Surface and atmospheric patterns for early and late rainy season onset years in South America

Isabella L. Talamoni1 · Iracema F. A. Cavalcanti3 · Paulo Y. Kubota1 · Dayana C. de Souza1 · Jessica C. A. Baker2 · Rita M. S. P. Vieira3

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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 analyze the atmospheric and surface patterns associated with early, neutral, and late rainy season onset in tropical regions of SA. The following years represented each rainy season onset: 1998, 2006, 2009 (early), 2001, 2004, 2005 (neutral), 2000, 2007, 2008 (late). The early (late) onset were negative (positive) rainy season onset date anomalies in comparison to the climatological mean (1998–2016) over central SA. Distinct atmospheric conditions were identified in the early and late rainy season onset. In the early onset, the northwesterly moisture flux and moisture advection were higher than average over central-east SA, where the precipitation increased. In the late onset, precipitation was enhanced in northwest SA and the configuration of multiple atmospheric blocking episodes contributed to delay the rainy season onset. Surface conditions also contributed to both the early/late rainy season onset. In the early onset, wetter and cooler pre-onset conditions over the central-east SA were verified. In the late onset, surface conditions were dry and warm before onset. Even though the atmospheric instability was promoted by the increase in sensible heating, dry atmospheric conditions were not favorable to deep convection, thus delaying the onset. These findings highlight how the onset variability promotes different atmospheric and surface patterns in SA. The results will contribute to the development of weather and climate models to better represent the rainy season onset focusing on biosphere–atmosphere processes improvements.

Keywords Rainy season onset · Biosphere–atmosphere · South America · Precipitation · Surface heating fluxes

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 and a rainy season every year (Zhou and 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 and Lau 1998; Marengo et al. 2012), involves the circulation associated with the following structures: Bolivian High, Upper Level South Atlantic 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 pentad precipitation from the 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. The second stage gradually extends to the 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 slow migration of the Intertropical Convergence Zone (ITCZ) 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 the rainy season onset can cause crops losses (Resende et al. 2019), energy generation deficiencies and water rationing (Marengo et al. 2015).

Several studies were developed to understand the SAMS patterns (Gan et al. 2004; Vera et al. 2006; Raia and Cavalcanti 2008) and its representation in weather and climate numerical models (Jones et al. 2012; Cavalcanti and 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 and Marengo 2001; Marengo et al. 2001), the Sea Surface Temperature (SST) of the South Atlantic Ocean 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 the atmosphere and land surface processes during the rainy season onset (Fu and Li 2004; Collini et al. 2008; Marengo et al. 2012; Bombardi et al. 2019). Surface processes are increasingly being recognized as influencing the rainy season onset (Fu and Li 2004; Wright et al. 2017), and land surface processes are themselves directly affected by rainy season onset date variations. 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 favorable to convection (Fu and 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 rainy season onset date variation affects the surface processes, modulating the energy fluxes and the biogeochemical cycles (carbon, water). Therefore, the objective of this study was to determine and analyze the atmospheric and surface patterns associated with selected early, neutral, and late rainy season onset in SA.

2 Data

2.1 Rainy and Dry Season (RADS)

RADS is a global dataset of the rainy season onset Julian day. This dataset uses the LM01 method (Liebmann and 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 and 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 × 0.25° longitude, with spatial coverage between 50° S and 50° N, from 1999 to 2016. The CPC_UNI dataset, on the other hand, has a spatial resolution of 0.5° latitude × 0.5° longitude, for the period from 1979 to 2018. RADS rainy season onset data was used to select the early, neutral, and late years.

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 analysis over land (see Table 1 for references and further information). GPCP precipitation data was used because it is an observational data and it is very similar to the precipitation climatology pattern of ERA5 (Fig. S4 a, b). There are positive and negative differences over South America (Fig. S4c), but the correlations between the two datasets are positive, presenting a global mean correlation of 0.66 (shown at upper left in S4 d) and 0.68 in the water budget analysis area (10°–20° S and 50°–60° W).

