after the rainy season start.

3.1 Selected Years Atmospheric and Surface Patterns Analysis

After selecting the early, neutral and late onset years, monthly precipitation anomalies from September to February were analysed. The anomalies were obtained from the difference between the respective monthly value and the annual climatological average for that month (Eq. 1), from 1981 to 2010, for the ERA5, ERA5-Land and GPCP datasets. We opted not to use monthly climatology, because the anomaly signal would be lower when compared to annual climatology. This is because, the rainy season onset relies on the precipitation annual cycle. This cycle has a maximum and a minimum peak during the year, and using the annual climatology ensures the maintenance of both winter and summer solstices signal. Eq. 1 shows how the anomaly was obtained using the annual climatology:

$$Anomaly = \bar{X}_i - \left(\frac{1}{y_f} \times \sum_{y=1}^{y_f} \left(\frac{1}{12} \times \sum_{i=1}^{12} \bar{X}_i \right)_y \right) \quad (1)$$

where $(\bar{x})$ is the variable's monthly mean in the i -th month, y_f is climatology years available number, for ERA5, ERA5-Land and GPCP data, y_f was 30 years.

3.2 Composite Analysis

To further investigate the rainy season onset patterns, the composite analysis of SLP and wind at 850hPa was obtained. According to Table 2, we selected the following years to represent each onset: 1998, 2006 and 2009 for the early onset, 2001, 2004 and 2005 for the neutral onset, 2000, 2007 and 2008 for the late onset. The composite analysis is an effective tool to identify climate patterns of specific events, e.g., ENSO (Boschat et al., 2016). In this study, the composite analysis consisted in obtaining the mean anomaly field for each onset year aforementioned.

3.3 Identification of Atmospheric Blocking Episodes

To identify atmospheric blocking episodes in each selected onset year, the Damião et al. (2009) methodology was applied. In this methodology, geopotential height at 500hPa from ERA5 was used. Over the domain between 0–90°S and 140°E–30°W, two Geopotential Height Gradient indices were calculated, one South (GHGS) and one North (GHGN), described by equations 2 and 3, respectively.

$$GHGS = Z(\lambda, \varphi_s) - Z(\lambda, \varphi_{02})$$

2

$$GHGN = Z(\lambda, \varphi_{01}) - Z(\lambda, \varphi_N)$$

3

$$\left\{ \begin{array}{l} \varphi_s = 65^\circ S + \Delta \\ \varphi_{02} = 50^\circ S + \Delta \\ \varphi_N = 40^\circ S + \Delta \\ \varphi_{01} = 55^\circ S + \Delta \end{array} \right.$$

In equations 2 and 3, $Z(\lambda, \phi)$ is the geopotential height at 500hPa, λ is the longitude, ϕ is the latitude and Δ is a latitudinal counter that can assume the following values -10° , -7.5° , -5° , -2.5° and 0° . A given latitude λ was considered as an atmospheric blocking episode configuration when the GHGS and GHGN indices satisfied in at least one value of Δ the following conditions: (GHGN > 0.0) e (GHGS < -10 mgp). A blocking episode was defined when the aforementioned conditions were verified in at least three consecutive longitudes (grid cells) and simultaneously when this condition persisted for at least 3 consecutive days.

3.4 Surface Water Budget Analysis

The surface water budget was evaluated over the area that according to Wang et al. (2011) is within the monsoon precipitation domain, between $10-20^\circ S$ and $50-60^\circ W$. We don't expect groundwater storage to have varied considerably between the years (Correia et al., 2007), thus we did not include this variable in our analysis. According to Correia et al. (2007), the following hydrological cycle components were considered: precipitation, evapotranspiration, drainage to rivers by surface runoff, and atmospheric moisture advection due to water vapour transport from (or to) other regions (Eq. 4).

$$WaterBudget = (Advection) + (Precipitation - Evapotranspiration + Runoff)$$

4

The data used to this analysis was from ERA5 for the following variables: u and v wind components, specific humidity, latent heat flux and runoff. The precipitation data was from GPCP.

4. Results

4.1 Atmospheric Patterns

In the three selected years (2006, 2004 and 2008), an anticyclonic circulation at 850hPa, characteristic of the South Atlantic Subtropical High (SASH; Vera et al., 2006; Raia; Cavalcanti, 2008; Marengo et al., 2012) was observed in its most westerly position in September (Fig. 3). As the rainy-season onset approached, the SASH moved away from the coast. The rainy season onset was characterized by the pressure reduction in the SA continent, observed with anomalies of up to -5hPa over the Chaco region (between east Paraguay and north Argentina) in October of the early onset year (Fig. 3b). In the same year, the SASH was weaker compared to the neutral and late onset years (Fig. 3a, b, g, h, m, n). On the other hand,

in the late onset year, positive SLP anomalies were observed since July (not shown), configuring a more intense SASH. In addition, in September, between 40–60°S and 60 – 30°W, a ridge and positive SLP anomalies with a magnitude of up to 12hPa were observed (Fig. 3m). It is suggested that this configuration was responsible for the late rainy season onset, which occurred only in November, when the continent's pressure reduction was verified (Fig. 3o). From November to February (Figure c, d, e, f) of the early onset year, the greatest negative SLP anomalies were concentrated in the central and southern areas of SA, while in the neutral and late onset years, the negative anomalies appeared throughout the SA, being more intense over the southeast, except in January of the late onset year.

