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Do the recent severe droughts in the Amazonia have the same period of length?

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Abstract We propose a new measure based on drought period length to assess the temporal difference between the recent two severe droughts of 2005 and 2010 in the Amazonia. The sensitivity of the measure is demonstrated by disclosing the distinct spatial responding mechanisms of the Northeastern and Southwestern Amazon (NA, SA) to the surrounding sea surface temperature (SST) variabilities. The Pacific and Atlantic oceans have different roles on the precipitation patterns in Amazonia. More specifically, the very dry periods in the NA are influenced by El Niño events, while the very dry periods in the SA are affected by the anomalously warming of the SST in the North Atlantic. Our analysis discloses convincingly that the drought 2005 hit SA, which is correlated to the North Atlantic only. Furthermore, it suggests that there are two phases in the drought 2010: (1) it was started in the NA in August 2009 co-occurred with the El Niño event, and (2) later shifted the center of action to SA resulted from anomalously high SST in North Atlantic, which further intensifies the impacts on the spatial coverage.

Keywords Amazonia droughts · Drought period length · SST · Tropical Atlantic · ENSO

1 Introduction

In Amazonia there remains the largest contiguous tropical forest of the planet. The vegetation, including its deep root system, is efficient in recycling water vapor, which is an important mechanism for the forests maintenance and helps to maintain evergreen canopies during dry seasons (Nepstad et al. 1994; Cox et al. 2008), demonstrating the adaptation of Amazon forest species to seasonal drought (Davidson et al. 2012). However, multi-year or extreme droughts can affect this adaptation to seasonal drought and eventually leading to mortality when roots are unable to extract enough soil water during multi-year droughts (Fisher et al. 2006; Davidson et al. 2012). Understanding drought events in Amazonia has fundamental importance especially because the droughts may result in increased length of the dry season and become more frequent during this century as a result of anthropogenic climate change (Salazar et al. 2007; Saatchi et al. 2013; Phillips et al. 2009).

The sea surface temperature (SST) variabilities in both the tropical Pacific and Atlantic Oceans play important roles in forming the climate conditions in the inter-annual rainfall variations over the Amazon (Aceituno 1988; Marengo 1992; Ronchail et al. 2002). Rainfall reductions and droughts in Amazonia have been associated with El Niño Southern Oscillation (ENSO) events, or with

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anomalous warming of SSTs in the tropical North Atlantic during the austral winter–spring, or both (Richey et al. 1989; Uvo et al. 1998; de Souza et al. 2005; Marengo et al. 2011; Coelho et al. 2012). In 2005, the drought affected the southern two-thirds of Amazonia and especially the southwest through reduced precipitation as well as higher-than-average temperatures, and this event was driven by elevated tropical North Atlantic SSTs (Marengo et al. 2008; Phillips et al. 2009). On the other hand, the drought event observed in 2010 was mainly caused by large-scale atmospheric circulation pattern forced by tropical SST anomalies in the equatorial Pacific and the drought affected more than half of the basin, resulting in the lowest discharge ever recorded at Manaus (Marengo et al. 2011; Lewis et al. 2011; Xu et al. 2011).

In this study we characterize the main statistical differences between the recent two severe droughts of 2005 and 2010 in the Amazonia by deriving drought period lengths, which are similar to analyzing waiting times in nonlinear time series (Zou et al. 2014). Therefore, our analysis essentially provides some nonlinear perspectives on the underlying process.

2 Data and methods

Precipitation is evaluated using the Princeton Global Forcings dataset at 0.5° resolution (Sheffield et al. 2006). This dataset blends surface and satellite observations with reanalysis and is available for 1948–2010. Sea Surface Temperature (SST) is evaluated using NOAA High Resolution SST data products (Reynolds et al. 2007). We subdivide the Amazon domain into Northeastern Amazonia (NA: 65°W–48°W, 5°N–10°S) and Southwestern Amazonia (SA: 75°W–50°W, 15°S–4°S) regions. Time series for precipitation of daily resolution were built for these two regions, while time series for SST, are respectively, obtained by area averaging over El Niño3.4, North Atlantic (n-Atlan) and South Atlantic (s-Atlan) domains, according to the definitions of (Yoon and Zeng 2009). Note that the following results do not change if the El Niño3 area is used instead.