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

Figure 1 shows the RADS Julian day onset climatology (1998–2016) over SA. The rainy season onset over central SA (larger area 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 early and late rainy season onset years, onset date anomalies were calculated for each year available in RADS using data from CPC_UNI and TRMM over the SA area outlined in black in Fig. 1. The percentage of grid points within the study area in which the rainy season onset occurred early (negative anomalies) and late (positive anomalies) was obtained by an algorithm. The early (late) onset years were selected from those whose percentage of negative (positive) grid points within the study area was greater than 60%. The neutral rainy season onset years were determined by the nearly 50% of positive/negative points.

To ensure that the year selection method was consistent, the results obtained with TRMM and CPC_UNI datasets were compared and are presented in Table 2. There were fewer years with early onset. The majority of years were identified in both TRMM and CPC_UNI datasets. All of the late onset years identified by TRMM were also identified by CPC_UNI (2002, 2003, 2007, 2008, 2015). There were three years identified as late onset in the CPC_UNI data (1999, 2012, 2014), after the start of the TRMM data. Therefore, the identification methodology used in the RADS database (Bombardi et al. 2019) was consistent between the TRMM and CPC_UNI databases. In this study, we selected years that were indicated as either early (1998, 2006, 2009), late (2000, 2007, 2008), or neutral (2001, 2004, 2005) onset. These years were selected considering the percentage of negative/positive points (Table 2). The 3 years for each early, neutral, and late rainy season onset criteria considered the

Table 1 Data description

| Dataset     | Type                          | Temporal resolution/coverage | Horizontal resolution | Variables                                                                 | References          |
|--------------|-------------------------------|-----------------------------|-----------------------|---------------------------------------------------------------------------|---------------------|
| ERA5         | Reanalysis                    | Monthly/1981–2010           | 0.25° × 0.25° ~ 25 km | U and V wind component (850 hPa; 200 hPa), sea level pressure (SLP),      | Hersbach et al. (2019) |
|              |                               |                             |                       | specific humidity from 1000 to 500 hPa, soil moisture, outgoing longwave   |                     |
|              |                               |                             |                       | radiation (OLR), geopotential height at 500 hPa, water soil content       |                     |
|              |                               |                             |                       | (first 100 cm), Sea Surface Temperature (SST)                              |                     |
| ERA5-Land    | H-TESSEL model                | Monthly/1981–2010           | 0.1° × 0.1° ~ 9 km    | U and V wind component at 10 m, 2 m temperature, surface sensible heat     | Muñoz (2019)        |
|              |                               |                             |                       | flux (H), surface latent heat flux (LE)                                    |                     |
| GPCP         | Rain-gauge and satellite data  | Monthly/1981–2010           | 2.5° × 2.5°           | Precipitation                                                             | Adler et al. (2003) |

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)
maximum number of years available for the early onset. The 1981 year of early onset was not considered because it was not available in ERA5, ERA5-Land, and GPCP data. The neutral years were those considered when the positive and negative grid points percentage was nearly 50% not shown in Table 2. Besides, the years 2001, 2004, and 2005 were selected as neutral onset due to its proximity to the majority of years selected as the early and late onset.

For each early, neutral, and late onset, 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 shows the rainy season onset Julian day smoothed frequency series over the area between 10°–20° S and 50°–60° W. According to Wang et al. (2011), this area is within the monsoon precipitation index domain. The red series represents the early onset year, where two frequency peaks between 15 and 30 September were verified. In the red series, the most common onset date was Julian day 270 (end of September), therefore, before the neutral onset represent by the yellow series, Julian day 283 (mid-October). Over this area, the frequency peaks in the late onset (blue series) were verified between late October and early November (Julian day 292).

Therefore, based on the date frequency series analysis, we verified that the early, neutral and late rainy season onset selected years were consistent, and also determined that the period between September and December, is the 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 onset.

### 3.1 Atmospheric and surface patterns analysis

After selecting the early, neutral, and late onset years, monthly precipitation anomalies from September to February were analyzed. The anomalies were obtained from the difference between the i-th monthly value and the annual climatological average (Eq. 1), from 1981 to 2010, using 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 depends on the precipitation annual cycle. This cycle experiences a maximum and a minimum peak during the year, and using the annual climatology ensures the maintenance of both winter and summer solstices signal. Equation (1) shows how the anomaly was obtained using the annual climatology:

\[
\text{Anomaly} = \bar{X} - \left( \frac{1}{y_f} \sum_{y=1}^{y_f} \left( \frac{1}{12} \sum_{m=1}^{12} \frac{X}{Y} \right) \right)
\]

