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The nature of the rainfall onset over central South America

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RESUMEN

El principal objetivo de este trabajo es describir detalladamente el comienzo del Monzón Sudamericano utilizando datos de precipitación disponibles en la zona tropical y subtropical de Sudamérica. El análisis fue comparado con el realizado utilizando datos de radiación saliente de onda larga (OLR), con el fin de evaluar la eficiencia de los datos de lluvia para detectar los principales patrones de la evolución del monzón durante la primavera austral. Los resultados muestran que tanto la OLR como la precipitación describen bien el desplazamiento de la convección desde el noroeste hacia el sudeste en el centro de Brasil a principios de octubre. La comparación de diferentes metodologías para establecer fechas de comienzo de la estación lluviosa muestran que el método de Kousky (1988), basado en la evolución de OLR, indica el comienzo del monzón en casi toda Sudamérica sin necesitar adaptación para cada región, tal como ocurre con los métodos basados en la precipitación. Los campos medios muestran que la lluvia en Brasil central comienza y se incrementa moderadamente, manteniéndose con valores menores a los observados en el noroeste y sudeste de la región tropical. Posteriormente, un abrupto cambio en la magnitud de la precipitación tiene lugar, en promedio tres péntadas después del inicio de la estación lluviosa, en Brasil central aunque similares cambios se observan en toda la región tropical. Se sugiere que la actividad de los transientes, que ocurre en el comienzo de la estación de lluvia cuando la inestabilidad aumenta y se aproximan las condiciones de verano, es uno de los factores que inciden en el desarrollo de este cambio abrupto en la precipitación. La caracterización de los incrementos en la lluvia provee información complementaria que puede ser utilizada adicionalmente a la fecha de inicio de la misma.

ABSTRACT

The objective of this work is to provide a detailed description of the onset of the South American Monsoon based on precipitation observations available over tropical and subtropical South America. The analysis was also performed using outgoing longwave radiation (OLR) data in order to assess the ability of this particular dataset to reproduce the main features associated with precipitation evolution during austral spring. Results show that both OLR and precipitation data agree in describing the progression of convection from the northwest and southeast into central Brazil by the beginning of October. Moreover the assessment of available methods to identify onset dates shows that the method of Kousky (1988), based on the OLR evolution, provides the onset date in most of South America, without regionally adaptation, as the methods based on rainfall generally require. Composite fields show that rainfall in central Brazil begins with moderate rates, which are still lower than those observed over the northwestern and southeastern tropical regions. After the rainfall jump, that on average occurs three pentads later than the onset of rainfall, precipitation rates increase over central Brazil and similar rates are observed over the entire tropical region. It is suggested that transient activity, which occurs around the onset period when the atmospheric mean conditions are getting more unstable as they approach summer-like conditions, is the one that imprints a rainfall-jump feature in the precipitation evolution. The character of changes in the precipitation rate, as the rainy season develops, provides complementary information that can be used together with onset date.

Keywords: Tropical climate, onset, summer monsoon, South America, rainfall.

1. Introduction

The annual cycles of precipitation and atmospheric circulation over tropical South America have characteristics of a monsoon (e.g., Zhou and Lau 1998; Gan *et al.,* 2004). However, the South American Monsoon System (SAMS) exhibits somewhat less distinct features compared to the Southeast Asian monsoon, which appears to be related to weaker seasonal temperature differences over South America (Vera *et al.,* 2005). SAMS and its counterpart in the Northern Hemisphere (known as the North American Monsoon System, NAMS) can be considered as extremes of the same cycle that exhibits a seasonal regularity and degree of symmetry with respect to the equator (Horel *et al.,* 1989).

Portions of the SAMS region experience distinct wet and dry seasons, with many areas receiving more than 50% of the annual precipitation during the austral summer (Figueroa and Nobre, 1990). In early austral spring, precipitation shifts southward from Central America and northwestern South America to the western Amazon, subsequently spreading eastward and southeastward to include central and southeastern Brazil by mid-spring (Kousky, 1988; Marengo *et al*., 2001; Gan *et al.,* 2004). The onset of the wet season in central and southeastern Brazil typically occurs between the end of September and early October when deep convection covers most of central South America from the equator to 20 °S, but is absent over the eastern Amazon basin and northeast Brazil (Sugahara,1991; Gonzalez and Barros, 1998, 2002). Intraseasonal oscillations may promote rapid onset over central Brazil (Vera and Nobre, 1999), although the mechanisms are still not clear.

The timing of the rainy season in tropical South America is of relevance to many economic activities in the region, such as agriculture and hydroelectric energy generation. However, a lack of a dense coverage of daily precipitation observations with long records has limited to some extent the progress in the prediction of SAMS onset dates. Outgoing longwave radiation (OLR) has been used to describe the convection evolution and to determine rainy season onset dates (Kousky, 1988). Marengo *et al.* (2001), Liebmann and Marengo (2001), and Gan *et al.* (2004) are the only authors that, to our knowledge, have used precipitation data to provide objective onset date criteria over the Amazon region.

Recently, a large number of daily precipitation in-situ data derived from a diversity of regional and national institutions is available that allows a more detailed study of the evolution of precipitation over tropical South America. The most relevant example is Tropical Rainfall Measuring Mission (TRMM), a joint project between National Aeronautic and Space Administration (NASA) and the Japan Aerospace Exploration Agency designed to monitor and study tropical rainfall. Therefore, the objective of this paper is to provide a detailed analysis of the SAMS wet season onset based on that precipitation data set in order to better understand the nature of the evolution of the wet season over tropical South America. The paper is organized as follows. Data and methodology are discussed in section 2, including a discussion of currently available onset date methodologies for SAMS. Pentad climatology of precipitation and OLR during austral spring is presented in section 3, while in section 4 the climatology of SAMS onset date is discussed. The nature of the evolution of rainfall in central Brazil during austral spring is discussed in section 5, and conclusions are presented in section 6.

2. Data and methodology

Historical daily rainfall data for the period 1976 to 1998, from stations in South America were used. Liebmann and Allured (2005) provide a detailed description of the database as well as of derived $1 \times 1°$ gridded fields that are also used in the paper to show the spatial distribution of precipitation. Caution should be taken with gridded data over western tropical South America, as stations are sparse. Twice-daily OLR measurements for the period 1976-1998, interpolated in space and time to yield a $2.5 \times 2.5°$ gridded global set with no missing data except from 15 March 1978 to 31 December 1978 (Liebmann and Smith 1996) were also used. The day and night observations of the OLR were averaged to minimize the effects of the diurnal cycle (Schmetz and Liu, 1988) and to reduce the differences between satellites due to various equator crossing times (Kousky, 1988). The 24-season study period spans July-December 1976 to 1999. The year with missing OLR (1978) is not used for this study.