Daily precipitation anomalies for the NA and SA are calculated relative to a base period of 1961–2000. This 40-year base period is chosen as it is representative of the record of the 20th century. From the daily rainfall anomaly series $A(t)$, we propose to calculate a drought period length $DPL(t)$ that characterizes the waiting time of the present day to have the next first non-negative rainfall anomaly. This captures the expecting time when anomaly series goes from negative to positive, characterizing the expectation to have a positive rain anomaly. More specifically, $DPL(t) = \min\{\tau : A(t+\tau) \geq 0, \tau \in [0, \infty)\}$. Note that $DPL(t)$ is different from computing the time length of each drought event which needs a proper definition of an event. Understanding the properties of the event times and their distribution provides an alternative way to characterize the underlying processes (Zou et al. 2014).

3 Annual variabilities of precipitation

We calculate $DPL(t)$ for the precipitation anomalies from NA and SA regions. As shown in Fig. 1, $DPL(t)$ captures the starting dates of the recent two severe droughts convincingly, in particular, 22 June 2005 and, respectively, 1 August 2009, as highlighted in Fig. 1.

Based on $DPL(t)$, in the following, we identify a date as mild dry, dry, and very dry condition if $DPL \leq 1/3 \max DPL(t)$, $1/3 \max DPL(t) < DPL \leq 2/3 \max DPL(t)$, and $DPL > 2/3 \max DPL(t)$, where $t \in [1, 365(6)]$. With respect to the climatological average period of 40 years, we find that

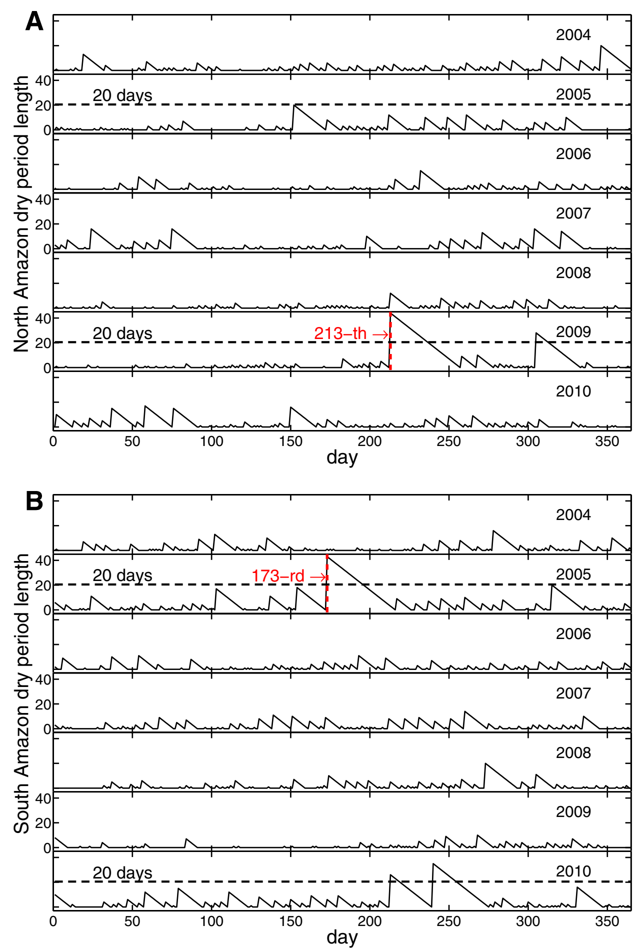

Fig. 1 Annual *DPL*. The drought periods longer than 20 days are highlighted, especially the extreme event starting from the 173rd day of 2005 (22 June 2005), and the event from the 213th day of 2009 (1 August 2009). **a** Northeastern Amazon, **b** Southwestern Amazon