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

### Table 2 Late and early rainy season onset years

| Late onset | Positive points (%) | Early onset | Negative points (%) |
|------------|---------------------|-------------|---------------------|
| TRMM       |                     |             |                     |
| 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                |             |                     |

In bold are the years identified in both data. The TRMM (CPC_UNI) data period was from 1998 to 2016 (1980–2016). In italics (bold italics) are the years selected in this study as late (early) rainy season onset.
Composites of each category (early, neutral and late years) were calculated using the monthly anomalies from the annual mean. The composite analysis is an effective tool to identify climate patterns of specific events, e.g., ENSO (Boschat et al. 2016). The statistical significance at a 95% confidence level was obtained by applying a one-sample t-test (Von Storch and Zwiers 2002). Raia and Cavalcanti (2008) also applied the significance test on composites anomaly for normal onset.

### 3.2 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 500 hPa 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 Eqs. (2) and (3), respectively.

\[
GHGS = Z(\lambda, \phi) - Z(\lambda, \phi_{01})
\]

\[
GHGN = Z(\lambda, \phi_{02}) - Z(\lambda, \phi_{01})
\]

\[
\begin{align*}
\phi_{01} &= 65^\circ S + \Delta \\
\phi_{02} &= 50^\circ S + \Delta \\
\phi_N &= 40^\circ S + \Delta \\
\phi_S &= 55^\circ S + \Delta 
\end{align*}
\]

In Eqs. (2) and (3), \(Z(\lambda, \phi)\) is the geopotential height at 500 hPa, \(\lambda\) is the longitude, \(\phi\) is the latitude and \(\Delta\) is a latitudinal counter that can assume the following values: \(-10^\circ, -7.5^\circ, -5^\circ, -2.5^\circ\) and \(0^\circ\). A given longitude \(\lambda\) was considered as an atmospheric blocking episode configuration when the GHGS and GHGN indices satisfied at least one value of \(\Delta\) with the following conditions: (GHGN > 0.0) and (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. There is not a minimum duration threshold for blocking episodes that is globally accepted (Trigo et al. 2004). Although the majority of studies adopt a 5 days threshold, Oliveira (2011) verified that a three days threshold was more appropriate to the Southern Hemisphere (SH). The SH blocking duration is reduced due to stronger westerly winds in the mid and high troposphere that accelerate the circulation in the SH compared to the Northern Hemisphere (Oliveira 2014).

### 3.3 Surface water budget analysis

The surface water budget was evaluated over the area that is within the monsoon precipitation domain, according to Wang et al. (2011), between 10°–20° S and 50°–60° W. We don’t expect groundwater storage to have varied considerably between the onset 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 vapor transport from (or to) other regions (Eq. 4).

\[
\text{WaterBudget} = (\text{Advection}) + (\text{Precipitation} - \text{Evapotranspiration} + \text{Runoff})
\] (4)

the following variables: \(u\) and \(v\) wind components, specific humidity, latent heat flux and runoff from ERA5 were used for this analysis, while precipitation was from GPCP data.

### 4 Results

#### 4.1 Atmospheric patterns

In all early, neutral and late composites, an anticyclonic circulation at 850 hPa, characteristic of the South Atlantic Subtropical High (SASH; Vera et al. 2006; Raia and Cavalcanti 2008; Marengo et al. 2012) was observed in its most westerly position in September (Fig. 3a, g, m). As the rainy-season onset approached, the SASH moved away from the SA coast. The rainy season onset was verified by the pressure reduction in the SA continent, especially over the Chaco region (between east Paraguay and north Argentina) in October of the early onset (Fig. 3b). In the early onset composite, the SASH was weaker compared to both neutral and late onsets during September and October (Fig. 3a, b, g, h, m, n). On the other hand, in the late onset, positive SLP anomalies were observed since July (not shown), configuring a stronger SASH, especially in September (Fig. 3m). Furthermore, in September of the late onset, between 40°–60° S and 60° W, statistically significant positive SLP anomalies with a magnitude of up to 12 hPa were observed (Fig. 3m). Positive geopotential at 500 hPa anomalies was also verified over this area (see Supplementary Material Fig. S1). It is suggested that this configuration was responsible for the late rainy season onset, which occurred only in November when the continent pressure reduction was verified (Fig. 3o). Furthermore, this result suggests 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 advance of frontal systems, thus, delaying the onset by enhancing atmospheric stability.