The average OLR and the accumulated precipitation were computed for each of the 73 pentads (5-day averages) for each year. The climatological mean for a particular pentad was obtained by taking an average for the corresponding pentad over the entire record. A list of the pentads and their corresponding calendar dates is available in Kousky (1988).

Three different SAMS onset date definitions, based on Kousky (1988), Marengo *et al.* (2001), and Liebmann and Marengo (2001), are discussed in this paper. Kousky (1988) defined the onset date as occurring when OLR falls below 240 Wm^{-2} in a given pentad, provided that 10 of the 12 preceding (subsequent) pentads had OLR above (below) 240 Wm^{-2}. Involving the OLR conditions in the preceding and subsequent pentads in the method prevents the onset date definition to be influenced by a single precipitation event. It is clear that the onset date defined in this way depends on the threshold value used. Marengo *et al.* (2001) pointed out that this onset date criteria with the 240 Wm^{-2} as the threshold value is almost never met in the extreme northwest of South America, since that region does not experience a dry season.

The onset date criteria defined by Marengo *et al.* (2001) uses daily rainfall data. Based on an analysis of the progression of the climatological mean precipitation over the Amazon basin, they defined the onset date of the rainy season as that pentad with daily average precipitation exceeding 4 mm day^{-1}, provided that 6 of the 8 preceding (subsequent) pentads had precipitation of less (more) than 3.5 (4.5) mm day^{-1}. As stated above, onset dates resulting from these types of methods are quite sensitive to the threshold value. Marengo *et al.* (2001) discussed extensively how a threshold value could work well for some regions, but be inappropriate for others.

The onset date definition of Liebmann and Marengo (2001) is based on the rainfall accumulation evolution and it differs from that of Marengo *et al.* (2001) essentially in that onset can be defined everywhere because the threshold is defined locally by the climatology. A quantity ‘anomalous accumulation’ is defined:

$$A_j = \Sigma A_i - A_m x_j$$

where *Aj* is the daily rainfall as a function of the calendar day *j* accumulated until day *xj*, *Ai* is the daily rainfall for day *i*, *xj* is the number of day and *Am* is the annual mean daily rainfall. If in every region of interest the rainy season is considered to be the period during which rainfall exceeds its climatological annual average, then a positive slope indicates the rainy season. This definition applies locally because it depends on the climatology in the area of interest. The results obtained from applying these methods over tropical South America are discussed in section 4.

3. Pentad climatology of rainfall and OLR

The OLR fields for selected pentads in the south american sector are shown in Figure 1. As described by Kousky (1988), by the end of August (Figs. 1a, b) convection shifts southward from the northwestern sector of the continent into the Amazon basin. During September the convection over southeastern South America (SESA) intensifies and extends northwestward (Figs. 1c-g). By the end of September (pentad 55, Fig. 1h), convection develops over central Brazil and intensifies over the entire region from the Amazon basin to SESA and southern Brazil, forming a NW-SE orientated band. An increase of the climatological mean OLR values (weakening of the convection) is evident during the first half of October (Figs. 1i, j) in Central Brazil, followed by a decrease of OLR (intensification of the convection) over the whole region by the end of the month (Figs. 1k-l).

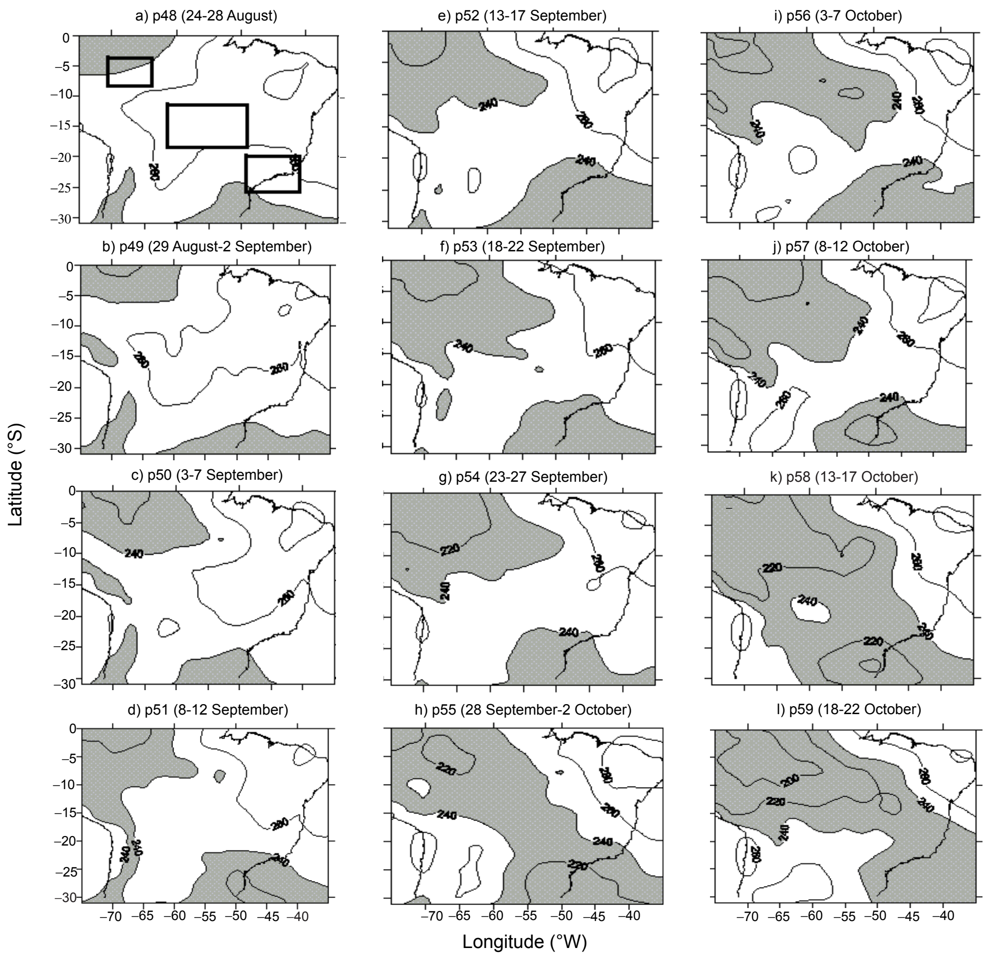


Fig. 1. Climatological 5-day mean OLR from pentads 48 to 59. Contour interval is 20 Wm^{-2}. Values less than 240 Wm^{-2} are shaded. Boxes defining the regions NWA, CB, and SEB described in section 3, are denoted in Figure 1a.