In October of the early onset year (Fig. 4b), positive moisture flux magnitude anomalies were observed over the eastern Andes, where the vectors indicate that the northwesterly moisture flux was intensified. This northwesterly flux with magnitudes of up to $30 \text{ kg.m}^{-2}.\text{s}^{-1}$, was maintained from December to February of the early onset year (Fig. 4d, e, f), and in January (Fig. 4e) the positive moisture flux magnitude anomalies extended from the Amazon Basin towards the Southeast region of Brazil and to the Atlantic Ocean, associated with the SACZ's configuration (Kodama, 1992).

In September of the late onset year (Fig. 4m), negative moisture flux magnitude anomalies between 40–60°S and 60 – 30°W were observed in an area where positive SLP anomalies were also verified, indicating that the pressure increase was coupled with the moisture flux reduction over this area. In November of the late onset year (Fig. 4o), negative moisture flux magnitude anomalies were observed across SA, but mainly over the Amazon basin and east of the Andes (between Peru and Paraguay), the negative moisture flux anomaly direction was predominantly from southeast, indicating a moisture transport reduction from the Amazon basin to the central and southwestern region of SA. Over these two areas, a moisture flux reduction of up to $30 \text{ kg.m}^{-2}.\text{s}^{-1}$ was observed in December (Fig. 4p). In the late onset year, it was not possible to identify characteristic moisture flux anomalies over the SACZ's configuration area, as observed in January of the early and neutral years (Fig. 4e, k). It is suggested that the predominance of moisture flux negative anomalies in the late year, may have contributed to rainfall reduction, in comparison to the other years studied.

In summary, there was a continuous increase in the moisture flux over SA from September to January of the early onset year (Fig. 4a, b, c, d, e, f). However, this pattern was not identified in the late onset year, in which the moisture flux anomalies oscillated from September to December (Fig. 4m, n, o, p, q, r).

From the OLR anomaly analysis accompanied by the 200hPa streamlines (Fig. 5), November to February were characterized by the persistence of negative OLR anomalies over central SA, indicating the presence of cloud vertical development, an indication of the rainy season (Fig. 5c, d, e, f, i, j, k, l, o, p, q, r; Kousky, 1988; Garcia, 2010). In addition, in the 200hPa streamlines, the configuration of an anticyclone, known as Bolivian High (BH; Lenters; Cook, 1997), and of a trough east of the BH, known as Northeast Trough (NET, Lenters; Cook, 1997) or Upper Tropospheric Cyclonic Vortices (UTCN) was observed. This upper tropospheric level circulation pattern is important for the SACZ's positioning (Kodama, 1992). In the early onset year, BH and NET started to configure in August, and in October, the two systems were more intense

compared to the neutral and late onset years (Fig. 5b). However, the circulation at 200hPa was more intense in the late onset year, it means the BH and NET structures were stronger (Fig. 5o, p, q, r). In the late onset year, an area with negative OLR anomalies accompanied by anticyclonic circulation at 200hPa covered SA's central and northern areas (Fig. 5o, p, q, r), while in the early year it concentrated over the central SA (Fig. 5c, d, e, f).

During the rainy season onset, positive precipitation anomalies were concentrated over SA's central-eastern portion, in October of the early (Fig. 6b) and neutral onset years (Fig. 6h) and in November of the late year (Fig. 6n). The low-level wind reversal (850hPa), observed when the annual average was removed (Zhou; Lau, 1998; Gan et al., 2004; Silva, 2012), is a rainy season onset feature. Thus, from July to September, the wind vector anomaly was mainly from the south over central-north SA (Figure a, g, m). From October (November) the wind anomaly became mainly from northwest in the early and neutral (late) years (Fig. 6b, h, o).

From the OLR (Fig. 5) and precipitation (Fig. 6) anomalies analysis, it was possible to identify the SA's rainy season onset conceptual model, developed by Nieto-Ferreira and Rickenbach (2011). Under this model, the rainy season onset's first stage occurs when precipitation persists over SA's northwest region and gradually extends to the southeast (October 18–22, Fig. 6d). The second stage is characterized by the SACZ's configuration (October 28 to November 1, Figs. 5 and 6c, i, o). The third stage involves the monsoon arrival (wind anomaly reversal) at the Amazon River mouth between the North and Northeast regions of Brazil (between February and March, Figs. 5 and 6f, l, r).