From November to February (Fig. 3c–f) of the early onset, significant negative SLP anomalies were concentrated in the central and southern areas of SA, while in the neutral and late onset, significant negative anomalies were verified throughout the SA in November and December (Fig. 3i, j, o, p). In January and February, significant negative anomalies were concentrated over the southeast of SA (Fig. 3e, f, k, l, q, r).

In September of the early onset (Fig. 4a), statistically significant positive moisture flux magnitude anomalies were observed over the eastern Andes, where vector magnitudes

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Fig. 3 Sea level pressure anomaly (hPa) and 850 hPa streamlines (m s⁻¹) composite from September to February. The SLP anomaly was obtained from ERA5 data for annual averages for 1981 to 2010. a–f Represents the early onset, g–l the neutral, m–r the late onset. Positive (negative) anomalies represent SLP increase (decrease). Hatching indicates statistical significance at 95% confidence level.

Fig. 4 Vertically integrated (from 1000 to 500 hPa) moisture flux magnitude and vector anomaly composite (10⁻⁵ 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–f Represents the early onset, g–l the neutral, m–r the late onset. Positive (negative) anomalies represent moisture flux increase (decrease). Hatching indicates statistical significance at a 95% confidence level.
indicate that the northwesterly moisture flux was enhanced. This northwesterly flux was maintained from December to February of the early onset (Fig. 4d–f), and in December (Fig. 4d) the positive moisture flux magnitude anomalies extended from the Amazon Basin towards the Southeast region of Brazil and the Atlantic Ocean, associated with the configuration of SACZ (Kodama 1992).

In September of the late onset (Fig. 4m), negative moisture flux magnitude anomalies between 40°–60° S and 60° W–0° were observed where positive SLP anomalies were also verified (Fig. 3m). The SLP increase associated with moisture flux reduction over this area may contribute to either reducing cold fronts advance or its intensity decrease, delaying the rainy season onset. In November of the late onset (Fig. 4o), negative moisture flux magnitude anomalies were observed over the Amazon basin and east of the Andes (between Peru and Paraguay). A narrow and weaker northwesterly moisture flux was also verified, indicating a moisture transport reduction from the Amazon basin to the central and southwestern region of SA in the late onset (Fig. 4o). The statistically significant weaker moisture transport over the SACZ region in the late onset suggested that it may have contributed to rainfall reduction, in comparison to the other study years. In summary, there was a continuous increase in the moisture flux over SA from September to January of the early onset (Fig. 4a–f) and a weaker pattern in the late onset (Fig. 4m–r).

From the OLR anomaly composite analysis accompanied by the 200 hPa streamlines (Fig. 5), November to February was characterized by the persistence of statistically significant negative OLR anomalies over central SA, associated with cloud vertical development, consistent with the rainy season (Fig. 5c–r; Kousky 1988; Garcia 2010). Besides, in October of the early onset, significant negative OLR negative anomalies were verified in central-east SA, centered in 15° S and 50° W, indicating the presence of convective clouds (Fig. 5b). In the 200 hPa streamlines, the configuration of an anticyclone, known as Bolivian High (BH; Lenters and Cook 1997) and of a trough eastward of the BH, known as Northeast Trough (NET, Lenters and Cook 1997) was observed. This upper tropospheric level circulation pattern is important to determine the positioning of SACZ (Kodama 1992). In the early onset, BH and NET started to configure in August, and in October, the two systems were already configured compared to the late onset (Fig. 5b). In the late and early onset, negative OLR anomalies accompanied by anticyclonic circulation at 200 hPa were verified over the central, southeast, and northern SA during the summer months (Fig. 5d–f, p–r).