The climatological mean precipitation fields for the same pentads are displayed in Figure 2. The southward intensification of the precipitation from northwestern South America (Figs. 2a-2g) is clear and agrees with the evolution shown in the OLR fields. On the other hand, the increase on rainfall over central Brazil occurs one pentad later (pentad 56) than indicated by the decrease in OLR (pentad 55, Fig. 1h). Souza and Ambrizzi (2003) presented a pentad climatology of precipitation over Brazil, and also show a precipitation increase over central Brazil around pentad 54-55 (Figs. 2g, h). By pentad 57 (Fig. 2j) a decrease in the mean precipitation over central and eastern Brazil is evident, in agreement with that observed in OLR (Fig. 1j) and in the results presented by Souza and Ambrizzi (2003). By mid-October (Fig. 2k) precipitation re-intensifies over central Brazil and a continuous rainfall increase is evident during the rest of the month (Fig. 2l) (Souza and Ambrizzi, 2003).

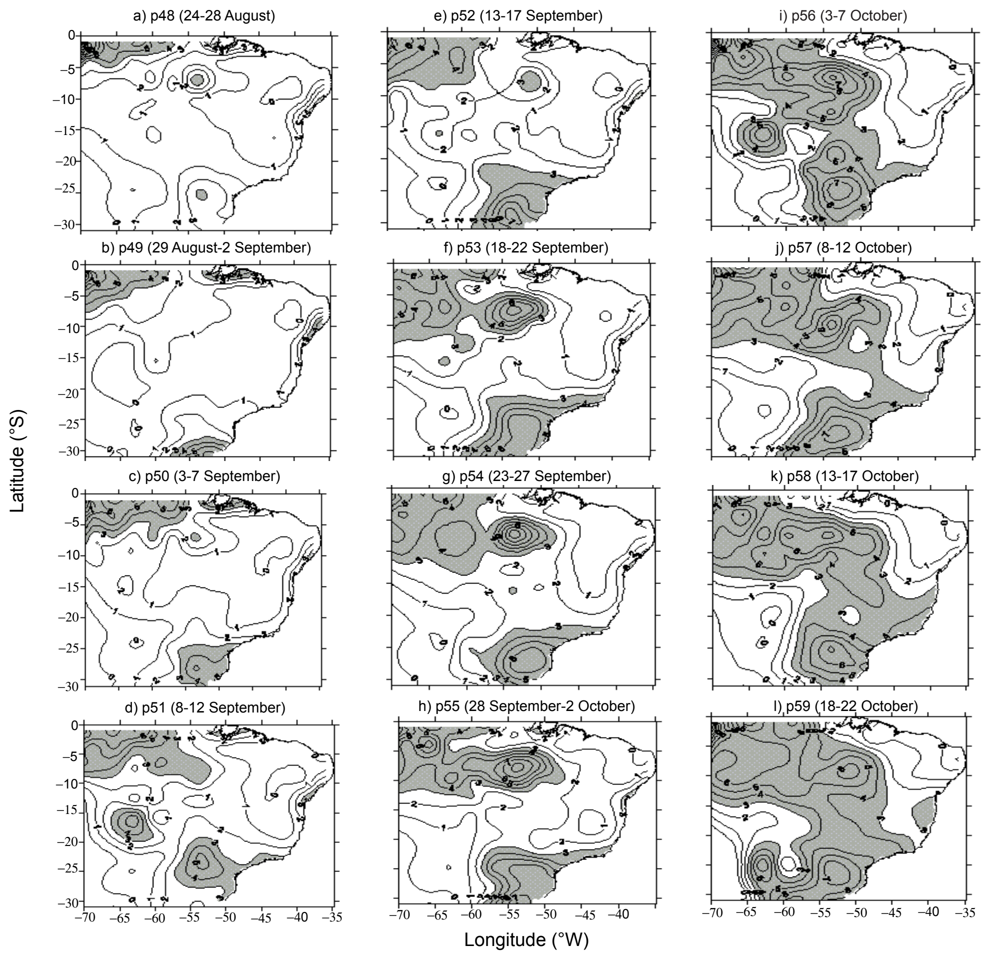
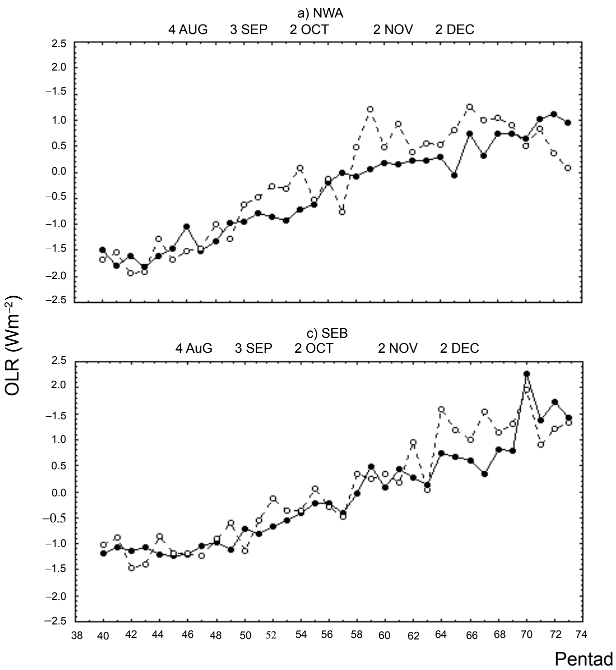


Fig. 2. Idem Figure 1 but for rainfall data. Contour interval is 1 mm day^{-1}. Values larger than 3 mm day^{-1} are shaded.

The regional differences identified in the precipitation and OLR evolution over tropical South America were further analyzed by defining the following three regions: norwthwestern Amazon (NWA, 65° W-70° W, 4° S-7° S), central Brazil (CB, 50° W-60° W, 12° S-18° S), and southeastern Brazil (SEB 50° W-42° W, 25° S-20° S). The station data are plagued by missing observations, so for each of the regions, a group with more complete data was selected (6 for NWA, 7 for CB, and 6 for SEB). The time series of the precipitation averaged over the selected stations in each region and OLR departures (from the annual mean) are displayed in Figure 3. The series were normalized by their respective mean and standard deviations calculated over the whole period (Table I) in order to better compare the changes in both variables. Table I shows that although NWA exhibits the largest annual mean values of both precipitation and convection, CB is the region that displays the largest variability associated with the seasonal cycle, while as expected, SEB exhibits the smallest mean and standard deviation values.