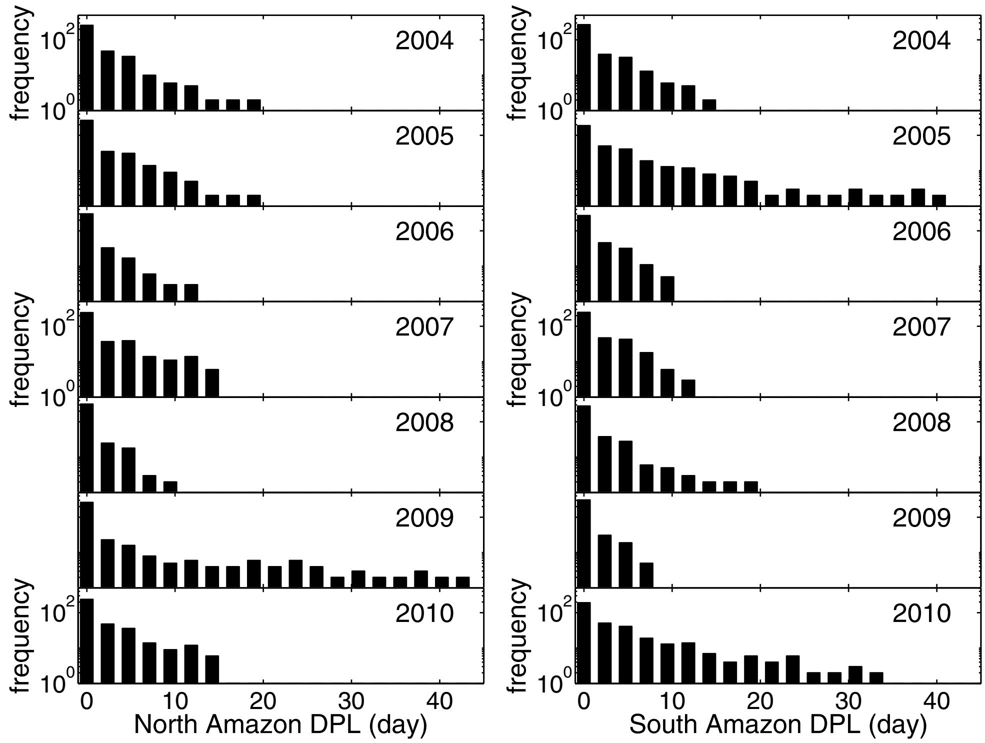

Fig. 2 Histograms of *DPL* in each year

max $DPL(t) = 42$ days (shown in Fig. 1), which yields that the mild dry days correspond to drought periods less than 2 weeks (14 days), while the drought periods for very dry days are typically longer than one month (29 days) of negative anomalies continuously. Furthermore, it is reasonable to regard mild dry conditions as for normal years, and very dry days as extreme events.

For both NA and SA, the dry periods vary considerably over annual scales. There are two ways to characterize the difference in the annual variabilities of the drought period lengths: (1) temporal variations of $DPL(t)$, and (2) frequency plots for *DPL* (shown in Figs. 1, 2, respectively). The results are summarized as follow:

1. Years 2004, 2006, 2007, and 2008 show no signs for very dry periods in either NA nor SA since all dry periods are less than 20 days. Only mild dry and dry days are observed in these years. Therefore, we term them as normal years of dry conditions.
2. In 2005: In NA, no signature for very dry period longer than 20 days is found. However, in SA, there is an event of very dry period starting from the 173rd day (22 June) (Fig. 1), reaching over 40 days of negative precipitation anomalies. About 60 days of rainfall less than 1mm/day in SA has been observed (similar statistics based on precipitation anomalies, not shown), which leads to the very dry period over 40 days of continuous negative rainfall anomalies as shown in Fig. 2.
3. In 2009: In NA, there is an event of dry period starting from the 213th day (1 August), reaching over 40 days of negative precipitation anomaly (Fig. 1). From the beginning of the year till this big event, NA has experienced much floods of rainfall (very small *DPL* values). In contrast, there is plenty of rain in SA throughout the year since the dry period is much less than 10 days (Fig. 2).
4. In 2010: In NA, no signature for very dry period longer than one month is found. Instead, we observe several dry periods longer than 2 weeks (but less than 20 days) in the first half year. In SA, however, starting from the 213th day (1 August), there are at least two big events of very dry periods reaching over 35 days of no rains (Fig. 2).

From the daily variation of *DPL*, we infer the crucial difference between the droughts 2005 and 2010 as follows. The drought 2005 affected mostly the SA area over 40 days of continuous negative rain anomalies, leading to very dry periods once-in-a-century event (Marengo et al. 2008). However, the drought 2005 has less serious effects in NA, resulting in dry periods less than 20 days.