In the early onset year, larger positive precipitation anomalies were observed between the southeast of the Amazon Basin and the southeast region of Brazil, where the SACZ's pattern was identified from November to January (Fig. 6c, d, e). In February (Fig. 6f), positive anomalies up to 250 mm (monthly cumulative) were concentrated over the central and eastern portion of SA including the Northeast and North regions of Brazil (the third stage rainy season onset area). The size of the wind vector anomalies at 850hPa (indicating the intensity) was bigger in the early onset year compared to the neutral and late years, mainly in February, when the precipitation anomaly magnitude was also greater (Fig. 6f). In the late onset year, precipitation positive anomalies concentrated between central SA, the Southeast region of Brazil and the adjacent Atlantic Ocean, in November (Fig. 6o). From December to February, positive precipitation anomalies extended to the North and Northeast regions of Brazil (Fig. 6p, q, r).

To summarise the analysis of atmospheric patterns in each onset year (early, neutral and late), the main large-scale patterns configuration associated with SAMS were consistent with previous studies (Zhou; Lau, 1998; Gan et al., 2004; Vera et al., 2006; Marengo et al., 2012) are shown in Table 3.

The main differences in the atmospheric pattern between the early and late onset years are shown in Fig. 7. In the early year, a more intense SLP reduction was observed over central-east SA (blue area), where the northwesterly moisture flux was also more intense (red arrow), enhancing the precipitation and the SACZ's configuration. In addition, the SASH's performance was less intense compared to the neutral and late onset years, so it is suggested that it favoured the advance of cold fronts over the SA's east

coast, and thus contributed to the earlier rainy season onset. These same configurations were observed by Raia and Cavalcanti (2008) in the early rainy season onset, in which the advance of an intense frontal system contributed to the soil and atmospheric moisture increase, in addition, the northwesterly flux was also more intense while the SASH's configuration and the east flux towards the continent were weakened.

In the late onset year, precipitation was enhanced over northwest SA, and the SACZ was positioned further north compared to the early onset year. The BH and NET configuration were also more intense. In addition, it is suggested that the configuration of a high-pressure system in September between 40–60°S and 60 – 30°W, suppressed the advance of cold fronts, and consequently contributed to the onset delay over central-east SA. For the late onset year, Raia and Cavalcanti (2008) found that the SLP was higher over central-east SA and the first precipitation episodes were associated with a frontal system, which, despite persisting for a few days and even resulting in a false onset, were not sufficient to promote the rainy season onset's necessary conditions.

4.2 Composite Analysis

The composite analysis of SLP and wind at 850hPa is shown in Fig. 8. The main motivation for this analysis was the identification of the SLP anomaly pattern in September of the late onset year.

In September, over southern SA and the Atlantic, SLP positive anomalies were observed in the three years characterized by early, neutral and late rainy season onset, however, in the late onset years, the magnitude of these anomalies reached 16hPa over the area between 40–60°S and 90 – 30°W (Fig. 8k). The most intense positive anomalies near south SA were shifted to the Pacific in early onset years and to the Atlantic in late onset years. It is therefore suggested that the position of these intense positive anomalies close to SA plays an important role in the onset timing: once a high pressure system is established over 40–60°S and 90 – 30°W, it would suppress the frontal systems advance, thus, delaying the onset by enhancing atmospheric stability.

The SLP composite configuration was also observed in the 850hPa wind composite, in which positive SLP anomalies were associated with anticyclonic circulation (Fig. 8e, f). The SLP pattern observed in the neutral and late onset years, suggests that the month in which a blocking pattern occurs, and its position, are fundamental for the onset timing. In these years, the high pressure system over the southwest Atlantic Ocean plays an important role in establishing the onset. In October of the early onset years, negative anomalies were observed across the SA and the Pacific between 50–60°S and 120 – 60°W accompanied by cyclonic circulation (Fig. 8d). It is suggested that the configuration of this pattern contributes to the frontal systems intensification that could later organize SA's precipitation and, therefore, promote the early rainy season onset.

4.3 Atmospheric Blocking Episodes

In September of the late onset year over the area between 40–60°S and 90 – 30°W, SLP positive anomalies and anticyclonic circulation were observed, both in the anomaly (Fig. 3) and composite analysis (Fig. 8). Therefore, the atmospheric blocking episodes' identification methodology applied by

Damião et al. (2009) was used to further analyse the SLP atmospheric patterns. In the early onset year (2006), although more blocking episodes were identified, they occurred between latitudes of 40–70°S and longitudes of 130 – 90°W, in the Pacific Ocean (Fig. 9b). In the neutral onset year (2004), the episodes were no more than 6, and were also concentrated over the Pacific area between 40–70°S and 130 – 120°W (Fig. 9d). Finally, in the late onset year (2008), up to 3 atmospheric blocking episodes between 40–70°S were identified over the Pacific at longitudes of 120°W and 80°W (near SA's west coast) and up to 4 episodes over the Atlantic between the longitudes of 60°W and 50°W (Fig. 9f). Therefore, the analysis identifying blocking episodes allowed us to verify that the configuration observed in September of the late onset year between 40–60°S and 90 – 30°W was caused by more than one atmospheric blocking episode, which configuration was important for the rainy season delay.