By the beginning of August, a gradual and continuous increase of rainfall and decrease in OLR is observed in NWA (Fig. 3a). OLR decreases at a larger rate than the rate of increase in precipitation, agreeing with Marengo *et al.* (2001) and indicating a possible increase in high cloud cover in the region prior to the increase in precipitation. Precipitation increases at slower rate after the beginning of October.



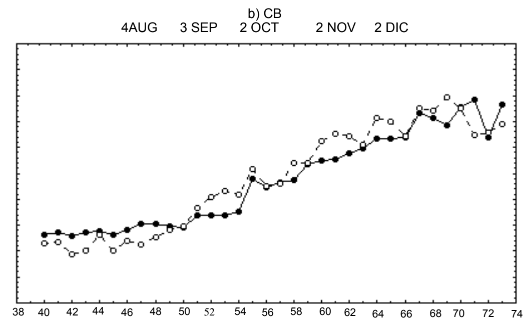


Fig. 3. Temporal series of standardized climatological means of OLR (multiplied by −1, open circles) and mean rainfall (full circles) from stations for a) NWA, b) CB, and c) SEB regions.

Table I. Annual mean pentad rainfall totals and OLR, and their corresponding standard deviations computed over the NWA, CB, and SEB areas defined in section 3.

Region	Mean rainfall (mm)	Rainfall standard deviation (mm)	Mean OLR (Wm^{-2})	OLR standard deviation(Wm^{-2})
NWA	37.5	17.3	214.2	19.5
CB	25.3	21.1	230.8	27.6
SEB	18.6	15.7	239.1	12.6

Mean precipitation in CB (Fig. 3b) shows an almost negligible increase until mid-September (around pentad 54), when an abrupt positive change of one standard deviation is observed. After that, the rainfall rate remains quite high. By the beginning of September (pentad 50) the OLR in CB starts to increase earlier than precipitation, and as was found in NWA, values of normalized OLR remain generally larger than those of precipitation during the rest of the study period. Furthermore, by the end of September, OLR normalized anomalies increase at a lower rate than do rainfall anomalies.

The evolution over SEB region (Fig. 3c) is characterized by a moderately increased rate of precipitation between the end of August (pentad 48) and middle of October (pentad 58). A rapid precipitation increase of around one standard deviation occurs within two pentads by pentad 59. After that, precipitation does not increase for at least four pentads. The OLR for this particular region is consistent with the precipitation rate until mid-October, while after that OLR standardized departures (multiplied by −1) are larger than those of precipitation.

4. Discussion of monsoon onset date determination over South America

The mean onset date of the SAMS was calculated for the OLR fields using the onset date definition of Kousky (1988) described in section 2. Figure 4a shows the average onset date computed over the period 1976-1998, while Figure 4b shows the number of years when the onset date could be defined following this methodology. It is evident from this last Figure that onsets in regions south of 18° S could not be defined in many years and that this method is not able to identify the onset date in southeastern Brazil in almost any of the years.

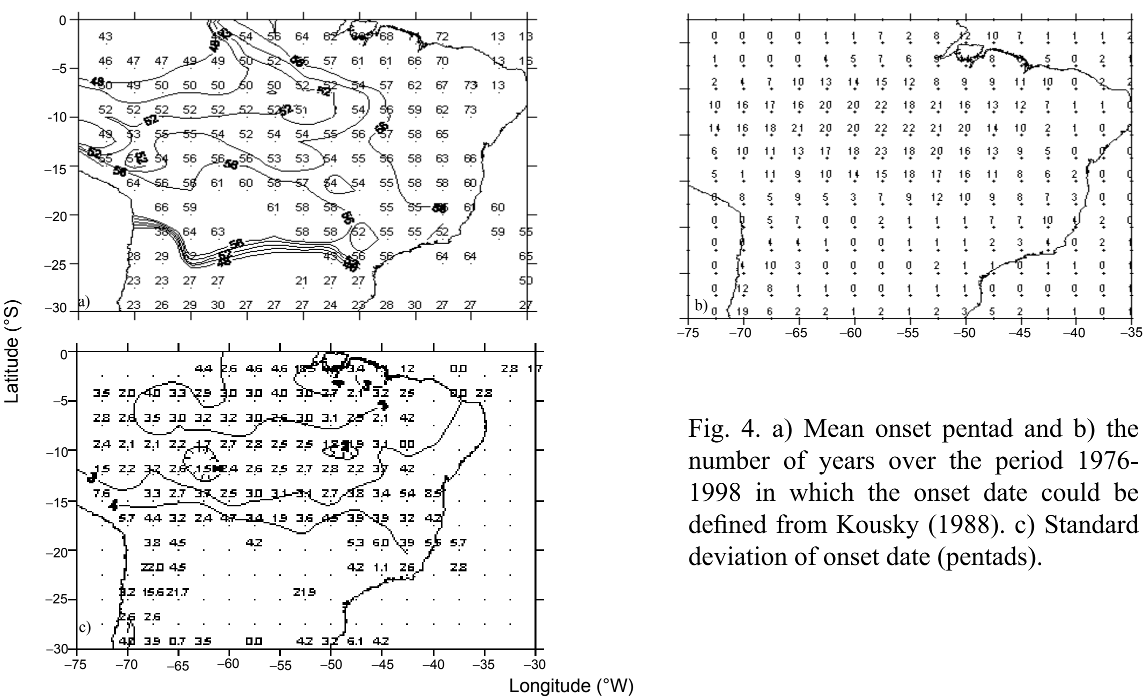


Fig. 4. a) Mean onset pentad and b) the number of years over the period 1976-1998 in which the onset date could be defined from Kousky (1988). c) Standard deviation of onset date (pentads).