During the rainy season, positive precipitation anomalies were concentrated over central-east SA, in October of the early (Fig. 6b) and neutral composites (Fig. 6h) and only in November of the late composite (Fig. 6n). The low-level wind reversal (850 hPa), observed when the annual average was removed (Zhou and Lau 1998), is a rainy season onset feature. Thus, from July to September, the wind vector anomaly was mainly from the southeast over central-east SA, stronger in the late composite (Fig. 6a, g, m). From October (November) the wind anomaly became mainly from the northwest in the early and neutral (late) onset (Fig. 6b, h, o).
From the OLR (Fig. 5) and precipitation (Fig. 6) composite analysis, it was possible to identify the SA rainy season onset conceptual model, developed by Nieto-Ferreira and Rickenbach (2011). In this model, the rainy season onset first stage occurs when precipitation persists over the northwest region of SA and gradually extends to the southeast (October 18–22, Fig. 6c, i, o). The second stage is characterized by the configuration of SACZ (October 28–November 1, Figs. 5 and 6d, j, p). The third stage involves the monsoon arrival in 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, larger statistically significant positive precipitation anomalies were observed between the southeast of the Amazon Basin and the southeast region of Brazil, where the SACZ pattern was identified from November to January (Fig. 6c–e). In February (Fig. 6f), positive anomalies were concentrated over the central and eastern portion of SA including the Northeast and North regions of Brazil, being the third stage rainy season onset area where the positive precipitation anomalies were connected with positive precipitation anomalies in the tropical Atlantic associated with the ITCZ. The size of the wind vector anomalies at 850 hPa was obtained from GPCP and ERA5 data, respectively, from 1981 to 2010. a–f represents the early onset, g–l the neutral, m–r the late onset. Hatching indicates statistical significance at a 95% confidence level. Positive (negative) anomalies represent precipitation increase (decrease).

![Fig. 6](image)

**Fig. 6** Precipitation (mm) and wind vector at 850 hPa (m s\(^{-1}\)) anomalies composite from September to February. Precipitation and wind anomalies at 850 hPa were obtained from GPCP and ERA5 data, respectively, from 1981 to 2010. a–f represents the early onset, g–l the neutral, m–r the late onset. Hatching indicates statistical significance at a 95% confidence level. Positive (negative) anomalies represent precipitation increase (decrease).
850 hPa wind in the early onset was verified especially over central SA, contributing to the precipitation pattern. Positive (negative) precipitation differences were verified over central-east (northwest) of SA in SON, indicating that more precipitation occurred in this area in the early (late) onset. A similar pattern was verified in DJF, where more precipitation was verified over the northwest and extending to the ITCZ in the late onset, while more precipitation was verified over southeast SA in the early onset. A scheme of the main atmospheric pattern associated with the early and late onset is shown in Fig. 8. In the early onset, a stronger SLP reduction was observed over central SA (blue area), where the northwesterly moisture flux was also stronger (red arrow), enhancing the precipitation and the SACZ configuration. In addition, the SASH was weaker compared to the late onset, suggesting that the advance of cold fronts over the SA east coast was favored. Stronger negative geopotential anomalies at 500 hPa were also verified over south SA in the early onset, reinforcing the configuration of stronger frontal systems (see Supplementary Material Fig. S1). Besides, it may also contribute to the organization of the cloudiness band (SACZ) thus contributing to the early rainy season onset. A similar pattern was observed by Raia and Cavalcanti (2008) in the early rainy season onset, with the advance of a strong frontal system that contributed to both soil and atmospheric moisture increase. In addition, the northwesterly flux was also more intense while the SASH configuration and the east flux towards the continent was weaker, in the early onset. In the late onset, precipitation was enhanced over northwest SA, and the SACZ was positioned further north compared to the early onset. 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. In the late onset, Raia and Cavalcanti (2008) verified higher SLP 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 necessary condition.