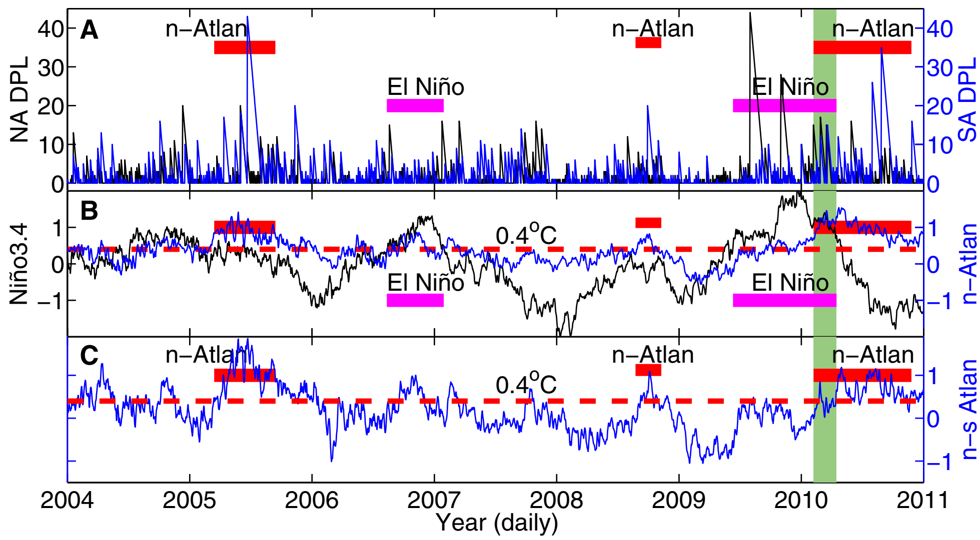

Fig. 3 Sensitivity of *DPL* to the SSTs of the Pacific and Atlantic. **a** *DPL* for the NA and SA. **b** SSTs of Niño3.4 and the tropical North Atlantic. The *horizontal dashed line* corresponds to a threshold of 0.4 °C, which is often used to define an El Niño event. Both a weak in 2006 and a strong El Niño events in 2010 are highlighted. Two time periods when the SST of the Atlantic Ocean is significantly above 0.4 °C are *highlighted*, together with a weak event in 2008. In 2010, a significantly overlapped window is highlighted between the El Niño event and the warming of SSTs in the North Atlantic. **c** Differential SST between the North and South Atlantic (a threshold of 0.4 °C is plotted for comparison)

The drought 2010 is rather special in the following sense. It may started as early as in the beginning of August 2009, hitting NA of very dry period over 40 days of negative rain anomalies, which forms the first phase of this drought event and affects NA only. This initial dry condition in 2009 essentially extends to the first half (about 160th day) of 2010. Therefore, we conclude that the drought 2010 in Amazonia started as early as in the beginning of August 2009. This detected starting time for the drought was earlier as was previously reported by the austral summer. Another important point is that, when this drought started in NA, there is plenty of rainfall in SA since *DPL* is much less than 10 days. The extension of the dry condition to August 2010 forms the second phase of the drought, affecting mainly in SA. Between these two phases, both NA and SA have experienced dry periods less than 20 days. In consequence, the whole Amazonian basin is severely affected by this basin-wide drought, which leads to a much larger spatial and temporal coverage of rainfall shortage than the year 2005.

4 Correlations to surrounding oceanic SST

Now, we investigate the relationship between the surrounding oceanic SST anomalies and the Amazonian rainfall. There are some hypothesis regarding to a possible causality of the respective droughts in 2005 and 2010. The drought 2005 is not linked to ENSO, but to the Atlantic Ocean, while the drought of 2010 started in early austral summer during El Niño and then was intensified as the warming of the tropical North Atlantic. We show these intricate correlations by the observed time series and disclose the distinct roles of ENSO and Atlantic over the spatial patterns of precipitation in the Amazonia.

The hypothetical relationship between the oceanic SSTs and precipitation anomalies has been confirmed over the entire time span from 2004 till 2010. In Fig. 3, we highlight those time periods when we have El Niño events and warming in the Atlantic (Fig. 3a, b). One traditional way to define these anomalously warming periods from the SSTs is to choose a threshold value for the temperature anomalies, i.e., 0.4 °C (Trenberth 1997). Typically, an El Niño event is identified if the 5-month running mean of SST in the Niño3.4 area is above this threshold for at least six consecutive months. We adopt the same threshold for defining an anomalously warming period in the Atlantic. We find that there are 2–3 months of delay for the precipitation in the Amazonian region in responding to the warming in the SSTs of ENSO, respectively, 1 month of delay in response to the warming in the North Atlantic. The temporal correlation patterns are validated by the differentiated SSTs between the North and South Atlantic Ocean (Fig. 3c).