4.4 Surface Patterns

This section focusses on the surface pattern analysis of the energy fluxes (sensible and latent heat) for each of the early (2006), neutral (2004) and late (2008) onset years. From September to October of the early onset year, negative sensible heat flux (H) anomalies were observed between northwest SA and southeast Brazil (Fig. 10a, b), indicating that the atmosphere was less warm compared to the other years. From November of the early and neutral onset years, positive H anomalies appeared throughout the SA (Fig. 10c, i) and gradually reduced in December and January, when they concentrated over south, northeast and northwest SA (Fig. 10e, f, k, l). The persistence of positive H anomalies after the rainy season onset in the neutral and early years seems important for the atmospheric instability maintenance, also verified by Silva (2012) and Garcia (2010). The H increase, when associated with the atmospheric warming, promotes pressure reduction and, consequently, mass convergence at surface. Convergence and cloud formation generate precipitation, characterizing the rainy season onset. In February of the early and neutral years, negative H anomalies were observed over central SA, being a possible effect of both precipitation and OLR negative anomalies persistence. It contributes to incident shortwave radiation reduction and, consequently, for the atmospheric cooling (Fig. 10f, l).

In the late onset year, positive H anomalies were observed from September to November concentrated over central-east SA, indicating a warmer condition before the onset (Fig. 10m, n, o). By promoting the atmospheric instability, this condition favours convection, however, the reduced moisture flux limited the convective process. From December to January, negative H anomalies appeared over central-east SA (Fig. 10p, q), a pattern that appeared only in February of the early and neutral onset years (Fig. 10f, l). It is suggested that the atmospheric cooling in December of the late onset year, has suppressed convection, by promoting a more stable atmospheric condition (warming reduction).

In September, positive latent heat flux (LE) anomalies of up to 80 W.m^{-2} were observed in northwest SA, in the three onset years (Fig. 11a, g, m). These positive anomalies were associated with the rainy season onset's first stage, involving the precipitation intensification over southeast Amazon. Also in September, negative LE anomalies were observed, mainly over central-east SA, which were associated with warming before onset, and the H increase was important to the atmospheric instability in this area, as verified in

the H analysis (Fig. 11a, g, m). From October to December, the positive LE anomalies extended from the northwest to the southeast of SA, indicating the increase in moisture from the second stage of the rainy season onset that involves the SACZ's configuration (Fig. 11b, c, d, h, i, j, n, o, p). From January onwards, the magnitude of positive LE anomalies began to decrease throughout SA, mainly in the late onset year (Fig. 11q). It means that in the late onset year there was less moisture transfer from the surface to the atmosphere, which is important to maintain the rainy season convection. According to Silva (2012), LE increases after the precipitation starts and consequently the soil moisture increases, which in turn increases evaporation and therefore acts to maintain convection after the onset. In general, the differences observed in LE anomalies between the studied years were smaller compared to the differences in H anomalies. It means, that the LE contribution to each onset year was smaller than the H contribution.

Figure 12 shows the differences in 2m temperature (Fig. 12a, e), soil water (Fig. 12b, f), H (Fig. 12c, g) and LE (Fig. 12d, h) anomalies between the early and late onset years for SON and DJF. In SON, negative temperature differences were observed over most of SA but mainly in the central-east, indicating that the temperature of the late onset year was up to 2.5°C higher than of the early onset year. This increase of temperature in the late onset year was also verified in the negative H differences that reached values of up to 50 W.m^{-2} over central-east and south SA in the early onset year (Fig. 12c). Regarding the soil water content in SON, positive differences were observed, indicating that the water content between the Northeast and Midwest regions of Brazil was higher in the early year compared to the late onset year. In northwest SA, negative soil water anomalies indicated more moisture in the late year compared to the early onset year (Fig. 12b). This differences pattern was also observed in LE, where positive differences were observed over the Northeast and Midwest regions of Brazil in SON (Fig. 12d), while negative LE differences were observed in northwest SA. The differences magnitude observed in soil water content and LE were smaller compared to the differences observed in temperature and H. Furthermore, the soil water and LE differences patterns seem to have been a consequence of the positive precipitation anomalies pattern, in which more precipitation occurred over the central-east (northwest) SA in the early (late) onset year.

In DJF, the temperature differences between the early and late onset years, shows that the temperature in the late onset year was up to 2.5°C higher compared to the early year, especially in the northern region of SA (Fig. 12e). In this area, in the late onset year, an increase in H (Fig. 12g), soil water content (Fig. 12f) and LE (Fig. 12h) was verified. This increase is characteristic of the rainy season during the austral summer, in which more energy is available at the surface to energy fluxes partitioning.