The southeastern progression of the convection from the northwest is clearly represented in Figure 4a by a continuous succession of the onset date from pentad 44 over northwestern Amazon towards pentad 52 (middle September) over southern Amazon, in agreement with Figure 2. The isoline associated with pentad 56 (beginning of October) extends well into southeastern Brazil in agreement with the spread of the climatological mean convection observed throughout tropical South America in a northwest-southeast oriented band (Figs. 2h, i). Values of onset dates displayed south of 22° S are questionable because OLR evolution in the subtropics is affected by more than convective activity (Kousky, 1988). Moreover, the seasonal cycle of precipitation in that region does not show a clear rainy season (e.g., Vera *et al.,* 2006). Figure 4c shows that the onset date exhibits considerable variability over central Brazil of around 2-3 pentads in agreement with the large variability of CB (Table I).

Figure 5 shows an x-t plot with the x-axis taken along the northwest-southeast direction of the convection displacement. The exact locations of x-axis points are detailed in Table II. The Figure shows that convection, represented by OLR values less than 240 Wm^{-2}, arrives to the point located in the northwestern part of the line in pentad 49 or 50, meanwhile in pentad 54 or 55 convection is over all the points. It is noticeable that convection reaches point 8, in the southeastern region, earlier (pentad 52) than the intermediate points.

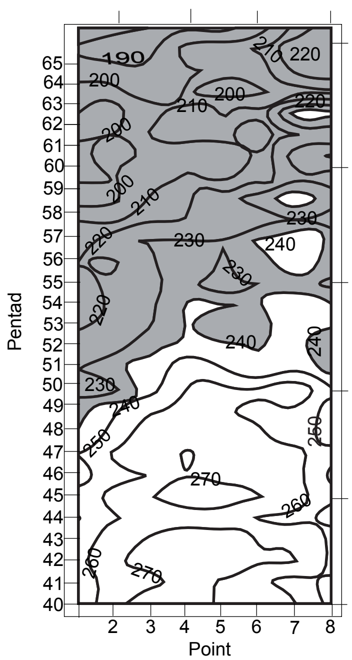


Fig. 5. X-t plot with the x-axis taken as horizontal line orientated in the northwest-southeast direction of the convection displacement. The exact location of x-axis points is detailed in Table II.

Table II. Location of the x-axis point used to construct Figure 5.

Point in x-axis	Longitude (°W)	Latitude (°S)
1	65	5
2	62.5	7.5
3	60	10
4	57.5	12.5
5	55	15
6	52.5	17.5
7	50	20
8	47.5	22.5

Figure 6 shows the climatological mean onset dates calculated following the methodology defined by Marengo *et al.* (2001), using a threshold value of 3 mm day^{-1}, lower than that used by Marengo *et al.* (2001) for the Amazon Basin but more suitable for the tropics as a whole. Onset dates could be defined only over a region extending between 5° S and 17° S, and 62° W and 42° W while the method is not able to define an onset date for central and southeastern Brazil. The onset progresses eastward from the Amazon from around pentad 50 (beginning of September) to pentad 58 (mid-October). A comparison between the climatological mean onset dates obtained by Kousky (1988) (Fig. 4) and Marengo *et al.* (2001) (Fig. 6), respectively, shows that both results are similar over the Amazon region, although the former defines an earlier onset date by about 3 pentads compared to the latter over eastern Brazil. The mean precipitation evolution observed over that particular region (Fig. 2) agrees better with the onset dates from the method of Marengo *et al.* (2001).

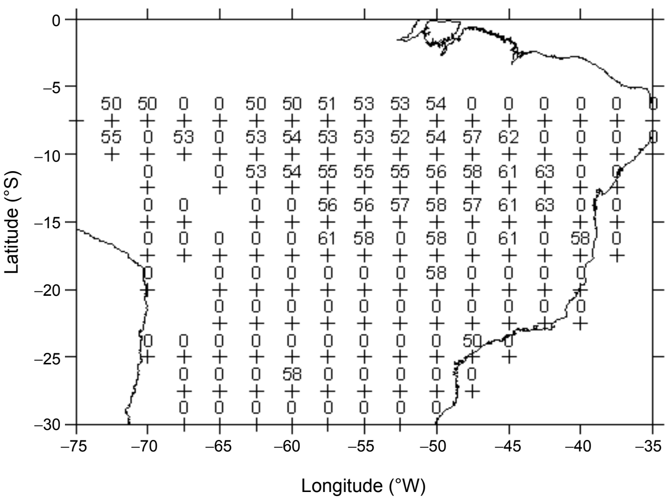


Fig. 6. Mean onset pentad following methodology from Marengo *et al.* (2001) for the period 1976-1998. "0" indicates that the onset could not be defined.

The climatological mean onset dates calculated following the methodology proposed by Liebmann and Marengo (2001) (Fig. 7a), clearly show an earlier onset of precipitation in both northwestern and southeastern regions of the SAM than over central Brazil. Nevertheless, the onset dates in the entire region are in general delayed from those of Kousky (1988) and Marengo *et al.* (2001), and in particular over the northwestern region. The differences in the onset date could be diminished by lowering the threshold. Figure 7b shows that the onset dates computed following Liebmann and Marengo (2001) for a threshold that is 50% of the annual mean daily rainfall are more similar to those obtained from the other methods (Figs. 4a, 6). Nevertheless, a more precise threshold determination for this particular method is beyond the scope of this paper.

Therefore, in the following sections the Kousky´s methodology will be the one considered as it provides results that are not that dependent on the regional features as those methods based on precipitation data.

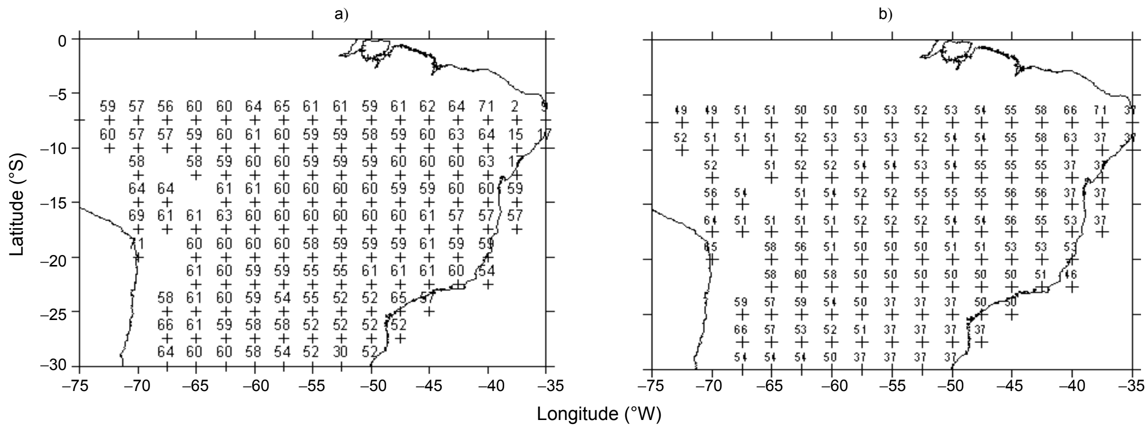


Fig. 7. Idem Figure 6 but a) from Liebmann and Marengo (2001) and b) idem a) using a threshold that is the 50% of the annual mean daily rainfall.