As discussed previously, mild dry days could be regarded as normal conditions, since the dry period is less than 2 weeks. Next, we focus on investigating details how the SST anomalies in the surrounding oceans vary when the Amazonian basin experiences dry and very dry days as

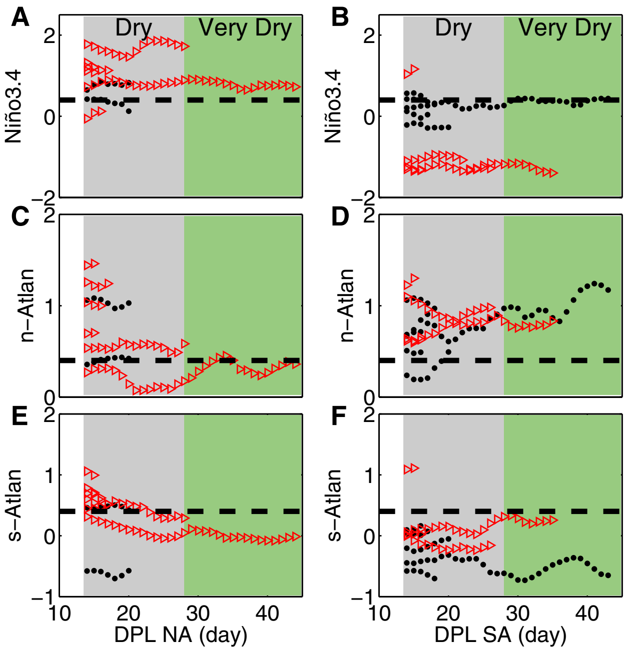

Fig. 4 Correlations between dry, very dry periods and SSTs of the Niño3.4 and Atlantic Ocean, respectively. *Black dots* are for the year 2005, while triangles are for 2010. The *horizontal dashed lines* are thresholds for temperature anomaly of 0.4 °C. Note, normal mild dry days (drought periods less than 2 weeks) are suppressed. **a**, **b** Niño3.4, **c**, **d** tropical North Atlantic, **e**, **f** South Atlantic. **a**, **c**, **e**) NA, **b**, **d**, **f** SA

observed in 2005 and 2010, respectively. Scatter plots are shown in Fig. 4 and the main results are summarized as follows (the results do not change if the Pacific Niño3 region is used).

1. In 2005, ENSO plays no role in linking the very dry days in the Amazon. The very dry days happen only in the SA (Fig. 4a, b). However, the time period for the SSTs in the Niño3.4 to exceed 0.4 °C is negligible (with small fluctuations around the threshold), which therefore suggests that the Pacific region can not explain the drought event in 2005.
2. In 2010, ENSO has a fundamental role in linking both dry and very dry days in the NA region as the SSTs in the Niño3.4 area are well above the threshold. This explains the phase (i) of drought 2010. However, ENSO has no link to the dry and very dry days in the SA, since there is a cooling period of SSTs in the Pacific.
3. In 2005, the anomalously warming of the SSTs of the tropical North Atlantic shows dominant correlations to the dry and very dry days of the drought in the SA. Since no significant changes of rainfall related to the very dry days as observed in the NA (in Fig. 4c, d), it suggests a rather weak role of the North Atlantic on the drought conditions in the NA.
4. In 2010, there is anomalously warming in the SSTs in the tropical North Atlantic. This abnormal rise of SSTs explains phase (ii) of the drought 2010, intensifying the drought initiated by the ENSO. Importantly, the influence of the North Atlantic on the very dry days in the NA is negligible, although having some mild effects only on dry days.
5. The tropical South Atlantic essentially is not correlated to the change of the very dry day patterns in either NA or SA. Although there is no direct correlations to the rainfalls, we notice that it has a significant role in forming the temperature gradient between the North and South Atlantic, since the SSTs in the South Atlantic experience an anomalously cooling phase when the very dry days happened in both 2005 and 2010 (in Fig. 4e, f).

5 Discussions and conclusions

We identify the annual variability of precipitation anomalies over Northeastern and Southwestern Amazonia, in particular disclosing a substantial difference between the droughts 2005 and 2010. By extracting the drought period length, we found that the drought condition in 2010 started as early as in August 2009 in the NA region forming phase (i) of this event. The phase (ii) of this event corresponds to the intensified drought in the SA due to the anomalous warming of the SSTs in the tropical North Atlantic. The two phases of the drought 2010 explain the severity on the Amazon basin from both temporal time span and spatially extensive coverage perspectives. One can perform similar analysis to drought events in other years, for instance, 1997–1998 (Coelho et al. 2012).