The differences observed between early and late onset years in surface variables are summarized in Fig. 13, especially for SON, where the red (blue) areas represent the soil water content reduction (increase) and the up (down) arrows indicate increase (decrease) of latent and sensible heat fluxes, Leaf Area Index (LAI) and temperature over each indicated area.

4.5 Surface Water Budget Analysis

From the surface water budget analysis obtained for the area between 10–20°S and 50–60°W (Fig. 14a), it was observed that from July to October, the three years (2004, 2006, 2008) had water budgets of the same mm.day^{-1} order. However, the water budget in the early onset year was higher compared to the neutral and late onset years, except in August. In November, the budget reduced compared to October, mainly in the late onset year, becoming negative. From December to February, the early onset year water budget remained between 20 and 25 mm.day^{-1} , while in the neutral year it varied from 5 to 20 mm.day^{-1} from December to January, becoming negative in February. In the late onset year, the negative budget in December turned positive (5 mm.day^{-1}) in January, and in February reached 20 mm.day^{-1} .

The analysis of water budget components allowed us to verify each individual contribution. The moisture advection pattern and its magnitude (Fig. 14b) were very similar to the water budget pattern (Fig. 14a), therefore, the moisture advection was the most important component for the differences between the onset years, while the other water budget components contribution were secondary.

In the precipitation component analysis (Fig. 14c), between the months of July and September, low rainfall was verified in the dry season. It is noteworthy that in September of the early onset year, precipitation was higher than the other two years, suggesting that this higher moisture condition may be associated with frontal systems advance, which favoured the early onset (Raia; Cavalcanti, 2008). From October to February, precipitation increased in the three years, more precipitation in the early onset year was observed in comparison to the late year. For the evapotranspiration component (Fig. 14d) it was observed that the differences between the onset years were subtler, and the evapotranspiration increase from October onwards was due to the rainy season precipitation increase. Finally, the runoff component (Fig. 14e) was also dependent on the precipitation increase, being observed from September in the early onset year and from October in the neutral and late onset years. In the early onset year runoff was also higher compared to the other years.

5. Conclusions

In our analysis of early, neutral and late rainy season onset years, distinct atmospheric conditions were identified. The early onset year was characterized by SLP reduction particularly over central-east SA, where the northwesterly moisture flux was more intense, promoting precipitation and the SACZ's configuration. The moisture advection was the most important component of the water budget: in the early onset year the moisture advection was enhanced compared to the neutral and late years, reinforcing the result of the intensified northwesterly moisture flux. On the other hand, the moisture advection and the northwesterly flux in the late onset year were weaker and the precipitation was concentrated over northwest SA, and the SACZ was in its northernmost position. In addition, more than one episode of atmospheric blocking between 40–60°S and 60 – 30°W, suppressed the advance of destabilising cold fronts and consequently, contributed to delay in the rainy season onset over central-east SA. Furthermore, this study verified the hypothesis that the timing of the rainy season onset affects land surface conditions, with an observed increase in LE over central-east (northwest) SA in the early (late) onset year, corresponding to the same area that the precipitation increased.

In addition, the study allowed us to verify that surface conditions also contributed to the early/late rainy season onset. By analysing the energy fluxes, it was found that H contributed more to the differences between early and late onset years compared to LE. In the early onset year, there was a wetter (more LE and greater water budget) and cooler (lower H) condition before the onset (September and October), over central-east SA. However, from November onwards, H increased throughout SA and gradually reduced in December and January, suggesting that the H increase after the onset was important for the atmospheric instability maintenance and consequently for the convective processes in the early onset year. In the late onset year, the atmospheric condition was dry (less LE and less water budget) and warm (more H) before the onset. Despite the atmospheric instability promoted by the H increase, the moisture condition did not favour convection. In December, right after the onset of the late year (November), the atmosphere cooled over central-east SA, which is also an indication that convection was not favoured in this area, even though H and LE increased in northwest SA where precipitation was concentrated in the late onset year. To conclude, while it is already known that much of the influence on the SAMS and the rainy season onset comes from variability of large-scale phenomena (Zhou; Lau, 2001; Marengo et al., 2012), the results of this work show that local phenomena and land-surface conditions also have an important impact on rainy season onset in SA. And for this reason, biosphere-atmosphere processes improvements are important to the rainy season onset representation in forecast numerical models.