4.2 Atmospheric blocking episodes

In September of the late onset, positive SLP anomalies were verified over the area between 40°–60° S and 90°–30° W, (Fig. 3m) that could indicate blocking occurrences. Therefore, the atmospheric blocking episodes’ identification methodology applied by Damião et al. (2009) was used to verify blocking events during the analyzed period. In the early onset, although more blocking episodes were identified (compared to late onset) they occurred between latitudes of 40°–70° S and longitudes of 115°–130° W, in the Pacific Ocean (Fig. 9a). Blocking episodes were not identified in the neutral onset. Finally, in the late onset up to three atmospheric blocking episodes between 40° and 70° S were identified over the Pacific at longitudes of 80° W and 70° W (near SA west coast) Therefore, the analysis identifying blocking episodes allowed us to verify that blocking episodes in the late onset was closer to the SA west coast. The influence of blocking events on the displacement of synoptic systems, as cold fronts, over South America was discussed in several studies, such as Mendes et al. (2008), Mendes et al. (2012), Mendes and Cavalcanti (2014), Rodrigues and Woolings (2017) and Silva and Dottori (2021).
During the transition season, there were negative SST anomalies in the equatorial Pacific extending to the west, in the late onset than in the early or neutral onset, that remained up to the summer season (see Supplementary Material Fig. S2). The late onset years were characterized as La Niña years (see Supplementary Material Table S3). In Canonical La Niña events, there are negative precipitation anomalies in central and south Brazil in SON (Tedeschi et al. 2013), which indicate the reduction of synoptic systems affecting the area and less moisture flux from the Amazon region. Negative precipitation anomalies in DJF were obtained by Grimm (2004) over the monsoon region in La Niña events. Then, the Equatorial Pacific SST anomalies could have contributed to the delay of the rainy season onset. It is also observed the weakening of the tropical Atlantic SST gradient in the late onset during spring. The Tropical South Atlantic presented low SST, and the tropical North Atlantic had fewer warm waters than the early and neutral onset. This pattern could enhance the trade winds from the south to the north, affecting the northeasterly flow directed to the continent, which is a normal feature of the rainy season onset (Raia and Cavalcanti 2008).

### 4.4 Surface patterns

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

In the late onset, positive H anomalies were observed in September and October (November) concentrated over central-east (north Northeast) SA, indicating a warmer condition before the onset (Fig. 10m–o). By promoting the atmospheric instability, this condition favors convection, however, the reduced moisture flux (Fig. 4m–o) limited the convective process. In December, significant negative H anomalies were present over central-east SA (Fig. 10p), a pattern that appeared only in February of the early and neutral onset (Fig. 10f, l). It is suggested that the atmospheric cooling in December of the late onset, has suppressed convection, by promoting a more stable atmospheric condition (warming reduction).

In September, statistically significant positive latent heat flux (LE) anomalies were observed in northwest SA, in the early, neutral, and late onset (Fig. 11a, g, m). These positive anomalies were associated with the first stage of the rainy season onset, involving either the precipitation or moisture flux increase over northwest Amazon. Also in September,
negative LE anomalies were observed, mainly over central-east SA, associated with warming before onset, and the H increase, which was important to the atmospheric instability in this area, as verified in the H analysis (Fig. 11a, g, m). From October to November, 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 configuration of SACZ (Fig. 11b, c, i, n, o). In December and January, the magnitude of significant positive LE anomalies began to decrease throughout SA, mainly in the late onset (Fig. 11p, q). It means that in the late onset 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 composites between the studied onsets were smaller compared to the differences in H. It means, that LE contribution to each onset was smaller than the contribution of H.

Fig. 11 LE anomaly (W m\(^{-2}\)) and streamlines at 10 m (m s\(^{-1}\)) composite from September to February. The latent heat flux anomaly was obtained from ERA5-Land data, from 1981 to 2010. a-f Represents the early onset, g-l the neutral, m-r the late onset. Hatching indicates statistical significance at a 95% confidence level. Positive (negative) anomalies represent an LE increase (decrease).

Fig. 12 Difference between early and late onset years for the temperature at 2 m (°C), soil water content, sensible heat flux (W m\(^{-2}\)), and latent heat flux (W m\(^{-2}\)) anomalies in SON and DJF. Temperature at 2 m, 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 12 shows the differences in 2 m temperature (Fig. 12a, e), first 100 cm soil water (Fig. 12b, f), H (Fig. 12c, g), and LE (Fig. 12d, h) anomalies between the early and late onsets for SON and DJF. In SON, negative temperature differences were observed mainly in the central-east of SA, indicating that the temperature of the late onset was greater than that of the early onset. This temperature increase in the late onset was also verified by negative H differences that reached values of up to 30 W m\(^{-2}\) over central-east and south of SA (Fig. 12c, g). Regarding the soil water content in SON, the differences indicate that the water content in central-east Brazil (northwest SA) was greater in the early (late) onset compared to the late (early) onset (Fig. 12b). This pattern was also observed concerning LE, where positive differences were observed over central-east SA in SON (Fig. 12d). In DJF, the temperature in the late onset composite was higher compared to the early composite in parts of the central and south regions of SA (Fig. 12e). In this area, in the late onset composite, an increase (decrease) in H (soil water and LE) was verified (Fig. 12f, g, h). This increase is characteristic of the rainy season during the austral summer, in which more energy is available at the surface to surface heating 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 and temperature over each indicated area.