Furthermore, we disclose that the drought events are strongly correlated to the anomalously warming of SST, which support the hypothetical causal relationships of the surrounding oceans. Note that a statistical correlation does not necessarily suggests a causality. The influences by the Pacific and Atlantic have a different center of action within the Amazon basin. The anomalous Walker circulation is a key mechanism linking the Pacific to the dry conditions over the Amazon basin, but it is limited to the lower latitude of northeast. On the other hand, the Hadley circulation is a key mechanism linking the tropical North Atlantic and the precipitation patterns over the Amazonia, and the warming of SST in the Atlantic Ocean plays a dominant role in the dry conditions in the SA. Our results are consistent with the results reported by other studies (Marengo et al. 2008; Yoon and Zeng 2009; Coelho et al. 2012; Andreoli et al. 2012). As discussed in Coelho et al. (2012), “particularly in 2010 SST in the tropical North Atlantic reached the highest values in history, contributing to the establishment of

a local meridional Hadley circulation with upward vertical motion over the North Atlantic and downward vertical motion (subsidence) over the Amazon, and the combination of El Niño conditions in the Pacific with warm SST in the North Atlantic reinforce subsidence conditions in the Amazon, which are unfavorable to the occurrence of precipitation". This might be the unique properties of phase transition from El Niño to La Nina in 2010. La Nina event corresponds to large northward temperature gradient in the Atlantic, which favors the high SST in the tropical North Atlantic. The El Niño condition in 2010 not only broke the record of the highest SST in the central Pacific, but also it went through the fastest phase transition to La Niña (Kim et al. 2011). In addition, one needs appropriate methods to assess the causalities of these events on the Amazonian droughts.

The tropical South Atlantic essentially has no clear direct correlations to the very dry days over the Amazonian region. It shows a mild influence on dry days. However, the tropical South Atlantic is important to form the temperature gradient in the Atlantic Ocean. More specifically, shortage of rainfall over the SA region is associated with anomalously warm of SSTs in the tropical North Atlantic, coupled with anomalously cooling of SSTs in the tropical South Atlantic. Such a situation resulted in the anomalous northward displacement of the Inter-Tropical Convergence Zone (ITCZ) associated with the north–south differential gradient circulation, which is a mechanism linking the Atlantic SSTs to SA rainfall (Nobre and Srukla 1996).

A key question is whether there is a general trend towards drought conditions and, if so, whether this is associated with anthropogenic climate change, namely deforestation (Fu et al. 2013). (Li et al. 2008) suggests a more pervasive drying trend over the southern Amazon between 1970–1999. Previously, tendencies studied by Marengo (2009) during 1929–1998 suggest that no unidirectional rainfall trend has been identified in the entire Amazon region, but a slight negative/positive trend has been identified in northern/southern Amazonia. Perhaps, the most important aspect is the presence of inter-annual and inter-decadal variability in rainfall, more noticeable than any trend. This decadal variability is linked to interdecadal variations in the SST in the tropical Atlantic (Wagner 1996).

Projections of IPCC AR4 and AR5 and regional climate models (Chou et al. 2012; Joetzjer et al. 2013; Marengo et al. 2009) suggest that the eastern Amazon may become drier in the future, and that this drying could be exacerbated by positive feedbacks with the vegetation. At the broadest temporal and spatial scale, most global circulation models predict that greenhouse gas accumulation and associated increases in the radiative forcing of the atmosphere will cause a substantial (more than 20 %) decline in rainfall in the eastern Amazonia by the end of the century, with the strongest decline occurring at the end of the rainy season and in the dry season (Malhi et al. 2009; Marengo 2009; Hilker et al. 2014). If severe droughts like those of 2005 and 2010 do become more frequent in the future, this demands adaptation measures to avoid impacts on the population, particularly those living on the river's bank. The impacts felt during the droughts in 2005 and 2010 show how local population are vulnerable to climate extremes (Marengo et al. 2011): local farmers are affected by drought due to high temperatures and drought conditions; and river levels are extremely low, making it impossible to transport along the main channels, which in many cases is the only way for populations to move around and becoming isolated. Two extreme record droughts in less than five years period is something that have brought the negative impacts of extremes of climate variability and climate change in the region. Therefore, a proper assessment of the intensity, spatial coverage, and climatic impacts of the future droughts is of fundamental importance to the society (Phillips et al. 2009; Malhi et al. 2008).

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