Declarations

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References

1. Bombardi RJ, Carvalho LM, Jones C, Reboita MS (2014) Precipitation over eastern South America and the South Atlantic Sea surface temperature during neutral ENSO periods. *Clim Dyn* 42(5–6):1553–1568
2. Bombardi RJ, Kinter III, J. L., & Frauenfeld OW (2019) A global gridded dataset of the characteristics of the rainy and dry seasons. *Bull Am Meteor Soc* 100(7):1315–1328
3. Boschat G, Simmonds I, Purich A, Cowan T, Pezza AB (2016) On the use of composite analyses to form physical hypotheses: An example from heat wave–SST associations. *Scientific reports* 6(1):1–10
4. Cavalcanti IFA, Raia A (2017) Lifecycle of South American Monsoon System simulated by CPTEC/INPE AGCM. *Int J Climatol* 37((51)):878–896. <https://doi.org/10.1002/joc.5044>

5. Carvalho LM, Jones C, Posadas AN, Quiroz R, Bookhagen B, Liebmann B (2012) Precipitation characteristics of the South American monsoon system derived from multiple datasets. *J Clim* 25(13):4600–4620
6. Cavalcanti IFA, Silveira VP, Figueroa SN, Kubota PY, Bonatti JP, Souza DC (2020) Climate variability over South America-regional and large scale features simulated by the Brazilian Atmospheric Model (BAM-v0). *International Journal of Climatology* 40:5, 2845–2869. <https://doi.org/10.1002/joc.6370>
7. Chen CT, Knutson T (2008) On the verification and comparison of extreme rainfall indices from climate models. *J Clim* 21(7):1605–1621
8. Correia FWS, Manzi AO, Cândido LA, Santos RMND, Pauliquevis T (2007) Balanço de umidade na Amazônia e sua sensibilidade às mudanças na cobertura vegetal. *Ciência e Cultura* 59(3):39–43
9. Damião Mendes MC, Cavalcanti IFDA, Trigo RM, Mendes D, Dacamara CDC, Aragão MRDS (2009) Episódios de bloqueios no hemisfério sul: comparação entre reanálises do NCEP/NCAR e modelo HADCM3. *Revista Brasileira de Meteorologia* 24:262–275
10. Franchito SH, Brahmananda Rao V, Gan MA, Santo CME (2010) Onset and end of the rainy season and corn yields in São Paulo State. *Brazil Geofísica internacional* 49(2):69–76
11. Fu R, Li W (2004) The influence of the land surface on the transition from dry to wet season in Amazonia. *Theoretical applied climatology* 78(1):97–110
12. Gan MA, Kousky VE, Ropelewski CF (2004) The South America monsoon circulation and its relationship to rainfall over west-central Brazil. *J Clim* 17(1):47–66
13. Grell G, Devenyi D (2002) A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys Res Lett*, 29, doi:10.1029/2002GL015311
14. GARCIA SR Sistema de monção da América do Sul: início e fim da estação chuvosa e sua relação com a Zona de Convergência Intertropical do Atlântico (2010) 230 p. Tese (Doutorado em Meteorologia) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2010. Disponível em: <<http://urlib.net/8JMKD3MGP8W/36STS88>>
15. Jones C, Carvalho LM, Liebmann B (2012) Forecast skill of the South American monsoon system. *J Clim* 25(6):1883–1889
16. Kodama Y (1992) Large-scale common features of subtropical precipitation zones (the Baiu frontal zone, the SPCZ, and the SACZ) Part I: Characteristics of subtropical frontal zones. *Journal of the Meteorological Society of Japan Ser II* 70(4):813–836
17. Kousky VE (1988) Pentad outgoing longwave radiation climatology for the South American sector. *Revista Brasileira de Meteorologia* 3(1):217–231
18. Lenters JD, Cook KH (1997) On the origin of the Bolivian high and related circulation features of the South American climate. *J Atmos Sci* 54(5):656–678
19. Liebmann B, Marengo J (2001) Interannual variability of the rainy season and rainfall in the Brazilian Amazon Basin. *J Clim* 14(22):4308–4318