5. Rainy season onset over central Brazil

In this section, a more detailed analysis of the conditions associated with the wet season onset is presented. The composites of the OLR fields computed three pentads before and after the onset date (Figs. 8a, b) clearly show the convection remaining north of 10° S before onset, while it is extended southward 20° S after it. Furthermore, it is known that considerable changes in the circulation occurred when the rainy season develops. A large-scale anticyclonic circulation (the "Bolivian High") centered near 65° W, 15° S, and a trough near the coast of northeast Brazil, are the most conspicuous features associated with the wet season upper-level circulation (Vera *et al.,* 2006, and references therein). Figures 8c, d shows the composite of 250-hPa wind fields (from NCEP Reanalysis Data, Kalnay *et al*., 1996) three pentads before and three pentads after onset date. The transition between the winter-like circulation with strong westerlies and the development of the Bolivian High is clearly depicted. From the analysis of Figure 8, it can be pointed out the ability of the Kousky´s method in describing the main features associated with the rainy season onset. In order to better understand the abrupt positive change observed in mean rainfall evolution in CB on pentad 55 (Fig. 3b) and SEB on pentad 59 (Fig. 3c), a description of the mean daily changes observed during those particular periods is presented here.

Figures 9a and 9b shows that by the end of September, mean precipitation areas extend over northwestern and southeastern Brazil while no precipitation is yet observed over central Brazil. By the beginning of October (Figs. 9c, d), a general increase of climatological precipitation is observed in the northwestern-southeastern band, with values of around 2 mm day^{-1} in CB and values up to 8 mm day-1 in both northwestern and southeastern Brazil. This pattern persists in the mean rainfall fields of the following pentads (not shown).

The daily evolution of the mean precipitation during pentad 59 associated with the precipitation increase in SEB is displayed in Figs. 9e-h. By 19 October (Fig. 9e), the mean rainfall field is very similar to that observed in the beginning of the month (Fig. 9d), although there is a rainfall increase over central and eastern Brazil. During the next three days (Figs. 9f-h), a considerable increase is observed over SEB which seems to be associated with an extension of the mean rainfall area that was previously concentrated in southern Brazil. The analysis of the mean rainfall over SEB during the next pentads (not shown) demonstrates that values of around 6 mm day^{-1} persist, confirming the development of the rainy season.

Between 20 and 22 October mean precipitation values over central Brazil (Figs. 9f-h) are approximately the same as those observed during the beginning of the month (Figs. 9c, d), and these values of around 4 mm day^{-1} persist. It seems that two distinctive moments characterize the monsoon onset over central Brazil, one in which rainfall starts in the region at a moderate rate (on average by the beginning of October), and a second one in which the rainfall rate dramatically increases (by the end of October).

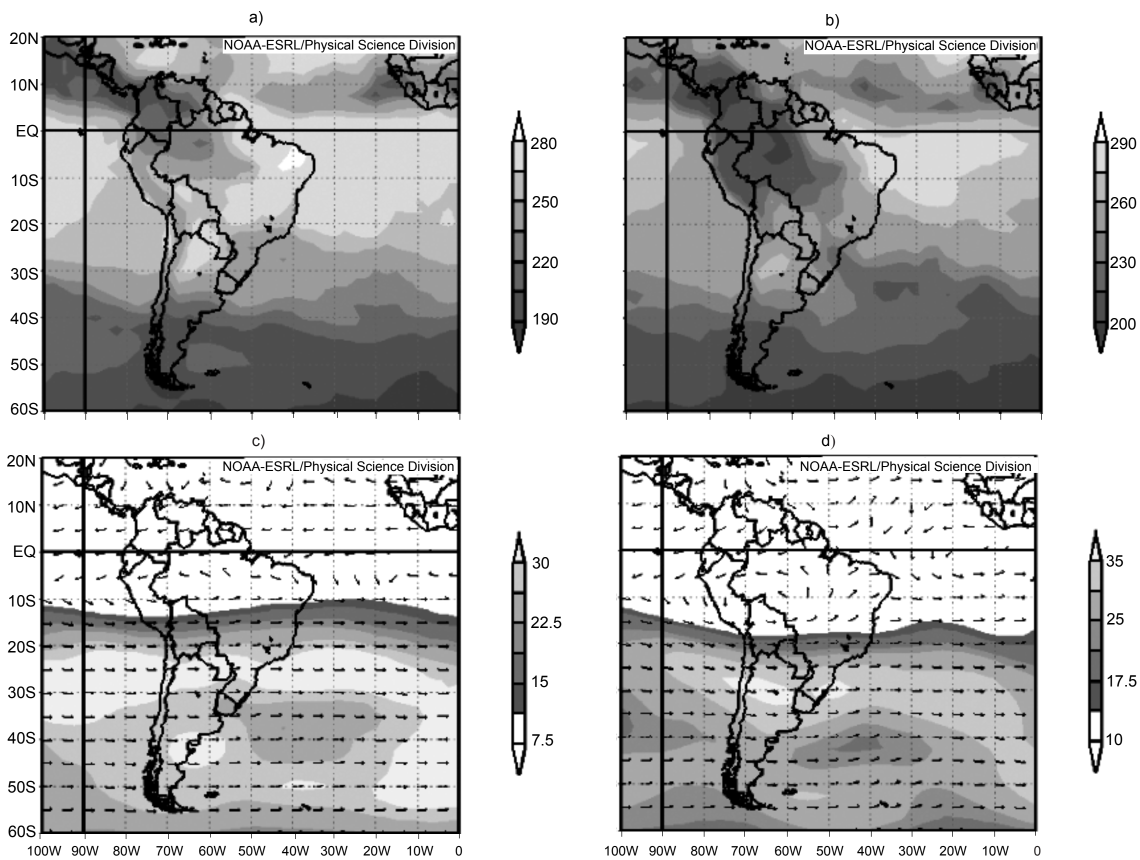


Fig. 8. a) OLR (Wm^{-2}) three pentads before Kousky´s onset and b) three pentads after it. c) and d) the same for 250 Hpa flow. Shaded colors represent wind intensity (ms^{-1}).