The analysis of water budget components allowed us to verify each 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 composites, while the other water budget components’ contribution was secondary. Greater moisture advection was verified in December and January. It suggests that the rainy season has a strong link with the northwesterly flux, as it was verified a stronger northwesterly flux along with more precipitation and a greater water budget in the early onset (Fig. 7). The suggestion that moisture advection can modulate the rainy season onset is reinforced by Fig. 14b, where in the early (late) onset, the moisture advection was greater in September (October) which coincides with the respective rainy season onset.

In the precipitation component analysis (Fig. 14c), between July and September, low rainfall was verified in the dry season. It is noteworthy that in September of the early onset, precipitation was greater than the other two onsets, suggesting that this higher moisture condition may be associated with frontal systems advance, which favored the early onset (Raia and Cavalcanti 2008). From October to February, precipitation increased in the three onset composites, more precipitation in the early onset was observed in comparison to the late onset, except in November. For the evapotranspiration component (Fig. 14d) it was observed that the differences between the onset composites were subtler, and the evapotranspiration increase from October onwards was due to the rainy season precipitation increase. Finally, the runoff component (Fig. 14e) was dependent on the precipitation increase. The gradual increase in precipitation from spring (SON) to summer (DJF) resulted in a runoff increase in the three composites, but the higher precipitation in September of the early composite produced the highest runoff in October.

Fig. 13 Rainy season surface pattern scheme for early and late onset composites
5 Conclusions

This study aimed to determine the main atmospheric and surface patterns associated with each early, neutral and late rainy season onset over SA. 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. Delays in the rainy season onset, for example, can cause crops losses, energy generation deficiencies, and water rationing. The early (1998, 2006, 2009), neutral (2001, 2004, 2005), and late (2000, 2007, 2008) onset years were obtained further on RADS onset date. To highlight the differences between early and late onset, composite analyses of atmospheric (SLP, vertically integrated moisture flux, OLR, precipitation, 850 and 200 hPa wind) and surface (2 m temperature, LE, H, and water soil content) variables were obtained.

Distinct atmospheric conditions were identified in the early, neutral, and late rainy season onset composites. The early onset composite was characterized by SLP reduction, particularly over central-east SA, where the northwesterly moisture flux was stronger, promoting precipitation...
and the SACZ configuration. The moisture advection was the most important component of the water budget: in the early onset composite, the moisture advection was enhanced compared to the neutral and late composites, 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. Besides, more than one episode of atmospheric blocking between 40° and 70° S was identified over the Pacific at longitudes of 80° W and 70° W (near SA west coast), suppressed the advance of cold fronts and consequently, contributed to delay the rainy season onset over central-east SA. The late onset years occurred in La Niña years, which could be another contributing feature. 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 composite, corresponding to the precipitation increase in the same area.

In addition, the study allowed us to verify that surface conditions also contributed to the early/late rainy season onset. By analyzing the surface heating fluxes, it was found that H contributed more to the differences between early and late onset compared to LE. In the early onset composite, wetter (more LE and greater water budget) and cooler (lower H) conditions were obtained 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 to maintain the atmospheric instability and consequently to develop the convective processes in the early onset. In the late onset, the atmospheric condition was dry (less LE and less water budget) and warm (more H) before the onset. Although the atmospheric instability was promoted by the H increase, the reduced moisture condition did not favor convection. In December, right after the onset of the late composite (November), the atmosphere cooled over central-east SA, which is also an indication that convection was not favored over this area. However, H and LE increased in northwest SA where precipitation was concentrated in the late onset. To conclude, while it is already known that much of SAMS and the rainy season onset are influenced by large-scale phenomena variability (Zhou and Lau 2001; Marengo et al. 2012), the results of this work show that local phenomena and land-surface conditions also have an important role on rainy season onset in SA. As the monsoon onset forecasts are important for the management of several sectors, the biosphere–atmosphere processes improvements in numerical models can contribute to a better representation of the associated features.

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Data Availability The following datasets analyzed during the current study are available in: RAD5, ERA5, ERA5-Land and GPCP.

Declaration

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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