20. Marengo JA, Nobre CA, Seluchi ME, Cuartas A, Alves LM, Mendonado EM, ... Sampaio G (2015) A seca e a crise hídrica de 2014–2015 em São Paulo. *Revista USP*, (106), 31–44
21. Marengo JA, Liebmann B, Grimm AM, Misra V, Silva Dias PD, Cavalcanti IFA, ... & Alves LM (2012) Recent developments on the South American monsoon system. *Int J Climatol* 32(1):1–21
22. Marengo JA, Liebmann B, Kousky VE, Filizola NP, Wainer IC (2001) Onset and end of the rainy season in the Brazilian Amazon Basin. *J Clim* 14(5):833–852
23. Minuzzi RB, Sedyama GC, Barbosa EDM, Melo Júnior JC F. D (2007) Climatologia do comportamento do período chuvoso da região sudeste do Brasil. *Revista Brasileira de Meteorologia* 22:338–344
24. Nieto-Ferreira R, Rickenbach TM (2011) Regionality of monsoon onset in South America: a three-stage conceptual model. *Int J Climatol* 31(9):1309–1321
25. Pirasteh-Anosheh H, Saed-Moucheshi A, Pakniyat H, Pessarakli M (2016) Stomatal responses to drought stress. *Water stress and crop plants*, 24–40
26. Raia A, Cavalcanti IFA (2008) The life cycle of the South American monsoon system. *J Clim* 21(23):6227–6246
27. Resende NC, Miranda JH, Cooke R, Chu ML, Chou SC (2019) Impacts of regional climate change on the runoff and root water uptake in corn crops in Parana, Brazil. *Agric Water Manag* 221:556–565
28. da Silva AE, de Carvalho LMV (2007) Large-scale index for South America monsoon (LISAM). *Atmospheric Science Letters* 8(2):51–57
29. SILVA AB (2012) Influência dos fluxos de calor em superfície no início e no final da estação chuvosa sobre a região centro-oeste do Brasil. *Dissertação (Mestrado em Meteorologia)* -. Instituto Nacional de Pesquisas Espaciais, São José dos Campos
30. Vera C, Higgins W, Amador J, Ambrizzi T, Garreaud R, Gochis D, ... & Zhang C (2006) Toward a unified view of the American monsoon systems. *J Clim* 19(20):4977–5000
31. Xie P, Chen M, Yang S, Yatagai A, Hayasaka T, Fukushima Y, Liu C (2007) A gauge-based analysis of daily precipitation over East Asia. *J Hydrometeorol* 8(3):607–626
32. Wang B, Kim HJ, Kikuchi K, Kitoh A (2011) Diagnostic metrics for evaluation of annual and diurnal cycles. *Climate dynamics* 37(5):941–955
33. Wright JS, Fu R, Worden JR, Chakraborty S, Clinton NE, Risi C, ... Yin L (2017) Rainforest-initiated wet season onset over the southern Amazon. *Proceedings of the National Academy of Sciences*, 114(32), 8481–8486
34. Zhou J, Lau KM (2001) Principal modes of interannual and decadal variability of summer rainfall over South America. *International Journal of Climatology: A Journal of the Royal Meteorological Society* 21(13):1623–1644
35. Zhou J, Lau KM (1998) Does a monsoon climate exist over South America? *J Clim* 11(5):1020–1040

Tables

Table 1: Description of the datasets. The ERA5 dataset has 37 vertical levels. *The model used to obtain ERA5-Land is the ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL).

Dataset	Type	Temporal Resolution/ Coverage	Horizontal Resolution	Variables	References
ERA5	Reanalysis	Monthly/ 1981 to 2010	0.25° x 0.25° ~25 km	U and V wind component (850 hPa; 200 hPa), sea level pressure (SLP), specific humidity from 1000 to 500 hPa, soil moisture, outgoing longwave radiation (OLR), geopotential height at 500 hPa	HERSBACH et al. (2019)
ERA5-Land	H-TESSEL model	Monthly/ 1981 to 2010	0.1° x 0.1° ~9km	U and V wind component at 10m, 2m temperature, surface sensible heat flux (H), surface latent heat flux (LE)	MUÑOZ (2019)
GPCP	Rain-gauge and satellite data estimates	Monthly/ 1981 to 2010	2.5° x 2.5°	Precipitation	ADLER et al. (2003)

Table 2: Late and early rainy season onset years. In bold are the years identified in both data. The TRMM (CPC_UNI) data period was from 1998 to 2016 (1980 to 2016). In blue (red) are the years selected in this

study as late (early) rainy season onset.

TRMM			
Late Onset	Positive Points (%)	Early Onset	Negative Points (%)
2000	61.57	1998	68.78
2002	67.03	2006	67.74
2003	61.62	2009	63.32
2007	63.79		
2008	72.62		
2015	70.68		
CPC_UNI			
1980	63.15	1981	61.15
1988	61.59	1998	61.54
1994	67.40	2006	61.78
1995	61.40		
1999	63.93		
2000	66.00		
2002	66.12		
2003	64.26		
2007	71.59		
2008	78.42		
2012	77.18		
2014	70.14		
2015	66.1		

Table 3: SAMS main atmospheric patterns in each rainy season onset year.

Pattern Configuration	Rainy Season Onset Year		
	Early	Neutral	Late
SLP reduction over central SA	October (more intense)	October	November
SASH displacement to easternmost position	October	October	November (persistent and more intense due to ridge and SLP positive anomalies configuration between 40-60°S and 60-30°W in September)
Northwesterly moisture flux	More moisture transport between the Amazon basin and the Brazilian Southeast region, including the Atlantic Ocean	More moisture transport in January	Less moisture transport over SACZ's configuration area
BH and NET configuration	Starts configuring in August and is already established by October	Configures in October	Strong configuration from November to February
SACZ's precipitation band (low OLR)	Stronger configuration in February	Stronger configuration in December/January	Greater extension over the Atlantic Ocean
850hPa wind direction anomaly reversal (southeast to northwest) over central SA	October (more intense)	October	November

Figures

Figure 1

Rainy season Julian day onset climatology from RADS based on TRMM satellite data. The climatology period is from 1998 to 2016. Outlined in black is the study area selected according to rainy season onset date proximity.