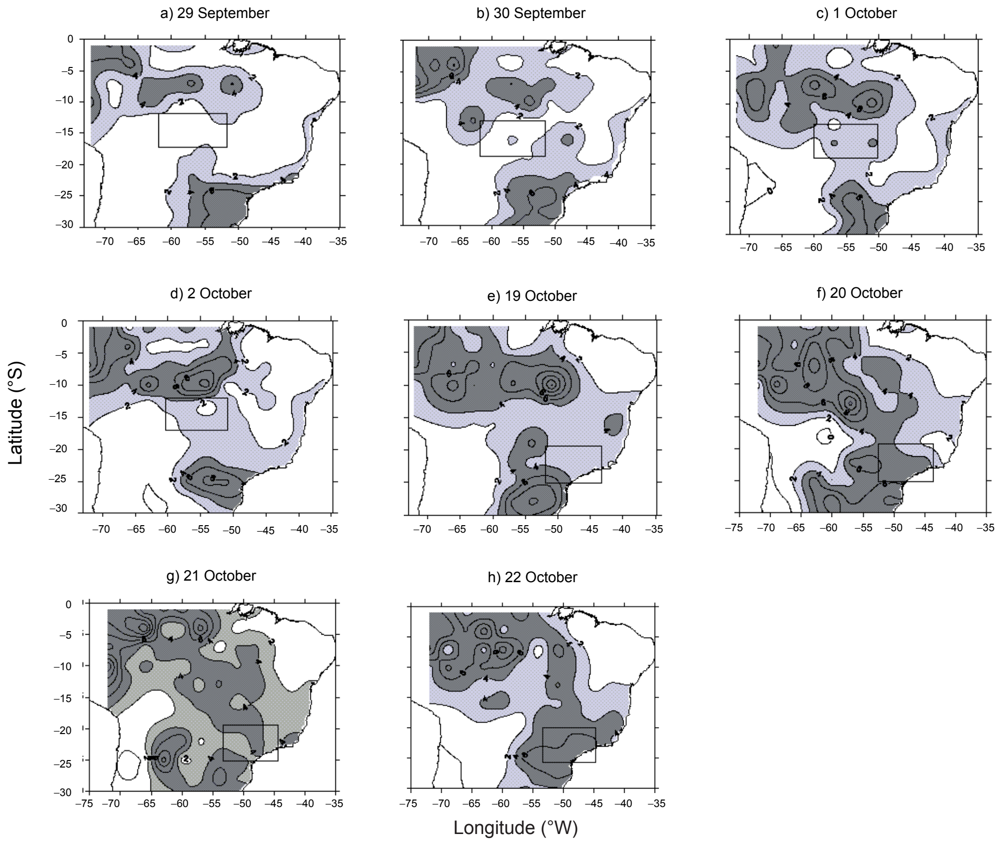


Fig. 9. Climatological daily mean precipitation from a) 29 September to d) 2 October, and from e) 19 October to h) 22 October. Contour level is 2 mm day^{-1}. Values larger than 4 mm day^{-1} are shaded with dark grey, and larger than 2 mm day^{-1} are shaded with light grey. e-h Panels include the box encompassing the CB (SEB) region.

In order to better describe this abrupt change in rainfall, a rainfall jump index, defined as the maximum rainfall difference between two consecutive pentads over CB, was applied to the rainy season onset period between 15 July and 1 November (pentads 40 and 61). Moreover, the precipitation difference was calculated between two consecutive pentads and not two consecutive days in order to avoid the influence of individual synoptic-scale systems. Table III lists the pentad in which the rainfall jump occurs and its corresponding magnitude for each of the years considered; also, it shows that the jump occurs on average in pentad 57 (8-12 October) with a variability of around 3 pentads, with a mean rainfall rate of 7.7 mm day^{-1} and a standard deviation of 3 mm day^{-1}. As well it includes information about the rainy season onset computed for each year following the Kousky (1988) definition, which shows that the mean onset date occurs in pentad 54 (23-27 Sept) with a standard deviation of 2.7 pentads. Finally, Table III shows that the rainfall jump tends to occur a few pentads after the rainfall onset, although in a few cases they occur simultaneously and in two rainfall extreme cases the rainfall jump occurs before onset.

Table III. Dates of occurrence and associated mean rainfall rate for rainfall onset and rainfall jump obtained over the period 1976-1998 from raingauges.

Year	Onset date (Kousky pentad)	Rainfall jump date (pentad)	Rainfall jump (mm day^{-1})	Year	Onset date (Kousky pentad)	Rainfall jump date (pentad)	Rainfall jump (mm day^{-1})
1976	56	59	10.2	1988	57	60	4.5
1977	55	55	6.2	1989	55	57	5.6
1979	53	51	11.6	1990	48	55	11.5
1980	51	52	9.4	1991	55	55	7.7
1981	54	59	9.7	1992	47	60	9.7
1982	52	52	11.7	1993	53	60	13.5
1983	54	54	11.7	1994	57	60	9.1
1984	54	54	6.7	1995	56	60	4.2
1985	54	57	4.7	1996	53	59	6.3
1986	56	59	12.4	1997	57	55	4.3
1987	57	59	4.3	1998	55	57	5.9
				Mean	54	57	7.7
				St. Dev.	2.7	2.9	15.1

Figure 10a shows the time series of normalized rainfall and OLR averaged over the CB region, relative to the pentad of the rainfall jump. While rainfall values increase slowly before the jump pentad, soon thereafter an increase of the precipitation rate as well as its variability is noticeable. Figure 10a also shows a continuous increase in convection (decrease in OLR) prior to the rainfall jump, although there is no abrupt change. Figure 10b shows the time series of both normalized rainfall and OLR averaged over the CB region, now relative to onset (as defined by Kousky, 1988). A precipitation increase is noticeable from pentad 0 that is more pronounced than that displayed in Figure 3b. This result might be expected considering that the averages displayed in Figure 3b were computed without accounting for differences in the onset date among the individual years.

The changes in both the mean and variance from before to after onset and judged by be statistically significant according to the results of T-Student and Chi-Square tests at 95% of significance. Moreover, a comparison between Figures 10a and b reveals that the rainfall jump generally does not occur at onset, but usually a few pentads later. Figure 11 shows the composites of 5-day rainfall averages relative to the rainfall jump and to onset. The onset of the rainy season over CB is associated with an increase of precipitation, with amounts less than those already observed over the northwestern and southeastern regions (Fig. 11d-f). On the other hand, the later occurrence of the rainfall jump over CB is related with the development of similar rainfall amounts along the NW-SE band (Fig. 11a-c).