Figure 2

Rainy season onset Julian day frequency time series from RADS data based on TRMM precipitation. (a) rainy season onset Julian day time series over the study area indicated in Figure 1, (b) rainy season onset

Julian day time series over the area between 10-20°S and 50-60°W. In red is shown the time series for the early onset year (2006), in yellow the neutral onset (2004) and in blue the late onset year (2008).

Figure 3

Sea level pressure anomaly (hPa) and 850hPa streamlines (m.s-1) from September to February. The SLP anomaly was obtained from ERA5 data for annual averages over the period of 1981 to 2010. (a), (b), (c), (d), (e) and (f) represents the early onset year (2006), (g), (h), (i), (j), (k) and (l) the neutral year (2004), (m), (n), (o), (p), (q) and (r) the late year (2008). Positive (negative) anomalies represents SLP increase (decrease).

Figure 4

Vertically integrated (from 1000 to 500hPa) moisture flux magnitude and vector anomaly (kg.m-1.s-1) from September to February. The vertically integrated moisture flux magnitude and vector anomaly was obtained from annual averages of ERA5 data over the period from 1981 to 2010. (a), (b), (c), (d), (e) and

(f) represents the early onset year (2006), (g), (h), (i), (j), (k) and (l) the neutral year (2004), (m), (n), (o), (p), (q) and (r) the late year (2008). Positive (negative) anomalies represent vertically integrated moisture flux increase (decrease).

Figure 5

Outgoing longwave radiation anomaly (W.m^{-2}) and 200hPa streamlines (m.s^{-1}) from September to February. The outgoing longwave radiation anomaly was obtained from annual averages of ERA5 data over the period from 1981 to 2010. (a), (b), (c), (d), (e) and (f) represents the early onset year (2006), (g), (h), (i), (j), (k) and (l) the neutral year (2004), (m), (n), (o), (p), (q) and (r) the late year (2008). Positive (negative) anomalies represents reduction (increase) cold top clouds.

Figure 6

Precipitation (mm) and wind vector at 850hPa (m.s^{-1}) anomalies from September to February. Precipitation and wind anomalies at 850hPa were obtained from GPCP and ERA5 data, respectively, from

1981 to 2010. (a), (b), (c), (d), (e) and (f) represents the early onset year (2006), (g), (h), (i), (j), (k) and (l) the neutral year (2004), (m), (n), (o), (p), (q) and (r) the late year (2008). Positive (negative) anomalies represent precipitation increase (decrease).

Figure 7

Atmospheric pattern diagram for early and late rainy season onset years.

Figure 8

Sea level pressure (hPa) and 850hPa wind vector (m.s-1) composite from July to October. The SLP and 850hPa wind anomalies composites were obtained from the ERA5 data. The early, neutral and late onset years were: 1998, 2006 and 2009; 2001, 2004 and 2005; 2000, 2007 and 2008, respectively.

Figure 9

Comparison of SLP anomaly (hPa) and 850hPa streamline (m.s-1) and the atmospheric blocking episodes' number in September. The colored lines express the number of blocking episodes identified over the marked area.

Figure 10

Sensible heat flux anomaly (W.m^{-2}) and streamlines at 10 meters (m.s^{-1}) from September to February. The sensible heat flux anomaly was obtained from ERA5-Land data, from 1981 to 2010. (a), (b), (c), (d), (e) and (f) represents the early onset year (2006), (g), (h), (i), (j), (k) and (l) the neutral year (2004), (m), (n), (o), (p), (q) and (r) the late year (2008). Positive (negative) anomalies represents an H increase (decrease).

Figure 11

LE anomaly (W.m^{-2}) and streamlines at 10 meters (m.s^{-1}) from September to February. The latent heat flux anomaly was obtained from ERA5-Land data, from 1981 to 2010. (a), (b), (c), (d), (e) and (f)

represents the early onset year (2006), (g), (h), (i), (j), (k) and (l) the neutral year (2004), (m), (n), (o), (p), (q) and (r) the late year (2008). Positive (negative) anomalies represents an LE increase (decrease).

Figure 12

Difference between early and late onset years for temperature at 2m ($^{\circ}\text{C}$), soil water content, sensible heat flux (W.m^{-2}) and latent heat flux (W.m^{-2}) anomalies in SON and DJF. Temperature at 2m, latent and sensible heat fluxes anomalies were from ERA5-Land data, soil water content anomalies from ERA5 data, over the period from 1981 to 2010.

Figure 13

Rainy season surface pattern scheme for early and late onset years.

Figure 14

Water budget components (mm.day⁻¹) calculated over the area between 10-20°S and 50-60°W. ERA5 and GPCP data were used to calculate the water budget components.