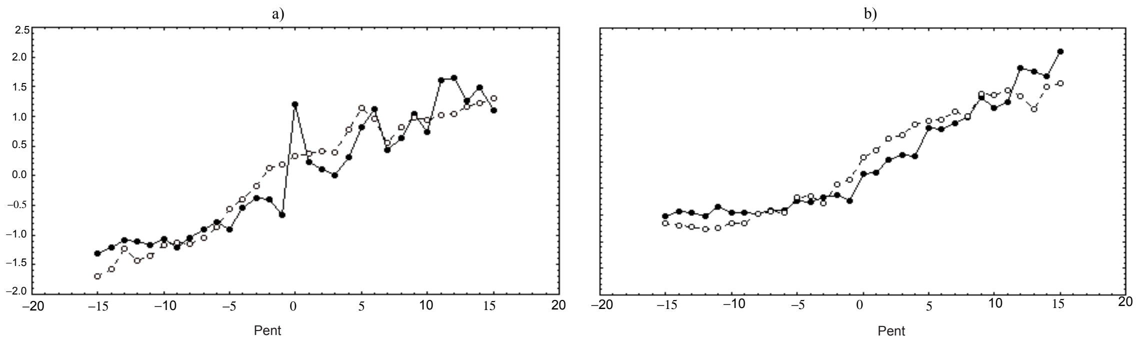


Fig. 10. Standardized time-series of composite OLR (multiplied by −1, open circles) and mean rainfall from stations (filled circles) relative to a) rainfall jump, and b) onset date.

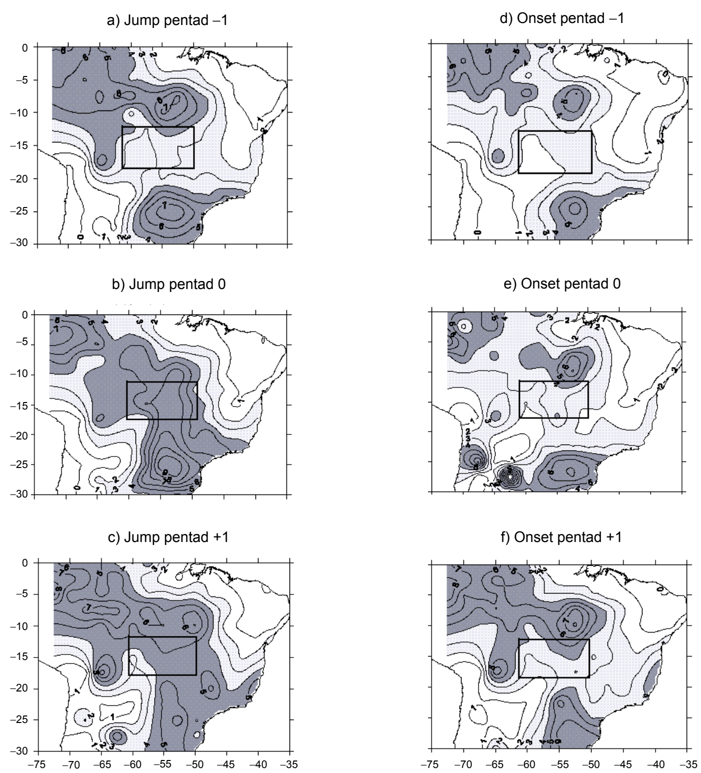


Fig. 11. Composite rainfall relative to rainfall jump date from a) pentad −1 to c) pentad +1 and relative to onset date from d) pentad −1 to f) pentad +1. Contour level is 1 mm day^{-1}. Values larger than 4 mm day −1 are shaded with dark grey, and larger than 2 mm day^{-1} are shaded with light grey. Panels include the box denoting the CB region.

6. Conclusions

The main features that characterize the increase of both rainfall and convection over tropical South America during the beginning of the rainy season were discussed. It was found that the climatological mean evolution of both OLR and rainfall data show a progression of intensified convection from northwestern (southeastern) South America southeastward (northwestward) with a subsequent increase over central Brazil by the beginning of October. This convection progression as well as that associated with the circulation, determine the onset of the SAMS (Vera *et al.,* 2006).

A detailed study of the different available methods to determine the SAMS onset date was made. It was found that those methods based on precipitation data (Marengo *et al.,* 2001, Liebmann and Marengo, 2001), require the determination of a threshold, which make it regionally dependent. On the other hand, those based on OLR data, like the one developed by Kousky (1988), was better able to represent the rainy season onset on continental scales.

A detailed analysis of the climatological daily mean precipitation progression over central Brazil shows that the intensification of convection begins with moderate mean precipitation rates of around 2 mm day^{-1} lower than those observed at the same time over the Amazon and southeastern Brazil. Some pentads later, mean precipitation rates abruptly increase to values above 4 mm day^{-1}, defining a rainfall jump. By this time, similar mean precipitation rates extend all along tropical South America from the Amazon to southern Brazil.

The conditions associated with the rainfall jump, as defined by the difference of 5-day precipitation between two consecutive pentads show that on average it occurs around three pentads later than the onset of rainy season. It was found that composites relative to either convection onset date or rainfall jump date are able to characterize the nature of rainy season onset over CB.

Therefore, it can be concluded that such abrupt increase in precipitation rates may be related with synoptic and intraseasonal variability. Nevertheless, besides the synoptic-scale events that occur all year around, the transient activity, which occurs around the onset period when the atmospheric mean conditions are getting more unstable as they approach summer-like conditions, is the one that imprints a rainfall-jump feature in the evolution precipitation. Moreover, it can be concluded that the rainfall jump is associated with the first synoptic-scale event that produces a significant change in precipitation during the rainy season (Fig. 10a).

Essentially, while the current methods to determine precipitation onset dates provide information about when the rainfall starts, the analysis of the rainfall jump could allow the identification of the big increase in the monsoon heat source (from a large scale perspective) although the heat calculations to justify this statement are over the scope of this paper. Therefore, the paper concludes that the character of changes in the precipitation rate, as the rainy season develops, provides complementary information that can be used together with the onset date. The development of new methods for determining the precipitation onset, however, is beyond the scope of this paper.

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